ASME PTC 51-2011

Gas Turbine Inlet Air-Conditioning Equipment

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

INTENTIONALLY LEFT BLANK

ASME PTC 51-2011

Gas Turbine Inlet Air-Conditioning Equipment

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

Three Park Avenue • New York, NY • 10016 USA

Date of Issuance: February 29, 2012

This Code will be revised when the Society approves the issuance of a new edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this document. Periodically certain actions of the ASME PTC Committee may be published as Code Cases. Code Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org/ as they are issued.

Errata to codes and standards may be posted on the ASME Web site under the Committee Pages to provide corrections to incorrectly published items, or to correct typographical or grammatical errors in codes and standards. Such errata shall be used on the date posted.

The Committee Pages can be found at http://cstools.asme.org/. There is an option available to automatically receive an e-mail notification when errata are posted to a particular code or standard. This option can be found on the appropriate Committee Page after selecting "Errata" in the "Publication Information" section.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

CONTENTS

Figures

Tables

Nonmandatory Appendices

NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Code. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

ASME Performance Test Codes (PTCs) have long existed for determining the performance of gas turbines units and for gas-turbine-based overall plant performance in electric power production facilities. These codes have advised the user to conduct testing of gas turbines and gas-turbine-based plants with inlet conditioning out of service and to correct the results of the test with results of a subsequent test of the inlet conditioning system. Yet users of the test codes were without a test code to provide guidance of the performance of such a test since a Performance Test Code has heretofore not existed to determine the performance of gas turbine inlet air-conditioning equipment. With the growing use of gas turbine inlet air-conditioning equipment in the electric power generation industry, the need for a code addressing gas turbine inlet air-conditioning equipment became very apparent. In response to these needs, the ASME Board on Performance Test Codes approved the formation of a committee (PTC 51) in September 2002 with the charter of developing a code for the determination of inlet air-conditioning equipment performance. The organizational meeting of this Committee was held in March 2003. The resulting Committee included experienced and qualified users, manufacturers, and general interest category personnel from both the regulated and nonregulated electric power generating industry.

In developing the first issue of this Code, the Committee reviewed common industry practices with regard to inlet air-conditioning equipment testing. The Committee was not able to identify any general consensus testing methods, and discovered many conflicting philosophies, approaches, and performance definitions. For some inlet air-conditioning equipment, correction approaches to standard conditions did not exist. The Committee has strived to develop an objective code that addresses the multiple needs for explicit testing methods and procedures, while attempting to provide maximum flexibility in recognition of the wide range of inlet air-conditioning designs and the multiple needs for this Code.

This Code was approved by the PTC 51 Committee on November 17, 2010. It was then approved and adopted by the Performance Test Code Standards Committee on December 9, 2010. It was also approved as an American National Standard by the ANSI Board of Standards Review on March 30, 2011.

ACKNOWLEDGMENTS

The PTC 51 Committee wishes to acknowledge the contribution of the following individuals to the development of Nonmandatory Appendix A: Keith Khasiak, Joseph Shakal, Paul Sojka, and especially Robert Burgess, who served as Chair of the developmental group.

ASME PTC COMMITTEE
Performance Test Codes

(The following is the roster of the Committee at the time of approval of this Code.)

STANDARDS COMMITTEE OFFICERS

STANDARDS COMMITTEE PERSONNEL

Honorary Members

PTC 51 COMMITTEE — GAS TURBINE INLET AIR-CONDITIONING EQUIPMENT

Contributing/Corresponding Members

CORRESPONDENCE WITH THE PTC COMMITTEE

General. ASME Codes are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Code may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990

Proposing Revisions. Revisions are made periodically to the Code to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Code. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Code. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Code to which the proposed Case applies.

Interpretations. Upon request, the PTC Standards Committee will render an interpretation of any requirement of the Code. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject: Cite the applicable paragraph number(s) and the topic of the inquiry.

Edition: Cite the applicable edition of the Code for which the interpretation is being requested.

Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not approve, certify, rate, or endorse any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC Standards Committee and PTC Committees hold meetings regularly, which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the PTC Committee.

INTENTIONALLY LEFT BLANK

GAS TURBINE INLET AIR-CONDITIONING EQUIPMENT

Section 1
Object and Scope

1-1 OBJECT

This Code provides procedures for in situ testing of inlet air-conditioning systems (cooling/heating) as they apply to gas turbines in simple, cogeneration, and combined-cycle applications.

The intent of this Code is to provide results with the lowest reasonably achievable uncertainty consistent with the best engineering knowledge and practice in the industry, such that appropriate instrumentation and measurement techniques and procedures be used to determine the following performance variables, as applicable:

– performance factor
– carryover
– auxiliary consumption (power/thermal)
– temperature change
– water discharge
– water consumption
– distribution/stratification
– pressure drop

This Code also provides procedures for the calculation of the results, and for the correction of the results to reference conditions, as a measure of gas turbine inlet air-conditioning systems performance.

1-2 SCOPE

This Code may be used for in situ testing of inlet air-conditioning systems (cooling/heating) as they apply to gas turbines in simple, cogeneration, and combined-cycle applications. Cooling systems covered by this Code include evaporative systems (foggers and media-based evaporative coolers) and mechanical/thermal refrigeration systems. Heating systems covered by this Code include compressor-bleed type systems and heating-coil systems.

This Code is limited to gas turbine inlet air-conditioning systems and does not apply to the following:

– building heating, cooling, or refrigeration systems
– gas turbine compressor intercoolers
– wet compression, overspray, deluge, overfogging, and similar technologies
– other power plant applications such as air-cooled electrical generators
– gas turbine performance

In addition, this Code does not apply to the testing of individual atomizing nozzles. However, the Committee recognizes that carryover is a critical characteristic of fogging systems. As such, there may be situations that require the quantification of water droplet size. To address this need, the Code further provides the procedures for determining water droplet size associated with laboratory bench testing of atomizing nozzles; please see Nonmandatory Appendix A.

This Code contains rules and procedures for conducting and reporting tests of gas turbine inlet air-conditioning systems, including requirements for pretest arrangements, testing techniques, instrumentation, methods of measurement, and methods for calculating test results and uncertainty.

1-3 UNCERTAINTY

A pretest uncertainty analysis is required to demonstrate that the proposed instrumentation and measurement techniques meet the requirements of this Code; this analysis shall include an estimate of the random uncertainty based on experience. A posttest uncertainty analysis is required to evaluate overall test uncertainty, including the actual random uncertainty and spatial uncertainties associated with the test result. To accomplish testing with reasonable accuracy, limits for both the test instrument uncertainty and the variation for each required measurement are established in this Code.

Limits on uncertainty and variations for each measurement were set in recognition of the fact that there is a diverse range of inlet air-conditioning system designs covered by this Code. Each unique system has corresponding uncertainty levels that are dependent on the system type, specific design complexity, and consistency of operation during a test and cannot be generally categorized for purposes of establishing uncertainty limits on the test results achievable from testing in accordance with this Code.

Table 1-3-1 Representative Test Uncertainties

Type of System	Performance Factor, %	Carryover [Note (1)], %	Auxiliary Consumption, %	Temperature Change, K (°R)	Water Discharge, %	Water Consumption, %	Temperature Distribution / Stratification, K (°R)	Pressure Drop, %
Evaporative cooler	3 [Note (2)]	Varies	5	0.6 (1)	5	5	0.6 (1)	5
Fogger	5 [Note (2)]	Varies	5	0.6 (1)	5	5	4.0 (7)	NA
Chiller	NA	Varies	1 (electrical) 3 (thermal)	0.6 (1)	5	NA	0.6 (1)	5
Heater (compressor-bleed type)	NA	Varies	3	0.6 (1) [Note (3)]	NA	NA	1.0 (2) [Note (3)]	NA
Heater (coil type)	NA	Varies	3	0.6 (1)	NA	3	0.6 (1)	5

GENERAL NOTES:

(a) Table 1-3-1 values should not be used as targets. The user of this Code should design a test for the lowest practical level of uncertainty based on current engineering knowledge.

(b) See Nonmandatory Appendix B for sample uncertainty analyses.

NOTES:

(1) The Committee recognizes that there may be different criteria for determining acceptable carryover limits (e.g., "none," "by visual inspection," "determined by droplet size," "quantified by %," "quantified by gpm," etc.) by technology and application. As such, no specific uncertainty limits are provided, but instead, it is left up to the parties of the test to determine what is acceptable, based on the method used to determine or quantify carryover.

(2) Performance factors for evaporative coolers and foggers are, respectively, effectiveness and fogging.

(3) The Committee recommends a minimum of 1 s of residence time from the hot-fluid injection point to instrument measurement.

Table 1-3-1 shows the calculated uncertainty for some typical systems derived using the limiting uncertainties of all measurement parameters and variables.

Most tests conducted in accordance with this Code will result in uncertainties that are lower than those shown in Table 1-3-1. Any departure from this Code's requirements could introduce additional uncertainty beyond that considered acceptable to meet the objectives of this Code. A test that exceeds the uncertainty and variation limits defined in this Code would be considered a non-Code level test.

1-4 OTHER REQUIREMENTS AND REFERENCES

The applicable provisions of subsection 1-2 are a mandatory part of this Code. The ASME PTC 19 series *Supplements on Instruments and Apparatus* should be consulted when selecting the instruments and when calculating test uncertainties.

Section 2
Definitions and Description of Terms

2-1 SYMBOLS

The symbols and subscripts in Tables 2-1-1 and 2-1-2 are used unless otherwise defined in the text.

Table 2-1-1 Symbols

		Units	
Symbol	Description	SI	U.S. Customary
$2s_{\bar{x}}$	Uncertainty (random) at 95% confidence	...	...
A	Area	m^2	ft^2
AD or D_{21}	Absorption diameter	μm	...
AMD or D_{10}	Arithmetic mean diameter	μm	...
AUX	Auxiliary load, electric or thermal	W or kJ/s	W or Btu/hr
C	Constant (generic)	Various	Various
c	Concentration, mole	%	%
C1	Time conversion constant	1	3,600 sec/hr
C2 [Note (1)]	Unit conversion factor	...	...
C_d	Discharge coefficient	...	...
C_f	Flow coefficient	...	...
C_p	Specified heat at constant pressure	kJ/(kg · K)	Btu/(kg · °F)
CV	Concentration volume	ppm	ppm
D	Diameter	μm	in.
E	Electric voltage	V	V
ED or D_{31}	Evaporative diameter	μm	...
e_k	Specific kinetic energy	J/kg	ft-lbf/lbm
FPF	Fogger performance factor	...	...
GT	Gas turbine	...	...
g_c [Note (2)]	Gravitational constant	$kg{\cdot}m/N{\cdot}s^2$	$lbm{\cdot}ft/lbf{\cdot}s^2$
H	Thermal load	W	Btu
h	Enthalpy	kJ/kg	Btu/lbm
I	Electric current	A	A
K_n	Conversion constant	Varies	Varies
k	Ratio of specific heats	...	...
MMD or Dv_{50}	Mass median diameter	μm	...
m	Mass flow rate	kg/s	lbm/hr
n	Number of readings	...	...
PF	Power factor	...	...
p	Pressure	kPa	psia
Q	Volumetric flow rate	m^3/s	cfm

Table 2-1-1 Symbols (Cont'd)

Symbol	Description	Units	
		SI	U.S. Customary
q	Heat flow rate	kJ/s	Btu/hr
R	Gas constant	J/(kg·K)	Btu/lbm·°R
RH	Relative humidity	%	%
$SAMD$	Surface area mean diameter	μm	...
SMD or D_{32}	Sauter Mean Diameter	μm	...
S_p	Frontal area of probe exposed to calibration stream	ft^2	m^2
T	Temperature	K (°C)	°R (°F)
U	Uncertainty (total)	...	...
VMD or D_{30}	Volume mean diameter	μm	...
Vol%	Percent by volume	%	%
v	Velocity	m/s	ft/sec
Wt%	Percent by weight	%	%
w	Weighting factor	...	...
X	Composition	Various	Various
z	Elevation	m	ft
α	Multiplicative correction factor	...	...
β	Error (systematic)	...	...
γ	Kinetic energy correction factor	...	...
δ	Error (total)	...	...
Δ	Difference	Varies	Varies
Δp	Differential pressure	Pa	in. H_2O
ε	Evaporative effectiveness	%	%
ε_r	Error (random)	...	...
η	Efficiency	...	...
Π	Product	...	...
ρ	Density	kg/m^3	lbm/ft^3
Σ	Sum	...	...
ϕ	Pitch angle	rad	deg
ψ	Yaw angle	rad	deg
ω	Specific humidity	kg_w/kg_{da}	lbm_w/lbm_{da}

GENERAL NOTE: The International Systems of Units (SI) is employed in this Standard. Values shall be based on the National Institute of Standards and Technology values, which, in turn, are based on the fundamental values of the International Bureau of Weights and Measures.

The unit of length is the meter, designated m, or the millimeter, designated mm. The unit of mass is the kilogram, designated kg. The unit of time is the minute, designated min, or the second, designated s. The unit of temperature is either the degree Celsius, designated °C, or the kelvin, designated K. The unit of force is the newton, designated N. The unit of barometric pressure is the atmosphere, designated atm.

NOTES:
(1) Units of C2 are 1×10^{10}.
(2) Units of g_c are 1 kg m/N s^2 (32.17 lbm-ft/lbf sec^2).

Table 2-1-2 Subscripts

Subscript	Description
0,..., 9	Numeric integer (used as value for *i*, *n*, or *j*)
12	Arithmetic mean
20	Surface area mean
21	Surface area-length (absorption)
31	Volume length (evaporative)
30	Volume mean
32	Sauter mean
Ar	Argon
a	Air
ave	Average
b	Barometric
CO2	Carbon dioxide
c	Constant
co	Carryover
cons	Consumed
corr	Corrected
D	Droplet
d	Discharge
da	Dry air
db	Dry bulb
dp	Dew point
dry	Dry
exh	Exhaust
f	Fluid
fuel	Fuel
g	Gage
H2O	Water
i	Generic plane number (integer)
j	Generic (discreet) point number (integer)
k	Kinetic
l	Liquid
meas	Measured
N_2	Nitrogen
n	Number (integer)
O2	Oxygen
ox	Oxidation
SO2	Sulfur dioxide
sp	Set point
st	Static
t	Total
v	Velocity
vap	Vapor
w	Water
wb	Wet bulb
x	Unknown

2-2 DEFINITIONS

absolute pressure: algebraic sum of the atmospheric pressure and gage pressure.

absolute pressure transmitter: an instrument that measures pressure referenced to absolute zero pressure and transmits the information.

accuracy: the closeness of agreement between a measured value and the true value.

air: mixtures of dry gases and associated water vapor surrounding the earth; dry air plus its associated water vapor.

air-assisted nozzle: fluid atomization device that incorporates an energized stream of air to facilitate atomization of the liquid.

air density: mass of air per unit volume.

air density, standard: air at density of 0.075 lbm/ft^3 (1.201 kg/m^3).

airflow, mass: mass of dry air flowing through a piece of equipment (e.g., a cooling tower, GT inlet duct, etc.).

airflow, volume: volume of air mixture flowing through a piece of equipment (e.g., a cooling tower, GT inlet duct, etc.).

ambient temperature: temperature of the atmosphere.

approach: difference between cold water temperature and entering wet-bulb temperature.

arithmetic mean diameter (AMD): see $D_{10.}$

atmosphere: see *air*.

atomizing nozzle: a nozzle designed to develop water droplets less than 200 μm in diameter.

auxiliary consumption: electrical or thermal energy used in the operation of a gas turbine inlet air-conditioning device or elsewhere as defined by the test boundary.

auxiliary load: see *auxiliary consumption*.

barometric pressure: force per unit area exerted by the atmosphere.

base reference conditions: the values of all the external parameters; that is, parameters outside the test boundary to which the test results are corrected. Also, the specified secondary heat inputs and outputs are base reference conditions.

bias error: the true systematic or fixed error, which characterizes every member of any set of measurements from the population. It is the constant component of the total measurement error.

bivariate correction: a correction that is a function of two independent parameters.

blowdown: water discharged from a system to control the concentration of minerals or other impurities, such as from an evaporative cooler or wet cooling tower.

bore area: the minimum cross-sectional flow area of a nozzle.

bore diameter: the minimum diameter of a nozzle.

calibration: the process of comparing the response of an instrument to a standard instrument over some measurement range and adjusting the instrument to match the standard, if appropriate.

calibration drift: a shift in the calibration characteristics.

carryover: excess moisture that is not evaporated into the air stream.

chiller: a device that uses a closed-loop refrigeration cycle where heat is exchanged with an external fluid after the refrigerant is expanded, resulting in a reduction in temperature of the external fluid. Typical refrigeration cycles include mechanical chilling where refrigerants (such as r134a) are compressed, condensed, expanded, and evaporated in a continuous loop similar to an air conditioner, or an absorption process using refrigerants (such as lithium bromide or ammonia).

circulating water flow: quantity of hot water flowing into the tower to be cooled.

class 1 instrument: an instrument that is used to determine a class 1 primary parameter.

class 1 primary parameter: a primary parameter that has a relative sensitivity coefficient of 0.2% or greater.

class 1 primary variable: a primary variable that has a relative sensitivity coefficient of 0.2% or greater.

class 2 instrument: an instrument that is used to determine a class 2 primary parameter.

class 2 primary parameter: a primary parameter that has a relative sensitivity coefficient of less than 0.2%.

class 2 primary variable: a primary variable that has a relative sensitivity coefficient of less than 0.2%.

closed-loop heater/chiller system: a heating/chilling system in which the working fluid does not become entrained in the gas turbine inlet air stream.

co-current flow: the flow of two or more fluids following a similar path with adjacent inlet and outlet connections.

coefficient of discharge (C_d): the ratio of the measured relieving capacity to the theoretical relieving capacity.

compressor inlet: the plane containing the furthest upstream portion of inlet bellmouth of the compressor.

compressor inlet temperature: the dry-bulb temperature of the air at the compressor inlet measured at a point prior to the rapid acceleration/pressure drop as the airflows into the bell mouth.

conditioning element: any physical device described in this Code that is used primarily for heating or cooling, and/or humidifying or dehumidifying the GT inlet air prior to entering the gas turbine.

control temperature: temperature or schedule of temperatures determined by the manufacturer that defines one of the operating conditions for the test. This temperature may or may not coincide with the temperature of the working fluid exiting the gas turbine. Regardless of measurement location, control temperature is internal to the test boundary.

cooling tower: a semienclosed device for cooling water by direct contact with air.

corrected performance: performance parameter adjusted mathematically to specified reference conditions.

counterflow: the flow of fluids through a heat exchanger in which the two fluids flow in opposite directions.

counterflow tower: a tower in which the air and water streams flow in opposing directions.

cross-flow: the flow of fluids through a heat exchanger in which the two fluids flow perpendicular to each other.

cross-flow tower: a tower in which the air and water streams are in crosscurrent (perpendicular) flow.

D_{10}: arithmetic mean diameter (*AMD*). The simple average diameter of all the droplets in a spray. D_{10} is equal to the sum of the diameter of all the droplets divided by the number of droplets.

$$D_{10} = \frac{\sum n_i D_i}{\sum n_i}$$

D_{20}: surface area mean diameter (*SAMD*). The *SAMD* value characterizes the spray by giving the diameter of a hypothetical droplet that has a surface area equal to the average surface area of all the measured droplets.

$$D_{20} = \left(\frac{\sum n_i D_i^2}{\sum n_i} \right)^{1/2}$$

D_{21}: surface area-length (absorption) diameter. This diameter is calculated using the surface-to-diameter ratio. It is equal to the sum of the square of all the droplet diameters divided their straight sum.

$$D_{21} = \left(\frac{\sum n_i D_i^2}{\sum n_i D_i} \right)$$

D_{30}: volume mean diameter (*VMD*). The VMD value characterizes the spray by giving the diameter of a hypothetical droplet that has a volume equal to the average volume of all the measured droplets.

$$D_{30} = \left(\frac{\sum n_i D_i^3}{\sum n_i} \right)^{1/3}$$

D_{31}: volume length (evaporative) diameter (*ED*). This diameter is calculated using the volume-to-diameter ratio. It is equal to the sum of the cube of all the droplet diameters divided by their straight sum.

$$D_{31} = \left(\frac{\sum n_i D_i^3}{\sum n_i D_i} \right)^{1/2}$$

D_{32}: sauter mean diameter (*SMD*). This diameter is calculated using the volume-to-surface-area ratio. It is equal to the sum of the cube of all diameters divided by the sum of the square of all diameters. This yields a characteristic droplet diameter that has a volume-to-surface-area ratio equal to the volume-to-surface-area ratio of the entire spray. This diameter is particularly important in gas turbine evaporative fogging system applications because the mass transfer happens at the interface of the droplets and the surrounding air (i.e., at the droplet surface). To enhance the evaporation of a population of droplets, one has to maximize the active surface areas and minimize the internal volumes.

$$D_{32} = \left(\frac{\sum n_i D_i^3}{\sum n_i D_i^2} \right)$$

differential pressure: the difference between the inlet pressure and the discharge pressure. Alternatively, the difference between two pressure zones, i.e., upstream and downstream of evaporative cooling media in the GT inlet.

dimensionless groups: the various dimensionless quantities that appear in this Code. Any consistent system of units may be employed to evaluate these quantities unless a numerical factor is included, in which case units shall be as specified.

direct evaporative cooler: an evaporative cooler that adds moisture to the inlet air stream.

droplet size: the physical size of water droplets in the inlet air stream. These are generally measured in units of microns using one or more of the diameter scales and reference test methods contained within this Code. (Note that for nozzle performance criteria, it is unacceptable to report droplet diameter in microns only; the reference scale and test method shall also be stated.)

$Dv_{01} = Dv_{10}$: this is a representative diameter where 10% of the total volume of the liquid sprayed is in droplets with diameters smaller than or equal to the stated value.

Dv_{05} (or Dv_{50})*:* mass median diameter (*MMD*). This is the same as the volume median diameter (VMD). This is the representative diameter where 50% of the total volume of the liquid sprayed is in droplets with diameters larger than the stated value and 50% is in droplets with diameters smaller than the stated value.

Dv_{09} (or Dv_{90})*:* This is the representative diameter where 90% of the total volume of the liquid sprayed is in droplets with diameters smaller than or equal to the stated value.

electric efficiency: the ratio of the electrical energy output to the energy supplied to the power system, expressed as a percentage. It is inversely related to heat rate.

emissions: nuisance discharges from power plant systems that are regulated by authorities having jurisdiction; examples include air pollutants, waste streams, and noise.

empirical formulation: a representative equation to determine the discharge coefficient for a flow meter, developed via theory and experience without application of meter-specific calibration data.

entering wet-bulb temperature: the wet-bulb temperature of air entering the tower; includes any effect of recirculation, interference, or both.

evaporation: the water evaporated from the circulating water into the atmosphere during the cooling process. It is independent of drift.

evaporative effectiveness: the ratio of temperature drop across an evaporative cooler to the potential amount of cooling ($t_{db} - t_{wb}$), expressed as percentage.

extraction air: air stream that leaves the test boundary.

field calibration: the process by which calibrations are performed under less controlled conditions and using less rigorous measurement and test equipment than that provided under a laboratory calibration.

flow-metering run: the entire section of piping consisting of the primary element, flow conditioner (if applicable), and upstream and downstream piping that conforms to the overall straight length and other manufacturing and installation requirements that are codified.

fluid-flow nozzle: fluid-flow measurement device in the style of an ASME-defined flow nozzle, with converging/diverging sections that use differential pressure to measure flow.

flux technique: measurement of droplets that pass through a fixed area during a specific time interval. It is a number or flux-weighted technique.

fogging: the humidification of gas turbine inlet air by direct contact with water droplets (e.g., no evaporative media is utilized).

fogging performance factor: relates the amount of water used to cool the inlet air to the target temperature to the amount of water used to cool the air to saturation.

fogging spray nozzle: component of a fogging system employed to cause high-pressure water to be emitted into the inlet air-flow stream of the combustion turbine in the form of appropriately sized droplets.

forced draft tower: a type of mechanical draft tower in which the air-moving device is located at the air inlet.

gage pressure: pressure measured with respect to the atmospheric pressure.

gage pressure transmitter: an instrument that measures pressure referenced to atmospheric pressure and transmits the information.

gas turbine (GT): a machine that converts thermal energy into mechanical work; it consists of one or several rotating compressors, one or several thermal devices that heat the working fluid (typically via combustion), one or several turbines, a control system, and essential auxiliary equipment. Any heat exchangers (excluding exhaust-heat recovery exchangers) in the main working-fluid circuit are considered to be part of the gas turbine. For the purposes of this Code, this definition is synonymous with "combustion turbine."

gas turbine power plant: gas turbine and all essential equipment necessary for the production of power in a useful form (e.g., electrical, mechanical, or thermal).

heat load: the rate of heat removal, or the amount of heat required to be dissipated from a heat exchanger.

heat loss: energy quantity that leaves the test boundary outside defined exits.

heat sink: the reservoir to which the heat rejected by the system is transferred. For a pond, river, lake, or ocean cooling system, the reservoir is the body of water. For an evaporative or dry air-cooled heat exchanger system, the reservoir is the ambient air.

heater: a device that is used to increase the temperature of ambient air prior to its entering the compressor inlet.

hot water temperature: weighted average temperature of heated water entering a system heat-rejection component (e.g., cooling tower for a chiller system, heat exchanger, etc.).

impingement nozzle: a fogging nozzle in which a stream of high-pressure water is directed to the tip of an impact pin where the stream of water is sheared to produce fog-size droplets.

indirect evaporative cooler: an evaporative cooling system in which the evaporation process is external to the inlet air stream and does not increase the moisture content of the inlet air stream. An example would be circulating water from a cooling tower through coils in the inlet air duct.

induced draft tower: a type of mechanical draft tower in which the air-moving device is located at the air exhaust.

injection fluid: gaseous or liquid stream that enters the test boundary.

inlet air treatment device: the device used to cool or heat the inlet air prior to entry into the gas turbine compressor.

inlet manifold: the last section of inlet duct that the airflows through before entering the inlet bellmouth.

instrument: a tool or device used to measure physical dimensions of length, thickness, width, weight, or any other value of a variable. These variables can include size, weight, pressure, temperature, fluid flow, voltage, electric current, density, viscosity, and power. Sensors are included that may not, by themselves, incorporate a display but that transmit signals to remote computer-type devices for display, processing, or process control. Also included are items of ancillary equipment directly affecting the display of the primary instrument (e.g., an ammeter shunt). Also included are tools or fixtures used as the basis for determining part acceptability.

laboratory calibration: the process by which calibrations are performed under controlled conditions with highly specialized measuring and test equipment that has been calibrated by approved sources, and remain traceable to the National Institute of Standards and Technology (NIST) or a recognized natural physical (intrinsic) constant through unbroken comparisons having defined uncertainties.

ligament: the relation of the liquid in the air stream prior to discreet atomization. Water initially sprayed from an atomizing nozzle initially shears from the water flow stream into ligaments before achieving a spherical droplet shape.

light-scattering (diffraction) instrument: a measurement system that is used to determine the size distribution of particles based on the light-scatter pattern that is measured using diodes. The scatter pattern from a population of particles can be deconvoluted mathematically to infer a size distribution based on known light-scattering principles.

loop calibration: the calibration of the instrument through the signal-conditioning equipment including the recording device.

makeup: water added to the system to replace water lost by evaporation, drift, blowdown, and leakage.

mass median diameter (MMD): see Dv_{05}.

measurement error: the true, unknown difference between the measured value and the true value.

measurement uncertainty: estimated uncertainty associated with the measurement of a process parameter or variable.

mechanical draft tower: a type of cooling tower through which the air movement is affected by mechanical devices. See *forced draft tower* and *induced draft tower*.

natural draft tower: a type of cooling tower through which the air movement is affected by the difference in densities of the entering and exhaust air.

nozzle: a generic term for any of the defined types of nozzles in this Code. The user should take into account the context in which the term is used and the individual nozzle of interest to determine which specific nozzle type applies for their specific situation.

nozzle area, nozzle throat area: see *bore area*.

Nukiyama-Tanasawa: a three-parameter model curve fit describing the droplet-size distribution.

obscuration (optical concentration): the amount of incident laser light as measured by the detector that is "blocked" by the presence of the spray droplets.

open-loop heater/chiller system: a heating/chilling system that operates in such a way that the working fluid becomes entrained in the gas turbine inlet air stream.

parameter: a direct measurement; also, a parameter is a physical quantity at a location that is sensed by direct measurement of a single instrument, or determined by the averaged measurements of several similar instruments of the same physical quantity.

performance factor: a generic term that describes a test goal that is used to define the overall performance characteristic of a specific technology:

Technology	Performance Factor
Evaporative cooling	Effectiveness
Fogging	Fogging performance factor
Chilling	N/A
Heating	N/A

primary element: the component of a differential-pressure flow-metering run that is flanged or welded between specially manufactured pipe sections, across which the pressure drop is measured to calculate flow. The component may be an orifice plate, a nozzle, or a venturi.

primary parameter: a direct measurement and a physical quantity at a location that is determined by a single instrument, or by the average of several similar instruments, that is used in the calculations of test results.

primary variables: variables used in calculations of test results. They are further classified as

(a) *Class 1* — primary variables are those with a relative influence coefficient of 0.2 or greater.

(b) *Class 2* — primary variables are those with a relative influence coefficient of less than 0.2.

NOTE: Refer to ASME PTC-19.1 for the determination of relative sensitivity coefficients.

random error, ε_r: sometimes called *precision error*; the true random error, which characterizes a member of a set of measurements [varies in a random, Gaussian (normal) manner, from measurement to measurement].

random uncertainty, 2S: an estimate of the plus/minus (±) limits of random error with a defined level of confidence (usually 95%).

range: difference between hot water and cold water temperatures.

recirculation: that portion of the tower exhaust air that reenters the tower inlet. It can be expressed as a difference between the average entering and windward side wet-bulb temperatures.

records: a complete set of measurements for a particular point of operation of a nozzle. The measurements must be sufficient to determine all nozzle performance variables as defined in this standard.

redundant instrumentation: two or more devices measuring the same parameter with respect to the same location.

reference heat balance: diagram indicating the base thermodynamic conditions for the steam turbine to which test results are corrected.

relative span factor (RSF): a dimensionless parameter indicative of the uniformity of the drop size distribution. It is given by $RSF = (Dv_{09} - Dv_{01})/Dv_{05}$.

Rosin-Rammler [Rosin Rammler Sperling Bennett (RRSB)]: a two-parameter model curve fit describing the droplet-size distribution. Refer to DIN Standard 66145.

run: the readings and/or recordings sufficient to calculate performance at one operating condition.

Sauter mean diameter (SMD): see D_{32}.

secondary parameter: a parameter that is not used in the calculation of test results, but is used to ensure the required test condition was not violated.

secondary variables: variables that are calculated but do not enter into the calculation.

sensitivity: the ratio of the change in a result to a unit change in a parameter.

spatial technique: measurements of droplets contained within a volume under conditions such that the contents of the volume do not change during any single measurement.

specific volume: the volume of air-vapor mixture per unit mass of dry air.

standard atmospheric conditions: 101.325 kPa (14.696 psia), 288.15 K (519°R), and relative humidity of 60% [also called STP (standard temperature and pressure)].

stratification: the condition in which an inlet air condition is measurably different (greater than the accuracy of instrumentation) throughout the flow stream in a given cross section of inlet air duct when operating an inlet air-cooling or air-heating system (also called nonhomogeneous).

NOTE: Preexisting stratification conditions caused by other equipment within the power plant (e.g., cooling towers, open air-cooled generator vents, finned-fan heat exchangers, etc.) can cause significant stratification that makes determination of stratification by the cooling or heating system impractical.

surface area-length (absorption diameter): see D_{21}.

surface area mean diameter (SAMD): see D_{20}.

swirl nozzle: a fogging nozzle in which water enters a whirl chamber behind the faceplate of a nozzle from an angle that is tangential to the orifice in the faceplate through one or more passages. Water flowing through the orifice is sheared into ligaments by the whirling movement of water flowing from the orifice. This type of nozzle is also referred to as a pinless-type nozzle.

systematic error, â: see *bias error*.

systematic uncertainty, β: an estimate of the plus/minus (±) limits of systematic error with a defined level of confidence (usually 95%).

temporal technique: see *flux technique.*

test: a group of test runs comprising a series of points and results adequate to establish the performance over the specified range of operating conditions.

test boundary: the thermodynamic control volume defined by the scope of the test, and for which the mass and energy flows must be determined. Depending on the test, more than one boundary may (need to) be applicable.

test goal: the object or resulting parameter of interest from performing a test.

test plane: a reference plane for measurement or parameter designation.

test reading: one recording of all required test instrumentation.

test run: a group of test readings taken over a specific time period over which operating conditions remain constant or nearly so.

test uncertainty: uncertainty associated with a corrected test result.

total (measurement) error, ä: the true, unknown difference between the assigned value of a parameter or test result and the true value.

traceable: a term used to indicate that records are available demonstrating that the instrument can be traced through a series of calibrations to an appropriate ultimate reference such as the National Institute for Standards and Technology (NIST).

transmission: 1 − obscuration, or if obscuration is a percent value, then it is equal to the quantity of (100 − obscuration)%.

uncertainty, U: ±*U* is the interval about the measurement or result that contains the true value for a given confidence level.

univariate correction: a correction that is a function of only one independent parameter.

variable: a variable is an unknown quantity in an algebraic equation that must be determined.

verification: a set of operations that establish evidence by calibration or inspection that specified requirements have been met.

vignetting (optical cutoff): an optical effect that occurs when the diffraction from any droplet in the spray is at such an angle that it reaches the plane of the receiving lens outside the aperture of the lens. In general, the farthest edge of the spray should be within the "working distance" of the collecting lens, as defined by the instrument manufacturer.

volume length (evaporative) diameter (ED): see D_{31}.

volume mean diameter (VMD): see D_{30}.

water carryover (general): water in the form of droplets or coalesced and flowing along inlet surfaces that cross the defined test boundary. In the case of inlet fogging, this would be water droplets that enter the compressor or flow along the inlet bellmouth and inlet struts. In the case of inlet-chilling or inlet-fogging systems, the boundary will generally be upstream of the inlet silencing panels.

water consumption: water evaporated into the inlet air stream.

water discharge: water streams including blowdown, drain flow, condensed water, and other water effluent streams from the boundary, as applicable.

wet-bulb depression: the difference between dry-bulb and wet-bulb temperatures.

wet-bulb temperature: the temperature indicated by a properly designed wet-bulb instrument. This closely approximates the thermodynamic wet-bulb temperature (i.e., temperature of adiabatic saturation).

Section 3
Guiding Principles

3-1 PREPARATIONS FOR TESTING

3-1.1 General Precaution

Reasonable precautions should be taken when preparing to conduct a Code test. Records shall be made to identify and distinguish the equipment to be tested and the exact method of testing selected. Descriptions, drawings, or photographs all may be used to give a permanent, explicit record. Instrument location shall be predetermined, agreed to by the parties to the test, and described in detail in test records. Redundant, calibrated instruments should be provided for those instruments susceptible to in-service failure or breakage or where spatial variations in readings are expected, and where results are highly sensitive to the primary reading, such as for a Class 1 primary variable.

3-1.2 Agreements

Prior to any tests, a test procedure shall be prepared with agreement on the test objective, test scope, exact method of testing, and method of measurement. The test procedure should include the following:

(a) the object of the test, including any secondary demonstration tests such as pump performance, alarm points, and fogging spray-nozzle atomization, etc.

(b) identification of the test lead, herein referred to as a Test Coordinator, who will direct the testing, as well as direct the other personnel involved in testing. All parties to the test shall be privileged to be present at all times to certify that the test is conducted in accordance with this Code and any agreements made prior to the tests.

(c) designation of the party to the test that is responsible for the preparation of the inlet air-conditioning system for the test.

(d) conditions required for execution of the test.

(e) procedure for recording readings and observations.

(f) frequency of observations and duration of the test.

(g) definition of the base reference conditions.

(h) determination of the number of significant figures to meet the uncertainty requirements for the test.

(i) type, number, calibration method, and measurement uncertainty of all instruments to be used in accordance with this Code.

(j) method of recording and archiving data.

(k) method of operation of the equipment to be tested, including definition of stable operation prior to commencing a test run, which shall be consistent with operating requirements of the equipment supplier.

(l) identification of allowable changes in the control system, if any, during the test.

(m) operating characteristics of the inlet air-conditioning system during the test.

(n) list of auxiliary loads accountable to the operation of the inlet air-conditioning system during testing.

(o) curves, thermodynamic models, and/or numerical values for corrections or adjustments to be applied to the test data for test conditions differing from the specified conditions (see Section 5).

(p) method of computing test corrections and test results.

(q) method of comparing test results with specified performance.

(r) type, duration, and number of tests to be run.

(s) definition of the test boundary for the test. A sample test boundary is provided in Fig. 3-1.2-1, and detailed examples can be found in Section 5.

(t) limit for deviation of test conditions from the specified conditions of the inlet air-conditioning system (see Table 3-3.1-1) and actions to take if limits are exceeded.

(u) conditions for rejection of outlier test readings or runs.

(v) intent of contract or specification if ambiguities or omissions appear evident.

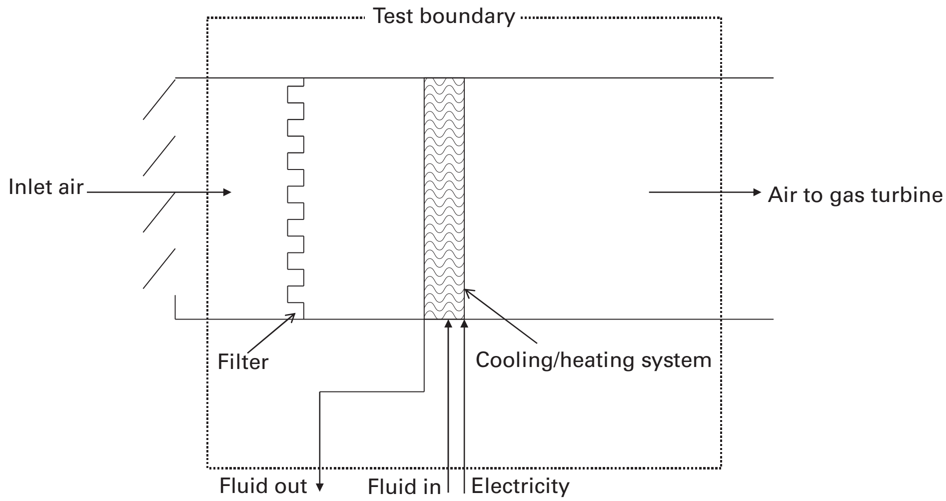
(w) method of determining the overall test uncertainty.

(x) pretest uncertainty analysis.

3-1.3 Preliminary Test Runs

Recorded preliminary test runs serve to determine if equipment is in suitable condition to test, to check instruments and methods of measurement for consistency with requirements in Section 4, to check adequacy of organization and procedures, and to train personnel. Parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If such a preliminary test run complies with all the necessary

Fig. 3-1.2-1 Sample Test Boundary



requirements of the test Code, it may be used as an official test run within the meaning of the applicable Code.

Section 5 contains several specific test-boundary examples.

3-1.4 Agreements and Compliance to Code Requirements

This Code is suitable for use whenever performance must be determined with minimum uncertainty. Strict adherence to the requirements specified in this Code is critical to achieving that objective.

This Code may be incorporated by reference into contracts to serve as a means to verify commercial guarantees. If the test is to be conducted as a part of contractual requirement and/or involves more than one independent party, the pertinent parties to the test shall agree on issues not explicitly prescribed by the Code. The following list identifies specific requirements for conducting a Code test:

(a) The manufacturer or supplier shall have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust equipment or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the equipment for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions of the equipment and the equipment outside the test boundary. Actions taken pertinent to the performance test shall be documented and immediately reported to all pertinent parties to the test.

(b) Testing should be undertaken as soon as possible after commissioning of the inlet air-conditioning system, or immediately following an inspection and possible correction of defects, which satisfies the pertinent parties that the equipment is suitable to undergo the test.

(c) The test procedure shall be approved by all pertinent parties to the test, and any deviations to the Code that are permitted in the commercial test procedure shall be identified prior to the test.

(d) Representatives from each of the pertinent parties to the test shall be designated who will be part of the test team and who will observe the test and confirm that it was conducted in accordance with the test requirements. They should also have the authority, if necessary, to approve any agreed-upon revisions to the test requirements during the test.

(e) The pertinent parties shall agree upon contract or specification requirements regarding operating conditions, base reference conditions, performance guarantees, test boundary, and environmental compliance.

(f) Requirements shall be in support of a Code test, including equipment operation, ambient conditions, and condition of the equipment.

(g) Notification requirements shall be established prior to test preparation to ensure all pertinent parties have sufficient time to be present for the test.

(h) The pertinent parties shall have reasonable opportunity to examine the inlet air-conditioning equipment and agree that it is ready to test.

(i) Modifications to the Test Procedure Based on Preliminary Testing. A pretest meeting shall be conducted among the pertinent parties as described in para. 3-2.1.

(j) Those conducting the test shall operate the equipment within the suppliers' design and operating specifications.

(k) The pertinent parties shall determine what actions to take if site conditions are outside the limits listed in Table 3-3.1-1.

(l) Stability criteria shall be clearly defined prior to starting a test.

Table 3-3.1-1 Maximum Permissible Deviation From Base Reference Conditions and Minimum and Maximum Requirements

Variable	Media-Type Evaporative Cooler	Inlet Fogger	Inlet Chiller	Inlet Heating [Note (1)]
Maximum Permissible Deviations				
Inlet temperature (dry bulb)	±8.3°C (15°F)	±8.3°C (15°F)	±8.3°C (15°F)	±13.9°C (25°F)
Inlet temperature (wet bulb)	±5.6°C (10°F)	±5.6°C (10°F)	±2.8°C (5°F)	...
Barometric pressure	±3.45 kPa (0.5 psia)	±3.45 kPa (0.5 psia)	±3.45 kPa (0.5 psia)	±3.45 kPa (0.5 psia)
Heat load	...	...	...	10%
Minimum Requirements				
Minimum ambient wet-bulb depression	5.6°C (10°F)	85% of cooling capacity [Note (3)]	...	...
Minimum ambient wet-bulb temperature [Note (2)]	4.4°C (40°F)	4.4°C (40°F)	...	...
Maximum Requirements				
Maximum dry-bulb temperature	46°C (115°F)	...	...	...

NOTES:
(1) Heat duty within 20% of design value per ASME PTC 30, subsection 3-14.
(2) The greater of the values in the table and the equipment manufacturer's minimum to prevent icing.
(3) Wet-bulb suppression of 85% is provided as a minimum to reduce the uncertainty that the fogging-system test corrections will represent system performance at rated conditions. System performance at reduced wet-bulb suppression levels are recommended to verify that other test objectives such as overspray are satisfied (e.g., 50% and 70% of system-related cooling capacity).

(m) Permissible adjustments to equipment operations during stabilization and between test runs shall be agreed upon by the pertinent parties.

(n) All test data (manual and electronic) shall be distributed to all pertinent parties in accordance with para. 3-4.1, including the signing of all hard copies of the test data by at least one member of each pertinent party.

(o) Resolution of nonrepeatable test runs results shall be agreed upon by the pertinent parties.

(p) Rejection of test readings shall be done by mutual agreement by the pertinent parties consistent with the requirements of para. 3-5.1.

3-2 TESTS

3-2.1 Pretest Meeting

After readying the inlet air-conditioning system for the test and prior to initiation of the performance test, the Test Coordinator should conduct a meeting with relevant testing and plant staff personnel. The following subjects should be addressed during the pretest meeting:

(a) deviations in the test setup from the test procedure.

(b) agreement on a method for addressing deviations from the procedure during the test and after the test. All decisions and agreements are to be documented and attached to the test raw-data distribution.

(c) roles and readiness of manual data takers.

(d) readiness of the inlet air-conditioning system.

(e) readiness of the instrumentation that will be used to record test data.

(f) official start time for the performance test.

3-2.2 Pretest Records

Dimensions and physical conditions of parts of the inlet air-conditioning system required for calculations or other test purposes shall be determined and recorded prior to the test.

3-2.3 Equipment Inspection

Prior to conducting a test, the equipment should be inspected to document its condition. The observations that should be documented include cleanliness, condition, operability, and age.

3-2.4 Preliminary Operation

Before starting the test, the inlet air-conditioning equipment should be operated to demonstrate thermal and mechanical operation, stability, and test readiness of the equipment.

3-3 OPERATION OF TEST

3-3.1 Specified Conditions

Efforts shall be made to conduct the test at or near to the specified test reference conditions, as practical.

Table 3-3.1-1 provides the maximum permissible deviations from the base reference conditions for the inlet dry-bulb and wet-bulb temperatures and the barometric pressure that shall be met prior to conducting a Code test. Table 3-3.1-1 also lists the minimum requirements for the wet-bulb depression, wet-bulb temperature, and maximum dry-bulb temperature prior to conducting a Code test. In addition, water discharge and makeup may be isolated if doing so materially benefits the uncertainty of the test. In addition, for evaporative coolers, foggers, and chillers, a visual inspection, on a periodic basis during the test duration, downstream of the air stream (existing view ports at the bell mouth to the compressor could be used for observation), shall be conducted. In the case of evaporative coolers and chillers, there shall be no observable fog at the gas turbine bell mouth. However, there may be periodic water droplets on certain surfaces within the inlet duct and bell mouth. In the case of foggers, there shall be no greater than a light fog, as described in paras. 4-9.3 and 4-9.4, within the air stream. If this requirement is not met or if that the air stream contains greater than a light fog, the test shall be voided and the operation of the equipment changed to reduce the carryover to an acceptable level for performance testing.

3-3.2 Stabilization

Before starting the test, the inlet air-conditioning system shall be run until stable conditions have been established. Stability will be achieved when the Test Coordinator identifies that the continuous monitoring indicates the readings have been within the maximum permissible variation as defined in Table 3-3.1-1 and calculated in para. 3-3.3, over a continuous 30-min period.

3-3.3 Maximum Permissible Variation in Test Parameters

Each observation of a test parameter during a test run shall not vary from the computed average for that test parameter during the complete test run by more than the amount shown in Table 3-3.3-1. If the test parameters vary during any test run beyond the limits prescribed in Table 3-3.3-1, and if such variations are not covered by written agreement, the results of the test run shall be not be considered Code compliant.

3-3.4 Adjustments

Once testing has started, adjustments to the equipment that can influence the results of the test shall require repetition of any test runs conducted prior to the adjustments.

3-3.5 Duration of Test Run and Frequency of Readings

A sufficient number of readings shall be spaced in time to show the range of fluctuations, to provide a reliable average for the test run, and to meet the uncertainty requirements of this Code. No less than 30 measurements of each primary parameter shall be taken during the test run, and every effort should be made to take all parameters simultaneously. If manual measurements must be taken, no less than 10 readings shall be taken for a 30-min test run. Due to the sensitivity of inlet air-conditioning systems to ambient conditions, the test run should not exceed 30 min.

3-3.6 Number of Test Runs

A run is a complete set of observations with the station at stable operating conditions. A test is a single run or the average of a series of runs. While not requiring multiple runs, the advantages of multiple runs should be recognized. Conducting more than one run will

(a) provide a valid method of rejecting bad test runs.

(b) examine the validity of the results.

(c) verify the repeatability of the results. Results may not be repeatable due to variations in either test methodology (test variations) or the actual performance of the equipment being tested (process variations).

After completing the first test run that meets the criteria for an acceptable test run (which may be the preliminary test run), the data should be consolidated and preliminary results calculated and examined to ensure that the results are reasonable.

3-3.7 Evaluation of Test Runs

When comparing results from two test runs (X_1 and X_2) and their uncertainty intervals, the three cases illustrated in Fig. 3-3.7-1 should be considered.

(a) *Case I*. A problem clearly exists when there is no overlap between uncertainty intervals. Either uncertainty intervals have been grossly underestimated, an error exists in the measurements, or the true value is not constant. Investigation to identify bad readings, overlooked or underestimated systematic uncertainty, etc., is necessary to resolve this discrepancy.

(b) *Case II*. When the uncertainty intervals overlap completely, as in this case, one can be confident that there has been a proper accounting of all major uncertainty components. The smaller uncertainty interval, $X_2 \pm U_2$, is wholly contained in the interval, $X_1 \pm U_1$.

(c) *Case III*. This case, where a partial overlap of the uncertainty exists, is the most difficult to analyze. For both test run results and both uncertainty intervals to be correct, the true value lies in the region where the uncertainty intervals overlap. Consequently, the larger the overlap the more confidence there is in the validity of the measurements and the estimate of the uncertainty intervals. As the difference between the two measurements increases, the overlap region shrinks.

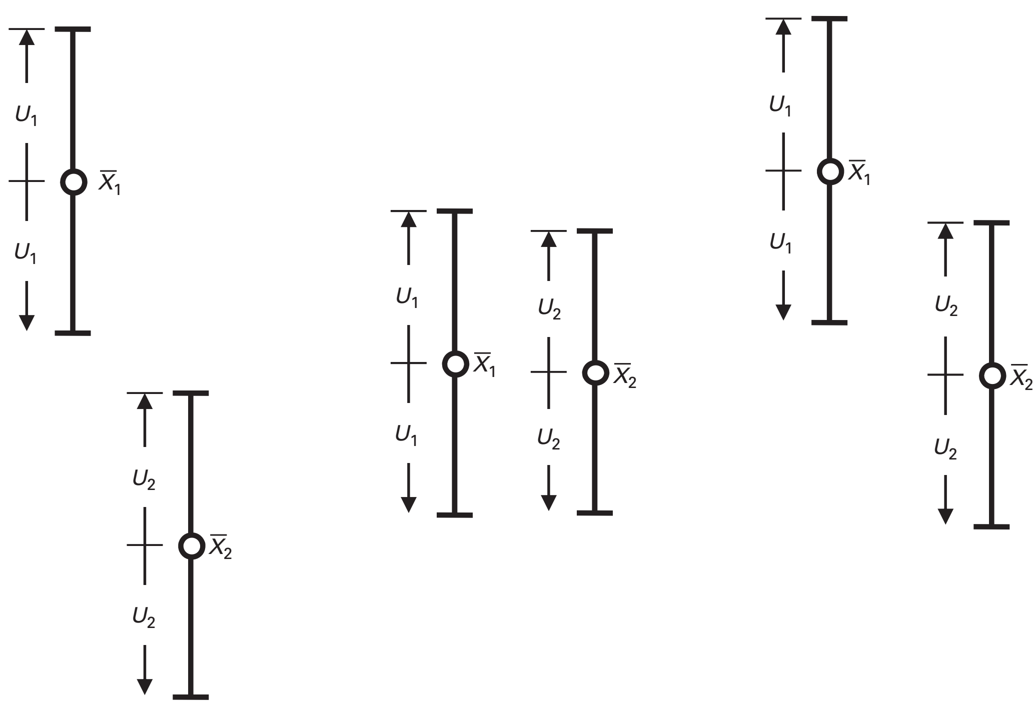
Should a run or set of runs fall under Case I or Case II, the results from all of the runs should be reviewed in an

Table 3-3.3-1 Maximum Permissible Variation in Test-Run Conditions

Variable	Variation of Any Test Parameter From Calculated Average Test Condition During a Test Run [Note (1)]			
	Evaporative Cooler	Inlet Fogger	Inlet Chiller	Inlet Heating
Airflow, %	2.5	2.5	2.5	2.5
Inlet temperature (dry bulb), K (°R)	2.2 (4)	2.2 (4)	2.2 (4)	2.2 (4)
Inlet temperature (wet bulb), K (°R)	2.2 (4)	1.1 (2)	NA	NA
Barometric pressure, %	1	1	1	1
Water-mass flow rate, %	N/A	N/A	N/A	N/A
Water pressure, %	N/A	5	N/A	N/A
Downstream temperature (dry bulb), K (°R)	2.2 (4)	2.2 (4)	2.2 (4)	2.2 (4)
Downstream temperature (wet bulb), K (°R)	2.2 (4)	2.2 (4)	N/A	N/A
Inlet air stream pressure drop, %	5	5	5	5
Coolant temperature – outlet, K (°R)	N/A	N/A	3 (5.4)	3 (5.4)
Coolant temperature – inlet, K (°R)	N/A	N/A	3 (5.4)	3 (5.4)

NOTE:
(1) Use average of multiple instruments if used for any station observation.

Fig. 3-3.7-1 Three Posttest Cases



(a) Case I: No Overlap **(b) Case II: Complete Overlap** **(c) Case III: Partial Overlap**

attempt to explain the reason for excessive variation. If the reason for the variation cannot be determined, then either increase the uncertainty band to encompass the runs to make them repeatable, or conduct more runs so that the random component of uncertainty may be calculated directly from the test results.

3-4 RECORDS

3-4.1 Test Observations

Test observations shall be recorded on a data acquisition system (DAS) or entered on manual data sheets. Automatic data logging and advanced instrument systems shall be calibrated to the required accuracy. Where manual data is taken, no observer shall be required to take so many readings that lack of time may result in insufficient care and precision. Where DAS data and manual data are to be used to calculate performance, it is recommended to synchronize watches to the DAS and to accurately record the time of manual data. In addition, every effort should be made to measure all parameters simultaneously.

Redundant instrumentation should be used to measure the primary variables that most greatly impact the uncertainty of the test results (Critical Test Parameters). Refer to subsection 5-1 and Section 7 for guidance. Any deviation between the redundant readings of test parameters that are measured in the same location shall be within the accuracy range of the instruments used to measure the test parameter. In the case of any Critical Test Parameters that are manually recorded, two data takers shall be used to record the Critical Test Parameter.

A complete set of unaltered data from the DAS and manual data sheets, or facsimiles thereof, shall become the property of the pertinent parties. Copies of the manual data sheets and electronic files shall be made and distributed to all relevant personnel. The observations shall be the actual readings without the application of any corrections and shall include the date and time of day of each observation and shall be labeled such that all relevant personnel can recognize the data. The log sheets and all recorded charts constitute a complete record. Any pertinent additional data/documentation shall be submitted and signed by the pertinent parties at the time of test completion; it may not be utilized in the test or evaluation but shall be recorded by all relevant personnel.

3-4.2 Test Recording Errors

In case of error in a manually recorded observation, a line shall be drawn through the incorrect entry; the correct reading shall be recorded above the incorrect entry and initialed, and an explanation entered in the proper place of the test records.

3-5 CALCULATION AND REPORTING OF RESULTS

The data taken during the test should be reviewed and rejected in part or in whole if not in compliance with the requirements for the constancy of test conditions. Each Code test shall include pretest and posttest uncertainty analyses, and the results of these analyses shall fall within Code requirements for the type of system being tested.

3-5.1 Causes for Rejection of Readings

Immediately upon completion of the test or during the test itself, the test data shall be reviewed to determine if a data point or a series of data points should be rejected prior to the calculation of test results. In addition, if the removal of such data violates any of the uncertainty requirements of this Code, the test in its entirety shall be discarded.

A test log shall be kept to document any events that may adversely impact plant stability. Any plant upsets that cause test data to violate the requirements of Table 3-3.1-1 shall require that data to be rejected and void that test run. A new test run may begin after the requirements of Table 3-3.1-1 have been met.

3-5.2 Uncertainty

Test uncertainty and test tolerance are not interchangeable terms. This Code does not address test tolerance, which is a contractual term.

Procedures relating to test uncertainty are based on concepts and methods described in subsection 3-1. ASME PTC 19.1 specifies procedures for evaluating measurement uncertainties from both random and systematic errors, and the effects of these errors on the uncertainty of a test result.

This Code addresses test uncertainty in the following four sections:

(a) Section 1 defines representative test uncertainties.

(b) Section 3 defines the requirements for pretest and posttest uncertainty analyses, and how they are used in the test. These uncertainty analyses and limits of error are defined and discussed in para. 3-5.2.1.

(c) Section 4 describes the uncertainty limits required for each test measurement.

(d) Section 7 and Nonmandatory Appendix B provide applicable guidance for determining pretest and posttest uncertainty analysis results.

3-5.2.1 Pretest and Posttest Uncertainty Analyses

3-5.2.1.1 Pretest. A pretest uncertainty analysis shall be performed so that the test can be designed to meet Code requirements. Estimates of systematic and random errors for each of the proposed test measurements shall be used to help determine the number and quality of test instruments required for compliance with Code or contract specifications.

The pretest uncertainty analysis shall use an estimate of random uncertainty based upon fluctuations of key parameters based on experience to calculate allowable uncertainties. In addition, a pretest uncertainty analysis can be used to determine the correction factors that are significant to the corrected test. For simplicity, this Code allows elimination of those corrections that change the test results by less than 0.05%. Also, pretest uncertainty analysis should be used to determine the level of accuracy required for each measurement to maintain overall Code standards for the test.

3-5.2.1.2 Posttest. A posttest uncertainty analysis shall also be performed as part of a Code test. The posttest uncertainty analysis will reveal the actual quality of the test, which should meet or exceed the representative test uncertainties described in Section 1.

3-5.3 Test Report

Copies of all data will be distributed by the Test Coordinator to those requiring it at the conclusion of the test. A test report shall be written in accordance with Section 6 and distributed by the Test Coordinator. A preliminary report incorporating calculations and results may be required before the final test report is submitted.

Section 4
Instruments and Methods of Measurement

4-1 GENERAL REQUIREMENTS

4-1.1 Introduction

This Section presents the mandatory provisions for instrumentation utilized in the implementation of an ASME PTC 51 test for gas turbine inlet air-conditioning equipment. Per the philosophy of ASME Performance Test Codes (PTC 1) and subsection 1-1 herein, it does so in consideration of the minimum reasonably achievable uncertainty. The Instruments and Apparatus supplements to ASME Performance Test Codes (ASME PTC 19 Series) outline the details concerning instrumentation and the governing requirements of instrumentation for all ASME Code performance testing. The user of this Code shall be familiar with ASME PTC 19.1, ASME PTC 19.2, ASME PTC 19.3, ASME PTC 19.5, and ASME PTC 19.22 as applicable to the instrumentation specified and explained in this Section.

For the convenience of the user, this Section reviews the critical highlights of portions of those supplements that directly apply to the requirements of this Code. This Section also contains details of the instrumentation requirements of this Code that are not specifically addressed in the referenced supplements. Such details include classification of measurements for the purpose of instrumentation selection and maintenance, calibration and verification requirements, and other information specific to an ASME PTC 51 test.

If the instrumentation requirements in the Instrument and Apparatus supplement become more rigorous as they are updated, due to advances in the state of the art, their requirements shall supersede those set forth in this Code.

Both U.S. Customary and SI units are shown in all equations in this Section. In text, tables, and figures, the SI value is followed by the U.S. Customary value in parentheses. However, any other consistent set of units may be used.

4-1.2 Criteria for Selection of Instrumentation

4-1.2.1 Measurement Designation. Measurements may be designated as either a parameter or variable. The terms "parameter" and "variable" are sometimes used interchangeably in the industry and in some other ASME Codes. This Code distinguishes between the two.

parameter: a direct measurement and a physical quantity at a location that is determined by a single instrument, or by the average of several similar instruments. In the latter case, several instruments may be used to determine a parameter that has potential to display spatial gradient qualities, such as inlet air temperature. Similarly, multiple instruments may be used to determine a parameter simply for redundancy to reduce test uncertainty, such as utilization of two temperature measurements of the air in a plenum in the same plane, where the temperature gradient is expected to be insignificant. Typical parameters measured in an ASME PTC 51 test are temperature and pressure.

variable: an indirect measurement and an unknown quantity in an algebraic equation that is determined by parameters. The performance equations in Section 5 contain the variables used to calculate the performance results. Typical variables in these equations are airflow, correction factors, and electrical power consumption. Each variable can be thought of as an intermediate result needed to determine the performance result.

Parameters are therefore the quantities measured directly to determine the value of the variables needed to calculate the performance results per the equations in Section 5. Examples of such parameters are temperature, pressure, and differential pressure for the calculation of the variable airflow.

4-1.2.2 Measurement Classification. A parameter or variable is classified as primary or secondary dependent upon its usage in the execution of this Code. Parameters and variables used in the calculation of test results are considered primary parameters and primary variables. Alternatively, secondary parameters and secondary variables do not enter into the calculation of the results but are used to ensure that the required test condition was not violated.

Primary parameters and primary variables are further classified as Class 1 or Class 2 depending on their relative sensitivity coefficient to the results of the test. Class 1 primary parameters and Class 1 primary variables are those that have a relative sensitivity coefficient of 0.2% per percent or greater. The primary parameters and primary variables that have a relative sensitivity coefficient of less than 0.2% per percent are classified as Class 2 primary parameters and Class 2 primary variables. Due to an arbitrary zero point, in the case of temperature measurements for primary parameters and primary variables, the relative sensitivity coefficient of 0.2% per percent shall be substituted as 0.2% per degrees Celsius (0.11% per degrees Fahrenheit).

4-1.2.3 Instrumentation Categorization. The instrumentation employed to measure a parameter will have different required type, uncertainty, redundancy, and handling depending upon whether the parameter is Class 1 primary, Class 2 primary, or secondary. For the determination of secondary parameters, less accuracy is required. The instruments that measure secondary parameters may be permanently installed plant instrumentation. This Code does require verification of instrumentation output prior to the test period. This verification can be by calibration or by comparison against two or more independent measurements of the parameters referenced to the same location. The instruments should also have redundant or other independent instruments that can verify the integrity during the test period. Instrumentation is categorized as Class 1 or Class 2 depending on the instrumentation requirements defined by that parameter. Care shall be taken to ensure the instrumentation meets the requirements set forth in this Code with regard to classification.

4-1.2.3.1 Class 1 Instrumentation. Class 1 instrumentation shall be used to determine Class 1 primary parameters. Class 1 instrumentation requires high accuracy instrumentation shall meet specific manufacturing and installation requirements, as specified in the ASME PTC 19 Series supplements. Class 1 instrumentation requires precision laboratory calibration except in the instance where the uncertainty limits set forth in this Code can be met without precision laboratory calibration.

4-1.2.3.2 Class 2 Instrumentation. Class 2 instrumentation, or better, shall be used to determine Class 2 primary parameters. Class 2 instrumentation does not require laboratory calibrations other than that performed in the factory for certification, but it does require field verification by techniques described herein.

4-1.3 Instrument Calibration and Verification

4-1.3.1 Introduction. The result of a calibration permits the estimation of errors of indication of the measuring instrument or measuring system, or the assignment of values to marks on arbitrary scales. The result of a calibration is sometimes expressed as a calibration factor, or as a series of calibration factors in the form of a calibration curve. Calibrations shall be performed in a controlled environment to the extent necessary to ensure valid results. Due consideration shall be given to temperature, humidity, lighting, vibration, dust control, cleanliness, electromagnetic interference, and other factors affecting the calibration. Where pertinent, these factors shall be monitored and recorded, and as applicable compensating corrections shall be applied to calibration results obtained in an environment that departs from acceptable conditions. Calibrations performed in accordance with this Code are categorized as either laboratory or field calibrations.

4-1.3.1.1 Laboratory Calibration. Laboratory calibrations shall be performed in strict compliance with established policy, requirements, and objectives of a laboratory's quality assurance program. Consideration shall be taken to ensure proper space, lighting, and environmental conditions such as temperature, humidity, ventilation, and low noise and vibration levels. Laboratory calibration applications shall be employed on all Class 1 instrumentation, with the exception of devices that can meet the uncertainty limits set forth in this Code without laboratory calibration.

4-1.3.1.2 Field Calibration. Adequate measures shall be taken to ensure that the necessary calibration status is maintained during transportation and while on-site. The response of the reference standards to environmental changes or other relevant parameters shall be known and documented. Field calibration measurement and test equipment requires calibration by approved sources that remain traceable to NIST, a recognized international standards organization, or a recognized natural physical (intrinsic) constant through unbroken comparisons having defined uncertainties. The achievable uncertainties of field calibrations can normally be expected to be larger than those for laboratory calibrations due to allowances for aspects such as the environment at the place of calibration and other possible adverse effects, such as those caused by transportation of the calibration equipment. Field calibration applications are commonly employed on instrumentation measuring secondary parameters and Class 2 instrumentation that are identified as out-of-tolerance during field verification as described in para. 4-1.3.2. Field calibrations should include loop calibrations as defined in para. 4-1.3.8. Field calibrations should be used as a check of Class 1 instrumentation that is suspected to have drifted or that does not have redundancy.

4-1.3.2 Verification. Verification provides a means for checking that the deviations between values indicated by a measuring instrument and corresponding known values are consistently smaller than the limits of the permissible error defined in a standard, regulation, or specification particular to the management of the measuring device. The result of the verification leads to a decision either to restore to service, to perform adjustments, to repair, to downgrade, or to declare obsolete.

Verification techniques include field calibrations, nondestructive inspections, intercomparison of redundant instruments, check of transmitter zeros, and energy-stream accounting practices. Nondestructive inspections include, but are not limited to, atmospheric pressure observations on absolute pressure transmitters, field checks including visual inspection, and no-load readings on power meters. Intercomparisons include, but are not limited to, water or electronic bath checks on temperature measurement devices and reconciliations on redundant instruments. The applicable field verification requirements shall be judged based on the unique requirements of each setup. As appropriate, manufacturer's recommendations and the Instruments and Apparatus supplements to ASME Performance Test Codes should be referenced for further field verification techniques.

4-1.3.3 Reference Standards. Reference standards shall be routinely calibrated in a manner that provides traceability to NIST, another recognized international standards organization, or defined natural physical (intrinsic) constants that have accuracy, stability, range, and resolution for the intended use. They shall be maintained for proper calibration, handling, and usage in strict compliance with a calibration laboratory quality program. When it is necessary to utilize reference standards for field calibrations, adequate measures shall be taken to ensure that the necessary calibration status is maintained during transportation and while on-site. The integrity of reference standards shall be verified by proficiency testing or interlaboratory comparisons. All reference standards should be calibrated as specified by the manufacturer or other frequency as the user has data to support extension of the calibration period. Supporting data is historical calibration data that demonstrates a calibration drift less than the accuracy of the reference standard for the desired calibration period.

The collective uncertainty of reference standards shall be known. The reference standards should be selected such that the collective uncertainty of the calibration standards contributes less than 25% to the overall calibration uncertainty. The overall calibration uncertainty of the calibrated instrument shall be determined at a 95% confidence level. A reference standard with a lower uncertainty may be employed if the uncertainty of the reference standard combined with the random uncertainty of the instrument being calibrated is less than the accuracy requirement of the instrument. For example, for some kinds of flow metering, the reference calibration standard contributes more than 25% to the overall calibration frequency. However, curve fitting from calibration is achievable from a 20-point calibration in a lab with an uncertainty of approximately 0.2%.

In general, all Class 1 and Class 2 instrumentation used to measure primary (Class 1 and Class 2) parameters shall be calibrated against reference standards traceable to NIST, another recognized international standards organization, or recognized natural physical (intrinsic) constants with values assigned or accepted by NIST. Instrumentation used to measure secondary parameters need not be calibrated against a reference standard. These instruments may be calibrated against a calibrated instrument.

4-1.3.4 Environmental Conditions. Calibration of instruments used to measure primary parameters (Class 1 or Class 2) should be performed in a manner that replicates the condition under which the instrument will be used to make the test measurements. As it is often not practical or possible to perform calibrations under replicated environmental conditions, additional elemental error sources shall be identified and estimated. Error source considerations shall be given to all process and ambient conditions that may affect the measurement system, including temperature, pressure, humidity, radiation, etc.

4-1.3.5 Instrument Ranges and Calibration Points. The number of calibration points depends upon the classification of the parameter the instrument will measure. The classifications are discussed in para. 4-1.2.2. The calibration should have points that bracket the expected measurement range. In some cases of flow measurement, it may be necessary to extrapolate a calibration (see ASME PTC 19.5).

4-1.3.5.1 Primary Parameters

(a) Class 1 Instrumentation. The instruments measuring Class 1 primary parameters should be laboratory calibrated at a minimum of 2 points more than the order of the calibration curve fit, whether it is necessary to apply the calibration data to the measured data, or if the instrument is of the quality that the deviation between the laboratory calibration and the instrument reading is negligible in terms of affecting the test result. Flow metering that requires calibration should have a 20-point calibration. Instrument transformers do not require calibration at 2 points more than the order of the calibration curve fit and shall be calibrated in accordance with para. 4-7.5.

Each instrument should also be calibrated such that the measuring point is approached in an increasing and decreasing manner. This exercise minimizes any possibility of hysteresis effects. Some instruments are built with a mechanism to alter the range once the instrument is installed. In this case, the instrument shall be calibrated at each range to be used during the test period.

Some devices cannot practically be calibrated over the entire operating range. An example of this is the calibration of a flow-measuring device. These devices are calibrated often at flows lower than the operating range and the calibration data is extrapolated. This extrapolation is described in subsection 4-5.

If a device meets the uncertainty requirements set forth in this Code without being calibrated, the device is not required by this Code to be calibrated.

(b) Class 2 Instrumentation. The instruments measuring Class 2 primary parameters should be calibrated at a minimum of the number of points equal to the order of the calibration curve fit. If the instrument can be shown to typically have a hysteresis of less than the required accuracy, the measuring point need only be approached from one direction (either increasing or decreasing to the point).

4-1.3.5.2 Secondary Parameters. The instruments measuring secondary parameters should undergo field verifications as described in para. 4-1.3.2 and, if calibrated, need only be calibrated at one point in the expected operating range.

4-1.3.6 Timing of Calibration. Because of the variance in different types of instrumentation and their care, no mandate is made regarding the time interval between the initial laboratory calibration and the test period. Treatment of the device is much more important than the elapsed time since calibration. An instrument may be calibrated one day and mishandled the next. Conversely, an instrument may be calibrated and placed on a shelf in a controlled environment and the calibration will remain valid for an extended time period. Similarly, the instrument can be installed in the field but valved-out of service, and/or it may, in many cases, be exposed to significant cycling. In these cases, the instrumentation is subject to vibration or other damage and shall undergo field verification.

All test instrumentation used to measure Class 1 primary parameters shall be laboratory calibrated prior to the test and shall meet specific manufacturing, installation, and operating requirements, as specified in the ASME PTC 19 series supplements. No mandate is made regarding quantity of time between the laboratory calibration and the test period. Test instrumentation used to measure Class 2 parameters and secondary parameters do not require laboratory calibration other than that performed in the factory for certification, but it does require field verification prior to the test.

Following a test, field verifications shall be conducted on instruments measuring parameters where there is no redundancy or for which data is questionable. For the purposes of redundancy, plant instrumentation may be used in the field verification. If results indicate unacceptable drift or damage, further investigation shall be conducted. Flow element devices meeting the requirements set forth by this Code to measure Class 1 and Class 2 primary parameters and variables need not undergo inspection following the test if the devices have not experienced conditions that would violate their integrity.

4-1.3.7 Calibration Drift. When field verification indicates the drift is less than the instrument accuracy, the drift is considered acceptable and the pretest calibration shall be used as the basis for determining the test results. Occasionally the instrument calibration drift is unacceptable. Should the calibration drift, combined with the reference standard accuracy as the square root of the sum of the squares, exceed the required accuracy of the instrument, it is unacceptable.

Calibration drift can result from instrument malfunction, transportation, installation, or removal of the test instrumentation. When field verification indicates unacceptable drift to meet the uncertainty requirements of the test, further investigation shall be conducted.

A posttest laboratory calibration might be ordered, and engineering judgment shall be used to determine whether the initial calibration or the recalibration is correct by evaluating the field verifications. Below are some recommended field verification practices that lead to the application of good engineering judgment.

(a) When instrumentation is transported to the test site between the calibration and the test period, a single-point check prior to and following the test period can isolate when the drift may have occurred. An example of this check is vented pressure transmitters, no load on watt meters, and ice-point temperature instrument check.

(b) In locations where redundant instrumentation is employed, calibration drift should be analyzed to determine which calibration data (the initial calibration or recalibration) produces better agreement between redundant instruments.

4-1.3.8 Loop Calibration. All analog instruments used to measure primary parameters (Class 1 or Class 2) should be loop calibrated. Loop calibration involves the calibration of the instrument through the signal-conditioning equipment. This may be accomplished by calibrating instrumentation employing the test-signal conditioning equipment either in a laboratory or on site during test setup before the instrument is connected to process. Alternatively, the signal-conditioning device may be calibrated separately from the instrument by applying a known signal to each channel using a precision signal generator.

Where loop calibration is not practical, an uncertainty analysis shall be performed to ensure that the combined uncertainty of the measurement system meets the uncertainty requirements described herein.

Instrumentation with digital output need be calibrated only through to the digital signal output. There is no further downstream signal-conditioning equipment as the conversion of the units of measure of the measured parameter has already been performed.

4-1.3.9 Quality Assurance Program. Each calibration laboratory shall have in place a quality assurance program. This program is a method of documentation where the following information can be found:

- calibration procedures
- calibration technician training
- standard calibration records
- standard calibration schedule
- instrument calibration histories

The quality assurance program should be designed to ensure that the laboratory standards are calibrated as required. The program also ensures that properly trained technicians calibrate the equipment in the correct manner.

The Parties to the test should be allowed access to the calibration facility for auditing. The quality assurance program should also be made available during such a visit.

4-1.4 Plant Instrumentation

Plant instrumentation shall not be used for primary measurements, unless the plant instrumentation (including signal-conditioning equipment) can be demonstrated to meet the overall uncertainty requirements.

In the case of flow measurement, all instrument measurements (process pressure, temperature, differential pressure, or pulses from metering device) shall be recorded.

4-1.5 Redundant Instrumentation

Where experience in the use of a particular model or type of instrument dictates that calibration drift may be unacceptable, and no other device is available, redundant instrumentation should be used. Redundant instruments should be used to measure all primary (Class 1 or Class 2) parameters, when practical. Exceptions are redundant flow elements and redundant electrical-metering devices, because of the large increase in costs.

Other independent instruments in separate locations can also monitor instrument integrity. A sample case would be a constant enthalpy process in which, by comparing enthalpies, the pressure and temperature at one point in a steam line are used to verify the pressure and temperature at another location in the line.

4-2 PRESSURE MEASUREMENT

4-2.1 Introduction

This subsection presents requirements and guidance regarding the measurement of pressure for this Code. Electronic pressure-measurement equipment should be used for primary measurements to minimize systematic and random error. Electronic pressure-measurement equipment is preferred due to inherent compensation procedures for sensitivity, zero balance, thermal effect on sensitivity, and thermal effect on zero. Other devices that meet the uncertainty requirements of this Section may be used. The uncertainty of the pressure measurement shall consider effects including, but not limited to, ambient temperature, resolution, repeatability, linearity, hysteresis, vibration, power supply, stability, mounting position, radio frequency interference (RFI), static pressure, water leg, warm-up time, data acquisition, spatial variation, and primary element quality.

The piping between the process and secondary element shall accurately transfer the pressure to obtain accurate measurements. Five possible sources of error include

- pressure transfer
- leaks
- friction loss
- trapped fluid (i.e., gas in a liquid line or liquid in a gas line)
- density variations between legs

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from devices that produce electromotive force (emf), such as motors, generators, electrical conduit, cable trays, and electrical service panels.

Prior to calibration, the pressure transmitter range may be altered to match the process better. However, the sensitivity to ambient temperature fluctuation may increase as the range is altered.

Additional calibration points will increase the accuracy but are not required. During calibration, the measuring point should be approached from an increasing and decreasing manner to minimize the hysteresis effects.

Some pressure transmitters have the capability of changing the range once the transmitter is installed. The transmitters shall be calibrated at each range to be used during the test period.

Where appropriate for steam and water processes, the readings from all static pressure transmitters and any differential pressure transmitters with taps at different elevations (such as on vertical flow elements) shall be adjusted to account for elevation head in water legs. This adjustment shall be applied at the transmitter, in the control system or data acquisition system, or manually by the user after the raw data is collected. Care shall be taken to ensure this adjustment is applied properly, particularly at low static pressures, and that it is only applied once.

4-2.2 Required Uncertainty

The required uncertainty depends upon the type of parameters being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussions on measurement classification and instrumentation categorization, respectively.

Class 1 primary parameters shall be measured with 0.1% accuracy class pressure transmitters or equivalent. These devices shall have an instrument systematic uncertainty of $\pm$0.3% or better of calibrated span.

Class 2 primary parameters shall be measured with 0.25% accuracy class pressure transmitters or equivalent. These devices shall have an instrument systematic uncertainty of $\pm$0.50% or better of calibrated span.

Secondary parameters and variables can be measured with any type of pressure transmitter or equivalent device.

4-2.3 Recommended Pressure Measurement Devices

Pressure transmitters are the recommended pressure-measurement devices. The three types of pressure transmitters due to application considerations are as follows:

− absolute pressure transmitters
− gage pressure transmitters
− differential pressure transmitters

4-2.3.1 Absolute Pressure Transmitters

(a) Application. Absolute pressure transmitters measure pressure referenced to absolute zero pressure. Absolute pressure transmitters should be used on all measurement locations with a pressure equal to or less than atmospheric. Absolute pressure transmitters may also be used to measure pressures above atmospheric pressure.

(b) Calibration. Absolute pressure transmitters can be calibrated using one of two methods. The first method involves connecting the test instrument to a device that develops an accurate vacuum at desired levels. Such a device can be a deadweight gage in a bell jar referenced to zero pressure or a divider piston mechanism with the low side referenced to zero pressure.

The second method calibrates by developing and holding a constant vacuum in a chamber using a suction-and-bleed control mechanism. The test instrument and the calibration standard are both connected to the chamber. The chamber shall be maintained at constant vacuum during the calibration of the instrument. Other devices can be utilized to calibrate absolute pressure transmitters provided that the same level of care is taken.

4-2.3.2 Gage Pressure Transmitters

(a) Application. Gage pressure transmitters measure pressure referenced to atmospheric pressure. The test-site atmospheric pressure shall be added to the gage pressure to obtain the absolute pressure.

$$P_{abs} = p_g + p_b \tag{4-2-1}$$

The test-site atmospheric pressure should be measured by an absolute pressure transmitter. Gage pressure transmitters should be used only on measurement locations with pressures higher than atmospheric. Gage pressure transmitters are preferred over absolute pressure transmitters in measurement locations above atmospheric pressure because they are easier to calibrate.

(b) Calibration. Gage pressure transmitters should be calibrated by an accurate deadweight gage. The pressure generated by the deadweight gage shall be corrected for local gravity, air buoyancy, piston surface tension, piston area deflection, actual mass of weights, actual piston area, and working medium temperature. If the above corrections are not used, the pressure generated by the deadweight gage may be inaccurate. The actual piston area and mass of weights shall be determined each time the deadweight gage is calibrated. Other devices can be utilized to calibrate gage pressure transmitters provided that the same level of care is taken.

4-2.3.3 Differential Pressure Transmitters

(a) Application. Differential pressure transmitters are used where flow is determined by a differential pressure meter or where pressure drops in a duct or pipe shall be determined and it is practical to route the pressure tubing.

(b) Calibration. Differential pressure transmitters used to determine Class 1 primary parameters and variables shall be calibrated at line static pressure unless information is available detailing the effect of line static pressure on the instrument accuracy that demonstrates compliance with the uncertainty requirements of para. 4-2.2. Calibrations at line static pressure are performed by applying the actual expected process pressure to the instrument as it is being calibrated. Calibrations at line static pressure can be accomplished by one of the following methods:

(1) two highly accurate deadweight gages
(2) a deadweight gage and divider combination
(3) one deadweight gage and one differential pressure standard

Differential pressure transmitters used to determine Class 2 primary parameters and variables or secondary parameters and variables do not require calibration at line static pressure and can be calibrated using one accurate deadweight gage connected to the "high" side of the instrument.

If line static pressure is not used, the span shall be corrected for high line static pressure shift unless the instrument is internally compensated for the effect. Once the instrument is installed in the field, the differential pressure from the source should be equalized and a zero value read. This zero bias shall be subtracted from the test-measured differential pressure. Other devices can be utilized to calibrate differential pressure transmitters provided that the same level of care is taken.

4-2.4 Absolute Pressure Measurements

4-2.4.1 Introduction. Absolute pressure measurements are pressure measurements that are below or above atmospheric pressure. Absolute pressure transmitters should be used for these measurements. A typical absolute pressure measurement in an ASME PTC 51 test is barometric pressure.

Barometric pressure transducers shall be configured to display absolute pressure with no additional elevation corrections. Many new barometric pressure gages have an option to display measured values corrected to sea-level elevations for aviation purposes. Weather station data from local airports and Internet websites may include corrections to sea level and shall not be used in performance testing calculations without making the necessary corrections.

For pressure transmitters that are calibrated to standard sea level, first, determine the difference between the reported airport pressure and standard sea-level atmospheric pressure, Δp_b. This value shall also be the difference between the site barometric pressure ($p_{baro\ site}$) and standard atmospheric pressure for the site at elevation Z.

(SI Units)

$$\Delta p_b = p_b \text{ (from device calibrated to standard sea level)} - 1.013 \quad (4\text{-}2\text{-}2)$$

(U.S. Customary Units)

$$\Delta p_b = p_b \text{ (from device calibrated to standard sea level)} - 14.696 \quad (4\text{-}2\text{-}3)$$

Add the difference to the standard atmospheric pressure for the site at elevation Z in meters (ft).

(SI Units)

$$p_{b\ site} = \Delta p_b + 101.325(1 - 2.25577 \times 10^{-5} \times Z)\text{\^{}}5.2559 \quad (4\text{-}2\text{-}4)$$

(U.S. Customary Units)

$$p_{b\ site} = \Delta p_b + 14.696(1 - 6.8753 \times 10^{-6} \times Z)\text{\^{}}5.2559 \quad (4\text{-}2\text{-}5)$$

For vacuum pressure measurements, differential pressure transmitters may be used with the "low" side of the transmitter connected to the source to effectively result in a negative gage that is subtracted from atmospheric pressure to obtain an absolute value. This latter method may be used but is not recommended for Class 1 primary parameters and variables since these measurements are typically small and the difference of two larger numbers may result in error.

4-2.4.2 Installation. Absolute pressure transmitters used for absolute pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than the one in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the varied mounting position. Impulse tubing and mounting requirements should be installed in accordance with manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing large enough to avoid friction effects and prevent blockage.

(f) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 2 ft horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form completely so the downward slope will be completely full of liquid.

The water leg is the condensed liquid in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head must be subtracted from the pressure measurement. The static head is calculated by multiplying the sensing line vertical height by gravity and the density of the liquid in the sensing line.

All vacuum measurement sensing lines should slope continuously upwards from the source to the instrument. A purge system should be used to isolate the purge gas during measurement of the process. A continuous purge system may be used; however, it shall be regulated to have no influence on the reading. Prior to the test period, readings from all purged instrumentation should be taken successively with the purge on and with the purge off to prove that the purge air has no influence.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check shall be conducted. For vacuum measurements, the leak check is performed by isolating first the purge system and then the source. If the sensing line has no leaks, the instrument reading will not change. For nonvacuum measurements, the leak check is performed using a leak detection fluid on the impulse tubing fittings.

Barometric pressure devices should be installed in the same general area and elevation that is most representative of the test boundary and minimizes test uncertainty.

4-2.5 Gage Pressure Measurements

4-2.5.1 Introduction. Gage pressure measurements are pressure measurements that are at or above atmospheric pressure. These measurements may be made with gage or absolute pressure transmitters. Gage pressure transmitters should be used since they are easier to calibrate and to check in situ. Typical gage pressure measurements in an ASME PTC 51 test may include water pressure and process-fluid pressure.

Caution shall be used with low-pressure measurements because they may enter the vacuum region at part-load operation.

4-2.5.2 Installation. Gage pressure transmitters used for gage pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation in which they were calibrated. If the transmitter is mounted in a position other than that used during calibration, the zero point may shift by an amount equal to the liquid head caused by the varied mounting position. Impulse tubing and mounting requirements should be installed in accordance with manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing large enough to avoid friction effects and prevent blockage

(f) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 2 ft horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form completely so the downward slope will be completely full of liquid.

The water leg is the condensed liquid or water in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head shall be subtracted from the pressure measurement. The static head is calculated by multiplying the sensing line vertical height by gravity and the density of the liquid in the sensing line.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check shall be conducted. The leak check is performed using a leak-detection fluid on the impulse tubing fittings.

4-2.6 Differential Pressure Measurements

4-2.6.1 Introduction. Differential pressure measurements are used to determine the difference in static pressure between pressure taps in a primary element. Differential pressure transmitters should be used for these measurements. Typical differential pressure measurements in an ASME PTC 51 test may include the differential pressure loss in a pipe or duct. The differential pressure transmitter measures this pressure difference or pressure drop, which is used to calculate the fluid flow.

4-2.6.2 Installation. Differential pressure transmitters used for differential pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation in which they were calibrated. If the transmitter is mounted in a position other than that used during calibration, the zero point may shift by an amount equal to the liquid head caused by the varied mounting position. Impulse tubing and mounting requirements should be installed in accordance with manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Ensure both impulse legs are at the same temperature.

(f) When using a sealing fluid, fill both impulse legs to the same level.

(g) Use impulse tubing large enough to avoid friction effects and prevent blockage.

(h) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 2 ft horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form completely so the downward slope will be completely full of liquid.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing lines upstream of the instrument. The instrument sensing lines should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing lines of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Differential pressure transmitters should be installed utilizing a five-way manifold shown in Fig. 4-2.6.2-1. This manifold is recommended rather than a three-way manifold because the five-way eliminates the possibility of leakage past the equalizing valve. The vent valve acts as a telltale for leakage detection past the equalizing valves.

Fig. 4-2.6.2-1 Five-Way Manifold

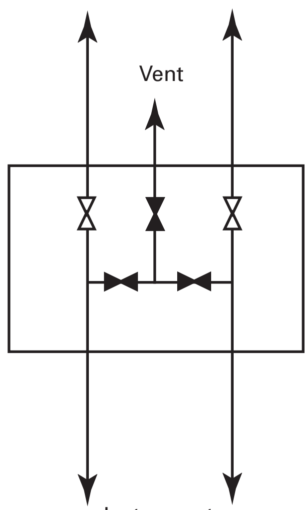
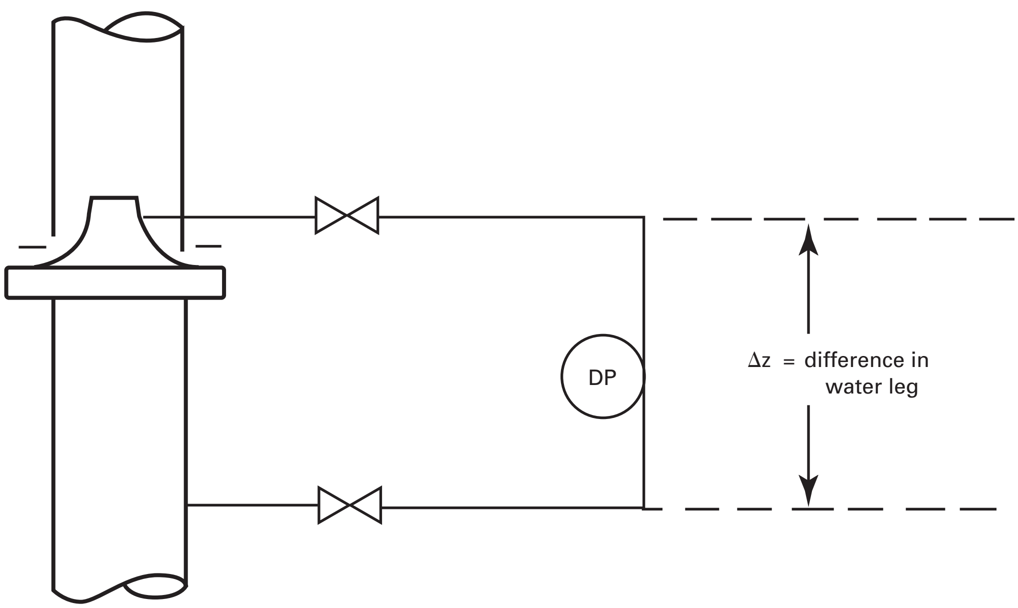


Fig. 4-2.6.2-2 Water Leg Correction for Flow Measurement



Once transmitters are connected to process, a leak check shall be conducted. The leak check shall be performed using a leak-detection fluid on the impulse tubing fittings.

When a differential pressure meter is installed on a flow element that is located in a vertical steam or water line, the measurement shall be corrected for the difference in sensing-line height and fluid-head change unless the upper sensing line is installed against a steam or water line inside the insulation down to where the lower sensing line protrudes from the insulation. The correction for the noninsulated case is shown in Fig. 4-2.6.2-2.

For upward flow

$$\Delta p_{true} = \Delta p_{meas} + (\rho_{amb} - \rho_{pipe}) \times (g/g_0) \times \Delta z \qquad (4\text{-}2\text{-}6)$$

For downward flow

$$\Delta p_{true} = \Delta p_{meas} - (\rho_{amb} - \rho_{pipe}) \times (g/g_0) \times \Delta z \qquad (4\text{-}2\text{-}7)$$

4-3 TEMPERATURE MEASUREMENT

4-3.1 Introduction

This subsection presents requirements and guidance regarding the measurement of temperature of this Code.

It also discusses recommended temperature-measurement devices, calibration of temperature-measurement devices, and application of temperature-measurement devices. Due to the state of the art and general practice, electronic temperature-measurement equipment should be used for primary measurements to minimize systematic and random error. The uncertainty of the temperature measurement shall consider effects including, but not limited to, stability, environmental, self-heating, parasitic resistance, parasitic voltages, resolution, repeatability, hysteresis, vibration, warm-up time, immersion or conduction, radiation, dynamic and spatial variation, and data acquisition.

Since temperature-measurement technology will change over time, this Code does not limit the use of other temperature-measurement devices not currently available or not currently reliable. If such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from emf-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

4-3.2 Required Uncertainty

The required uncertainty depends upon the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussion on measurement classification and instrumentation categorization, respectively.

Class 1 primary parameters and variables shall be determined with temperature-measurement devices that have an instrument systematic uncertainty of no more than ±0.1°C (±0.20°F) for temperatures less than 93°C (200°F) and no more than ±0.56°C (±1.0°F) for temperatures more than 93°C (200°F).

Class 2 primary parameters and variables shall be determined with temperature-measurement devices that have an instrument systematic uncertainty of no more than ±1.7°C (±3.0°F).

Secondary parameters and variables should be determined with temperature-measurement devices that have an instrument systematic uncertainty of no more than ±3.9°C (±7.0°F).

The uncertainty limits above are exclusive of the uncertainty effects of the temperature spatial gradient, which are considered to be systematic.

4-3.3 Recommended Temperature-Measurement Devices

Thermocouples, resistance temperature detectors, and thermistors are the recommended temperature-measurement devices. Economic, application, and uncertainty considerations should be taken into account when selecting the most appropriate temperature-measurement device.

4-3.3.1 Thermocouples. Thermocouples may be used to measure temperature of any fluid above 93°C (200°F). The maximum temperature is dependent on the type of thermocouple and sheath material used.

Thermocouples should not be used for measurements below 93°C (200°F). The thermocouple is a differential-type device. The thermocouple measures the difference between the measurement location in question and a reference temperature. The greater this difference, the higher the emf from the thermocouple. Therefore, below 93°C (200°F) the emf becomes low and subject to induced noise, causing increased systematic uncertainty and inaccuracy.

The primary sources of measurement errors associated with thermocouples are typically as follows:

- junction connection
- decalibration of the thermocouple wire
- shunt impedance
- galvanic action
- thermal shunting
- noise and leakage currents
- thermocouple specifications

"The emf developed by a thermocouple made from homogeneous wires will be a function of the temperature difference between the measuring and the reference junction. If, however, the wires are not homogeneous, and the in homogeneity is present in a region where a temperature gradient exists, extraneous emf will be developed, and the output of the thermocouple will depend upon factors in addition to the temperature difference between the two junctions. The homogeneity of the thermocouple wire, therefore, is an important factor in accurate measurements." [1]

"All base-metal-metal thermocouples become inhomogeneous with use at high temperatures; however, if all the inhomogeneous portions of the thermocouple wires are in a region of uniform temperature, the inhomogeneous portions have no effect upon the indications of the thermocouple. Therefore, an increase in the depth of immersion of a used couple has the effect of bringing previously unheated portion of the wires into the region of temperature gradient, and thus the indications of the thermocouple will correspond to the original emf-temperature relation, provided the increase in immersion is sufficient to bring all the previously heated part of the wires into the zone of uniform temperature. If the immersion is decreased, more inhomogeneous portions of the wire will be brought into the region of temperature gradient, thus giving rise to a change in the indicated emf. Furthermore, a change in the temperature distribution along inhomogeneous portions of the wire nearly always occurs when a couple is removed from one installation and placed in another, even though the measured immersion and the temperature of the measuring junction are the same in both cases. Thus the indicated emf is changed." [2]

The elements of a thermocouple shall be electrically isolated from each other, from ground and from conductors on which they may be mounted, except at the measuring junction. When a thermocuple is mounted along a conductor, such as a pipe or metal structure, special care should be exercised to ensure good electrical insulation between the thermocouple wires and the conductor to prevent stray currents in the conductor from entering the thermocouple circuit and vitiating the readings. Stray currents may further be reduced with the use of guarded intergrating analog/digital techniques. Further, to reduce the possibility of magnetically induced noise, the thermocouple wires should be constructed in a twisted uniform manner.

Thermocouples are susceptible to drift after cycling. Cycling is the act of exposing the thermocouple to process temperature and removing to ambient conditions. The number of times a thermocouple is cycled should be kept to a minimum.

Thermocouples can be used effectively in high vibration. High-vibration measurement locations may not be conducive to other measurement devices. The highest emf per degree should be used in all applications. NIST has recommended temperature ranges for each specific type of thermocouple.

4-3.3.1.1 Class 1 Primary Parameters. Thermocouples used to measure Class 1 primary parameters shall have continuous leads from the measuring junction to the connection on the reference junction. These high-accuracy thermocouples shall have a reference junction at 0ºC (32ºF) or an ambient reference junction that is well insulated and calibrated.

4-3.3.1.2 Class 2 Primary Parameters. Thermocouples used to measure Class 2 primary parameters can have junctions in the sensing wire. The junction of the two sensing wires shall be maintained at the same temperature. The reference junction may be at ambient temperature provided that the ambient is measured and the measurement is compensated for changes in the reference junction temperature.

4-3.3.1.3 Reference Junctions. The temperature of the reference junction shall be measured accurately with either software or hardware compensation techniques. The accuracy with which the temperature of the measuring junction is measured can be no greater than the accuracy with which the temperature of the reference junction is known. The reference junction temperature shall be held at the ice-point or at the stable temperature of an isothermal reference. When thermocouple reference junctions are immersed in an ice bath consisting of a mixture of melting shaved ice and water [3], the bulb of a precision thermometer shall be immersed at the same level as the reference junctions and in contact with them. Any deviation from the ice-point shall be promptly corrected. Each reference junction shall be electrically insulated. When the isothermal−cold junction reference method is used, it shall employ an accurate temperature measurement of the reference sink. When electronically controlled reference junctions are used, they shall have the ability to control the reference temperature to within ±0.03°C (±0.05°F). Particular attention shall be paid to the terminals of any reference junction since temperature variation, material properties, or wire mismatching can introduce errors. By calibration, the overall reference system shall be verified to have an uncertainty of less than ±0.1°C (±0.2°F). Isothermal thermocouple reference blocks furnished as part of digital systems may be used in accordance with the Code provided the accuracy is equivalent to the electronic reference junction. Commercial data acquisition systems employ a measured reference junction, and the accuracy of this measurement is incorporated into the manufacturer's specification for the device. The uncertainty of the reference junction shall be included in the uncertainty calculation of the measurement to determine if the measurement meets the standards of this Code.

4-3.3.1.4 Thermocouple Signal Measurement. Many instruments are used today to measure the output voltage. The use of each of these instruments in a system to determine temperature requires they meet the uncertainty requirements for the parameter. The thermocouple signal conversion should use ITS-90 software compensation techniques.

4-3.3.2 Resistance Temperature Detectors (RTDs). Resistance temperature detectors (RTDs) should only be used to measure from −270°C to 850°C (−454°F to 1,562°F). Reference [4] provides standard specifications for industrial platinum resistance thermometers; the specifications include requirements for manufacture, pressure, vibration, and mechanical shock to improve the performance and longevity of these devices.

The primary sources of measurement errors associated with RTDs are

- self-heating
- environmental factors
- thermal shunting
- thermal emf
- lack of stability
- immersion

Although RTDs are considered more linear devices than thermocouples, due to manufacturing technology, RTDs are more susceptible to vibrational applications. As such, care should be taken in the specification and application of RTDs with consideration given to the effect on the devices' stability. Field verification techniques should be used to demonstrate the stability is within the uncertainty requirements of para. 4-3.2.

Fig. 4-3.3.2.1-1 Four-Wire Resistance Temperature Detector (RTD)

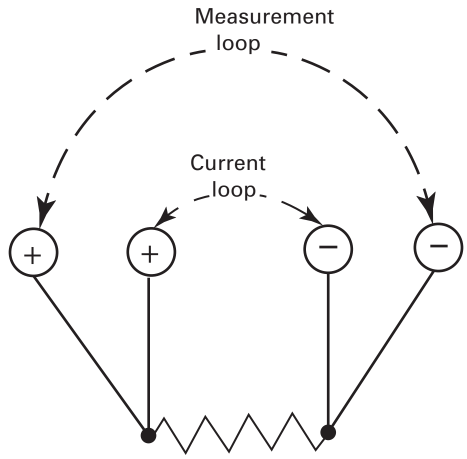
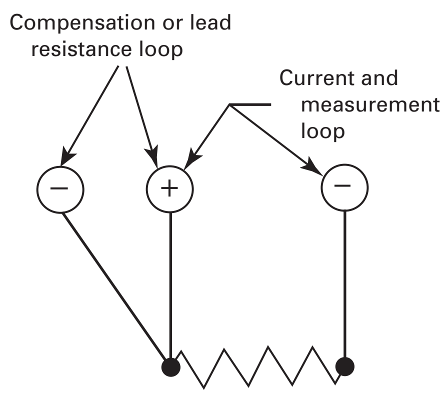


Fig. 4-3.3.2.2-1 Three-Wire Resistance Temperature Detector (RTD)



4-3.3.2.1 Class 1 Primary Parameters. RTDs used to measure Class 1 primary parameters should be measured with a Grade A four-wire platinum resistance thermometer as presented in Fig. 4-3.3.2.1-1. Three-wire RTDs are acceptable only if they can be shown to meet the uncertainty requirements of this Code.

4-3.3.2.2 Class 2 Primary Parameters. RTDs used to measure Class 2 primary parameters can be measured with Grade A three-wire platinum resistance thermometers as presented in Fig. 4-3.3.2.2-1. The four-wire technique is preferred to minimize effects associated with lead-wire resistance due to dissimilar lead wires.

4-3.3.2.3 RTD Signal Measurement. Many devices are available to measure the output resistance. The use of each of these instruments in a system to determine temperature requires they meet the uncertainty requirements for the parameter.

4-3.3.3 Thermistors. Thermistors are constructed with ceramic-like semiconducting material that acts as a thermally sensitive variable resistor. This device may be used on any measurement below 149°C (300°F). Above this temperature, the signal is low and susceptible to error from current-induced noise. Although positive temperature coefficient units are available, most thermistors have a negative temperature coefficient (TC); that is, unlike an RTD, their resistance decreases with increasing temperature. The negative TC can be as large as several percent per degree Celsius, allowing the thermistor circuit to detect minute changes in temperature that could not be observed with an RTD or thermocouple circuit. As such, the thermistor is best characterized for its sensitivity while the thermocouple is the most versatile and the RTD the most stable.

The primary sources of measurement errors associated with thermistors are typically

- self-heating
- environmental factors
- thermal shunting
- decalibration
- lack of stability
- immersion

Typically the four-wire resistance measurement is not required for thermistors as it is for RTDs measuring Class 1 primary parameters due to its high resistivity causing the connecting-wire lead resistance to be on an error magnitudes less than the equivalent RTD error. However, in the case where long lead-length wires or high-resistance wires are used, which are not a part of the calibration, the lead-wire resistance shall be compensated for in the measurement. Thermistors are generally more fragile than RTDs and thermocouples and shall be carefully mounted and handled in accordance with manufacturer's specifications to avoid crushing or bond separation.

4-3.3.3.1 Thermistor Signal Measurement. Many instruments are used today to measure the output resistance. The use of each of these instruments in a system to determine temperature requires they meet the uncertainty requirements for the parameter.

4-3.4 Calibration of Primary Parameter Temperature-Measurement Devices

The primary (Class 1 or Class 2) parameter instrumentation used in the measurement of temperature should have a suitable calibration history (three or four sets of calibration data). The calibration history should include the temperature level the device experienced between calibrations. A device that is stable after being used at low temperatures may not be stable at higher temperatures. Hence, the calibration history of the device should be evaluated to demonstrate the required stability of the parameter.

During the calibration of any thermocouple, the reference junction shall be held constant preferably at the ice-point with an electronic reference junction, isothermal reference junction, or in an ice bath. The calibration shall be made by an acceptable method, with the standard being traceable to a recognized national standards laboratory such as the NIST. The calibration shall be conducted over the temperature range in which the instrument is used.

The calibration of temperature-measurement devices is accomplished by inserting the candidate temperature-measurement device into a calibration medium along with a traceable reference standard. The calibration medium type is selected based upon the required calibration range and commonly consists of either a block calibrator, fluidized sand bath, or circulating bath. The temperature of the calibration medium is then set to the calibration temperature setpoint. The temperature of the calibration medium is allowed to stabilize until the temperature of the standard is fluctuating less than the accuracy of the standard. The signal or reading from the standard and the candidate temperature measurement device are sampled to determine the bias of the candidate temperature device. See ASME PTC 19.3 for a more detailed discussion of calibration methods.

4-3.5 Temperature Scale

The International Temperature Scale of 1990 (ITS-90) is realized and maintained by the NIST to provide a standard scale of temperature for use by science and industry in the United States.

Temperatures on the ITS-90 can be expressed in terms of International Kelvin Temperatures, with the symbol T_{90}, or in terms of International Celsius Temperatures, with the symbol t_{90}. The units of T_{90} and t_{90} are the kelvin (K) and the degree Celsius (ºC), respectively. The relation between T_{90} (in kelvin) and t_{90} (in degree Celsius) is

$$t_{90} = T_{90} - 273.15 \tag{4-3-1}$$

Values of Fahrenheit temperature, t_f (ºF), are obtained from the conversion formula

$$t_f = \left(\frac{9}{5}\right) t_{90} + 32 \tag{4-3-2}$$

The ITS-90 was designed in such away that the temperature values on it very closely approximate kelvin thermodynamic temperature values. Temperatures on the ITS-90 are defined in terms of equilibrium states of pure substances (defining points), interpolating instruments, and equations that relate the measured property to T_{90}. The defining equilibrium states and the values of temperature assigned to them are listed in NIST Technical Note 1265, "Guidelines for Realizing the International Temperature Scale of 1990 (ITS-90)," and ASTM Manual Series: MNL 12 "Manual on the Use of Thermocouples in Temperature Measurement."

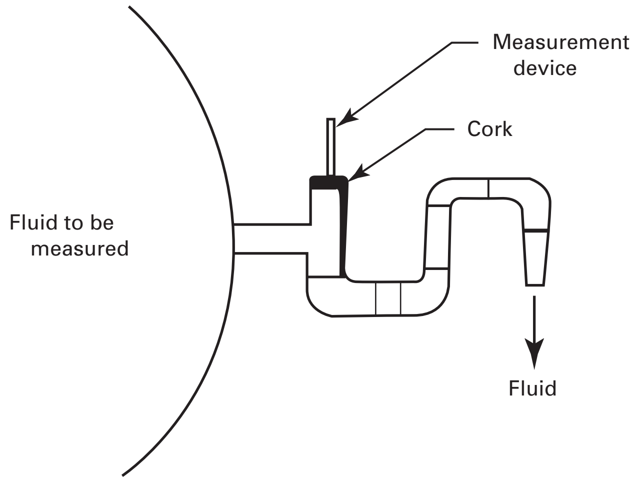
4-3.6 Typical Applications

4-3.6.1 Temperature Measurement of Fluid in a Pipe or Vessel. The temperature of a fluid that is inside of a pipe or vessel shall be measured utilizing a thermowell. A thermowell is a pressure-tight device that protrudes from the pipe or vessel wall into the fluid to protect the temperature-measurement device from harsh environments, high pressure, and flows. They can be installed into a system using a threaded, socket weld, or flanged configuration, and have a bore extending to near the tip to facilitate the immersion of a temperature-measurement device.

The bore should be sized to allow adequate clearance between the temperature-measurement device and the well. Often the temperature-measurement device becomes bent, causing difficulty in the insertion of the device.

The bottom of the bore of the thermowell should be the same shape as the tip of the temperature-measurement device. Tubes and wells should be as thin as possible, consistent with safe stress and other ASME Code requirements, and the inner diameters of the wells

Fig. 4-3.6.2-1 Flow-Through Well



should be clean, dry, and free from corrosion or oxide. The bore should be cleaned with high-pressure air prior to insertion of the device.

The thermowell should be installed so that the tip protrudes through the boundary layer of the fluid to be measured. Unless limited by design considerations, the temperature sensor shall be immersed in the fluid at least 75 mm (3 in.) but not less than one-quarter of the pipe diameter. If the pipe is less than 100 mm (4 in.) in diameter, the temperature sensor shall be arranged axially in the pipe by inserting it in an elbow or tee. If such fittings are not available, the piping should be modified to render this possible. The thermowell should be located in an area where the fluid is well mixed and has no potential gradients. If the location is near the discharge of a boiler, turbine, condenser, or other power plant component, the thermowell should be downstream of an elbow in the pipe.

If more than one thermowell is installed in a given pipe location, the second thermowell should be installed on the opposite side of the pipe from the first, and not directly downstream of another thermowell.

When the temperature-measurement device is installed, it should be "spring-loaded" to ensure positive thermal contact between the temperature-measurement device and thermowell.

For Class 1 primary parameter measurements, the portion of the thermowell, or lag section, protruding outside the pipe or vessel should be insulated along with the device itself to minimize conduction losses.

For measuring the temperature of desuperheated steam, the thermowell location relative to the desuperheating-spray injection location shall be carefully chosen. The thermowell shall be located where the desuperheating fluid has thoroughly mixed with the steam. This can be accomplished by placing the thermowell downstream of two elbows in the steam line, past the desuperheating-spray injection point.

4-3.6.2 Temperature Measurement of Low-Pressure Fluid in a Pipe or Vessel. As an alternate to installing a thermowell in a pipe, if the fluid is at low pressure, the temperature-measurement device can be installed directly into the pipe or vessel, or "flow-through wells" may be used.

The temperature-measurement device can be installed directly into the fluid using a bored-through-type compression fitting. The fitting should be of proper size to clamp onto the device. A ferrule made of graphite, plastic, or other appropriate material should be used so that the device can be removed easily and installed elsewhere. The device shall protrude through the boundary layer of the fluid. Care shall be taken so that the device does not protrude into the fluid far enough to experience vibration from the flowing fluid. If the fluid is a hazardous gas such as natural gas or propane, the fitting should be checked for leaks. If the fluid is unsaturated air, the device should be shielded to prevent water-droplet impingement on the sensor.

A flow-through well is shown in Fig. 4-3.6.2-1. This arrangement is applicable only for water in a cooling system where the fluid is not hazardous and can be disposed without great cost. The principle is to allow the fluid to flow out of the pipe or vessel, over the tip of the temperature-measurement device.

4-3.6.3 Temperature Measurement of Inlet Air. Inlet temperature of air streams at the planes in which they cross the test boundary are subject to spatial variations. Spatial variation effects are considered errors of method and contributors to the systematic uncertainty in the measurement system. As such, the number and location of temperature-measurement devices should be determined such that the overall systematic uncertainty of the devices measuring the average inlet air temperature is minimized as much as practically possible. ASME

PTC 19.1 should be consulted for the determination of the uncertainty associated with spatial variation.

4-3.6.3.1 Determination of Temperature and Velocity Grid. Measurement of temperature and velocity of inlet air requires several measurement points to minimize the uncertainty effects of temperature gradients. The number of measurement points necessary shall be determined to ensure that the measurement uncertainty for average inlet temperature is below 0.55°C (1°F).

(a) Fixed Temperature Measurements. Measurements of temperature at the inlet air stream should be taken at centroids of equal areas or as appropriate for the given geometry. A minimum of one temperature device per 9.30 m^2 (100 ft^2), or four devices, whichever is greater, shall be used to determine the inlet air temperature.

(b) Velocity Measurements. In this case, the velocity profile is determined using pitot traverses, hot-wire anenometers, or similiar devices. Measurements of temperature at the inlet air stream for this case shall be taken at the same point at which the velocity measurement is made. The velocity grid shall be selected such that the temperature difference between the maximum and minimum temperatures is less than or equal to 0.55°C (1°F).

4-3.6.3.2 Measurement of Dry-Bulb Temperature, T_{db2}, at the Compressor Inlet. The sensors shall be capable of measuring dry-bulb temperature at the GT compressor inlet without the effects of condensation or water-droplet impingement. Measurement frequency and locations shall be sufficient to account for stratification of the air temperature after the inlet cooling system. The number of locations and frequency of measurements shall be determined by the pretest uncertainty analysis. A minimum of one temperature device per 9.30 m^2 (100 ft^2), or four devices, whichever is greater, shall be used to determine the inlet air temperature.

4-4 HUMIDITY MEASUREMENT

4-4.1 Introduction

This subsection presents requirements and guidance regarding the measurement of humidity for this Code. It also discusses the recommended humidity-measurement devices, calibration of humidity-measurement devices, and the application of humidity-measurement devices. Due to the state of art and general practice, the primary measurements taken by humidity-measurement equipment should be recorded electronically to minimize systematic and random error. The uncertainty of humidity-measurement equipment shall consider effects including, but not limited to, resolution, stability, environmental factors, temperature-measurement errors, pressure-measurement errors, warm-up time, spatial variation, nonlinearity, repeatability, analog output, and data acquisition.

Measurements to determine moisture content shall be made in proximity with measurements of dry- or wet-bulb temperature to provide the basis for determination of air properties.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from emf-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

4-4.2 Required Uncertainty

The required uncertainty depends upon the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussion on measurement classification and instrumentation categorization, respectively.

Class 1 primary parameters and variables shall be measured with humidity-measurement devices that determine specific humidity to an uncertainty of no more than ±0.001 g water vapor/g dry air (±0.001 lbm water vapor/lbm dry air).

Class 2 primary parameters and variables shall be measured with humidity-measurement devices that determined specific humidity to an uncertainty of not more than ±0.002 g water vapor/g dry air (±0.002 lbm water vapor/lbm dry air).

Secondary parameters and variables can be measured with any type of humidity-measurement device.

4-4.3 Recommended Humidity-Measurement Devices

Relative humidity transmitters, wet- and dry-bulb psychrometers, and chilled-mirror dew point meters are the recommended humidity-measurement devices. Economic, application, and uncertainty considerations should be taken into account when determining the most appropriate humidity-measurement device.

The wet-bulb temperature and specific humidity can be calculated from the dry-bulb temperature, barometric pressure, and one other variable such as dew point temperature, wet-bulb temperature, or absolute humidity. The psychrometric calculations found in ref. [5] or other commercially available psychrometric calculator should be used.

Since humidity-measurement technology will change over time, this Code does not limit the use of other humidity-measurement devices not currently available or not currently reliable. If such a device becomes available or is shown to be of the required uncertainty and reliability, it may be used.

4-4.3.1 Relative Humidity Transmitters

4-4.3.1.1 Application. Relative humidity transmitters employ specifically selected hydrophilic materials. As the humidity changes at the ambient temperature, the material exchanges enough moisture to regain equilibrium, while corresponding measurable changes occur in the electrical resistance or capacitance of the device. Commercially available relative humidity transmitters use sensors with a wide variety of hygroscopic substances, including electrolytes and substantially insoluble materials. Relative humidity transmitters are commonly employed for the direct measurement of parameters including relative humidity and dry-bulb temperature, and use a thin polymer film as the sensor to absorb water molecules. These instruments are often microprocessor-based, and from the parameters of relative humidity and dry-bulb temperature, they can determine the values of variables including dew point temperature, absolute humidity, mixing ratio, wet-bulb temperature, and enthalpy. In cases where the instruments output moisture-indicating parameters or variables that are used in the calculation of the test results (primary parameter or primary variable), the instruments' internal calculation formulas and basis shall be verified to demonstrate compliance with the uncertainty requirements detailed herein. Relative humidity transmitters typically provide accuracy specifications that include nonlinearity and repeatability over relative humidity conditions (i.e., ±2% RH from 0% to 90% RH, and ±3% RH from 90% to 100% RH).

The application of relative humidity transmitters are highly sensitive to temperature equilibrium, as a small difference between the measured object and the sensor causes an error. This error is greatest when the sensor is colder or warmer than the surroundings and the humidity is high.

The sensor should be installed at a location that minimizes sensor contamination. Air should circulate freely around the sensor; a location that allows rapid airflow should be selected as it ensures that both the sensor and the surroundings are at temperature equilibrium. The installation orientation should be in accordance with the device manufacturer's specifications.

The primary sources of measurement errors associated with relative humidity transmitters are typically

- sensor contamination
- analog output
- installation location
- temperature equilibrium
- accuracy
- resolution

4-4.3.1.2 Calibration. Relative humidity transmitters are commonly calibrated using one of two methods. The first method involves calibrating against high-quality, certified humidity standards, such as those generated by gravimetric hygrometers to achieve the maximum achievable accuracy. The second method calibrates with certified salt solutions that may include lithium chloride (LiCl), magnesium chloride ($MgCl_2$), sodium chloride (NaCl), and potassium sulfate (K_2SO_4). During calibration, the temperature of the sensor and the measured object shall be in equilibrium to minimize the error associated with the temperature equilibrium. Further, when using the second method, the equilibrium humidity of the salt solutions shall be corrected for the solutions temperature using Greenspan's calibration corrections or equivalent.

Relative humidity transmitters shall be calibrated to meet the uncertainty requirements in specific humidity as described herein. This shall be demonstrated with the application of an uncertainty analysis with consideration for the uncertainty associated with other measured parameters including barometric pressure and ambient dry- or wet-bulb temperature.

4-4.3.2 Wet- and Dry-Bulb Psychrometers

4-4.3.2.1 Application. The wet- and dry-bulb psychrometer consists of two temperature sensors and uses the temperature effects caused by latent heat exchange. One sensor measures the ambient dry-bulb temperature while the other is covered by a clean wick that has been thoroughly wetted with water. When the wet bulb is placed in an air stream, water evaporates from the wick, eventually reaching an equilibrium temperature called the wet-bulb temperature.

The thermodynamic wet-bulb temperature is the air temperature that results when air is adiabatically cooled to saturation. Wet-bulb temperature can be inferred by a properly designed mechanically aspirated psychrometer. The process by which a psychrometer operates is not adiabatic saturation, but one of simultaneous heat and mass transfer from the wet-bulb-sensing element. The resulting temperature achieved by a psychrometer is sufficiently close to the thermodynamic wet-bulb temperature over most ranges of conditions. However, a psychrometer should not be used for temperatures below 5°C (40°F) or when the relative humidity is less than 15%. Within the allowable range of use, a properly designed psychrometer can provide a determination of wet-bulb temperature with an uncertainty of approximately ±0.14°C (±0.25°F), based on a temperature sensor uncertainty of ±0.08°C (±0.15°F).

The temperature sensors should be resistance temperature detectors or thermistors as discussed in paras. 4-3.3.2 and 4-3.3.3, respectively. Psychrometer measurement requires certain techniques to ensure careful control of a number of variables that can affect the measurement results.

A mechanically aspirated psychrometer is recommended for Class 1 humidity measurement. If the air velocity across the sensing element is greater than 457 m/min (1,500 ft/min), the sensing element shall be shielded to minimize stagnation effects.

The mechanically aspirated psychrometer should incorporate the following features:

(a) The sensing element should be shielded from direct sunlight and any other surface that is at a temperature other than the dry-bulb temperature. If the measurement is to be made in direct sunlight, the sensor shall be enclosed by a double-wall shield that permits the air to be drawn across the sensor and between the walls.

(b) The sensing element should be suspended in the air stream and not in contact with the shield walls.

(c) The sensing element should be snugly covered by a clean, cotton wick that is kept wetted from a reservoir of distilled water. The length of the wick shall be sufficient to minimize the stem-conduction effects of the sensing element and ensure it is properly wetted.

(d) The air velocity across the sensing element should be maintained constant in the range of 240 m/min to 360 m/min (800 ft/min to 1,200 ft/min).

(e) Air should be drawn across the sensing element in such a manner that it is not heated by the fan motor or other sources of heat.

(f) The psychrometer should be located at least 1.5 m (5 ft) above ground level and should not be located within 1.5 m (5 ft) of vegetation or surface water.

(g) When using a sling psychrometer, the instrument shall be slung for a sufficient amount of times for the wet-bulb temperature to reach a steady minimum value. Once this occurs, it is imperative that the temperature be read quickly. For liquid-in-glass thermometers, consideration should be made for inertial effects on the temperature element. Data should be averaged from at least three observations.

The primary sources of measurement errors associated with wet- and dry-bulb psychrometers are typically

− temperature sensor
− installation location
− radiation
− conduction (water in the reservoir is too warm)
− faulty capillary action (very large wet-bulb depression)
− too high or too low airflow across the wick

4-4.3.2.2 Calibration. Wet- and dry-bulb psychrometer temperature sensors shall be calibrated in accordance with para. 4-3.4 and meet the uncertainty requirements in specific humidity, as described herein. This shall be demonstrated with the application of an uncertainty analysis with consideration for the uncertainty associated with other measured parameters including barometric pressure.

4-4.3.3 Chilled-Mirror Dew Point Meters

4-4.3.3.1 Application. The dew point temperature is the temperature of moist air when it is saturated at the same ambient pressure and with the same specific humidity. The dew point temperature may be measured with chilled-mirror dew point meters. The operation of these instruments is based on the establishment of the temperature corresponding to the onset of condensation. The meter determines the partial pressure of water vapor in a gas by directly measuring the dew point temperature of the gas. The temperature of the sensor surface or mirror is manually or automatically adjusted until condensation forms as dew or frost. The condensation is controlled at equilibrium, and the surface temperature is measured with a high-accuracy temperature device. Commercially available chilled-mirror dew point meters use a piezoelectric quartz element as the sensing surface. A surface acoustic wave is generated at one side of the quartz sensor and measured at the other. Chilled-mirror dew point meters require a sampling system to draw air from the sampling location across the chilled mirror at a controlled rate. Commercially available chilled-mirror dew point meters measure the dew point temperature with accuracy ranges from ±0.1°C to ±1°C (±0.2°F to ±2°F) over a dew point temperate range from −75°C to 60°C (−103°F to 140°F).

The primary sources of measurement errors associated with chilled-mirror dew point meters are typically

− sensor contamination
− analog output
− installation location
− accuracy
− resolution

4-4.3.3.2 Calibration. Chilled-mirror dew point meters shall be calibrated to meet the uncertainty requirements in specific humidity as described herein. This shall be demonstrated with the application of an uncertainty analysis with consideration for the uncertainty associated with other measured parameters including barometric pressure and ambient dry- or wet-bulb temperature.

4-4.3.4 Humidity Measurement of Inlet Air. A minimum of one humidity device shall be used to determine the inlet air humidity. The measurement location shall be in close proximity to a dry-bulb temperature measurement. The measurement location shall be shielded from direct sunlight. Inlet air streams at the planes in which they cross the test boundary are typically homogenous with respect to specific humidity unless there are sources that expel or absorb moisture into or out of the inlet air steam that could result in spatial variations of humidity. An example of a piece of equipment that could affect the humidity variation at the inlet is a cooling tower, where the drift is being redirected into the inlet stream due to wind direction change. Spatial variation effects are considered to be errors of method and therefore contributors to the systematic uncertainty in the measurement system. As such, the number and location of humidity measurement devices should be increased so that the overall systematic uncertainty of the average inlet humidity measurement devices is minimized as much as practically possible. ASME PTC 19.1 should be consulted for the determination of the uncertainty associated with spatial variation.

4-5 LIQUID AND STEAM FLOW MEASUREMENT

4-5.1 Introduction

This subsection presents requirements and guidance regarding the measurement of liquid and steam flow for this Code. It also discusses recommended flow-measurement devices, calibration of flow-measurement devices, and application of flow-measurement devices. For air-flow measurement, see subsection 4-6.

Differential pressure meters (orifice, flow nozzle, and venturi) and mechanical meters (turbine and positive displacement) are the classes of meters recommended in this Code for the following specific applications. Differential pressure meters are recommended for steam and liquid flows in pipes equal to or greater than 8 cm (3 in.), and positive displacement or turbine meters are recommended for liquid flows in pipes smaller than 8 cm (3 in.). However, since flow-measurement technology will change over time, this Code does not limit the use of other flow-measurement devices. If such a device is available and is shown to be of the required uncertainty and reliability, it may be used.

Start-up procedures shall ensure that spool pieces are provided during conditions that may violate the integrity of the flow-measurement device to avoid altering the device's characteristics. Such conditions may include steam blows or chemical cleanings. While the flow-measurement device is stored, it shall be capped and protected from environmental damage such as moisture and dirt. During operation, a strainer should be installed upstream of the flow-measurement device to protect the meter from objects and debris.

In accordance with ASME PTC 19.5, the flow shall be steady or change very slowly as a function of time. Pulsations of flow shall be small compared with the total flow rate. The frequency of data collection shall adequately cover several periods of unsteady flow. Fluctuations in the flow shall be suppressed before the beginning of a test by very careful adjustment of flow and level controls or by introducing a combination of conductance, such as pump recirculation, and resistance, such as throttling the pump discharge, in the line between the pulsation sources and the flow-measuring device. Hydraulic damping devices such as restrictors on instruments do not eliminate errors due to pulsations and, therefore, shall not be permitted.

If the fluid does not remain in a single phase while passing through the flow-measurement device, or if it has two phases when entering the meter, then it is beyond the scope of ASME PTC 19.5. In passing liquid through the flow-measurement device, the liquid should not flash into steam. In passing steam through the flow-measurement device, the steam shall remain superheated. ASME PTC 12.4 describes methods for measurement of two-phase flow in instances when it is desirable to measure the flow rate of a two-phase mixture.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from emf-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

Mass flow rate, as shown by computer printout or flow computer, is not acceptable without showing intermediate results and the data used for the calculations. In the case of a differential pressure class meter, intermediate results would include the discharge coefficient, corrected diameter for thermal expansion, expansion factor, etc. Raw data includes static and differential pressures, and temperature. For the case of a mechanical meter, intermediate results include the meter constant(s) used in the calculation, and how it is determined from the calibration curve of the meter. Data includes frequency, temperature, and pressure.

4-5.2 Required Uncertainty

The required uncertainty depends upon the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussion about measurement classification and instrumentation categorization, respectively.

If not otherwise specified by this Code, Class 1 primary parameters and variables shall be determined with flow-measurement devices that have a systematic uncertainty of no more than ±0.5% of the mass flow rate. Flow-measurement devices used to determine Class 1 primary parameters and variables shall undergo a laboratory calibration unless the device can demonstrate a systematic uncertainty lower than ±0.5% without calibration.

Class 2 primary parameters and variables shall be measured with flow-measurement devices that have a systematic uncertainty of no more than 1.1% of mass flow rate. Class 2 primary parameters and variables may use the empirical formulations for the discharge coefficient for differential pressure class meters if the uncertainty requirements are met and the meter is manufactured, installed, and operated in strict accordance with ASME PTC 19.5.

Secondary parameters and variables can be measured with any type of flow-measurement device.

4-5.3 Recommended Flow-Measurement Devices

Differential pressure meters (orifice, flow nozzle, and venturi) and mechanical meters (turbine and positive displacement) are the recommended flow-measurement devices for the specific applications noted herein.

Economic, application, and uncertainty considerations should be taken into account when determining the most appropriate flow-measurement device.

In the case where a flow-measurement device is laboratory calibrated, the entire primary device shall be calibrated. This shall include the primary element, upstream and downstream metering runs, and flow conditioners, and the device shall be shipped as one piece, dirt and moisture free, and not disassembled for shipping, installation, inspection, or any other reason, in order for the laboratory calibration to remain valid. If a metering run is taken apart at the primary element's flanges, or the primary element is removed for inspection, then the empirical formulations for discharge coefficient and the associated uncertainty should be used for that meter unless a positive, mechanical alignment method is in place to replicate the precise position of the meter run or primary element when it was calibrated.

4-5.3.1 Differential Pressure Meters. In this subsection, the application and calibration requirements for the use of orifice, flow nozzle, and venturi meters are presented. Orifice meters are presented first, followed by flow nozzles and venturi meters, respectively.

All differential pressure meters used in the measurement of Class 1 primary parameters and variables shall be laboratory calibrated. If flow straighteners or other flow-conditioning devices are used in the test, they shall be included in the meter piping run when the calibration is performed. Qualified hydraulic laboratories commonly calibrate within an uncertainty of approximately 0.2%. Thus, with inherent curve-fitting inaccuracies, uncertainties of less than 0.3% in the discharge coefficients of laboratory-calibrated meters can be achieved. The procedures for fitting a curve through laboratory calibration data is provided in detail in ASME PTC 19.5 for each differential pressure meter. The procedures for extrapolation of a calibration to a higher Reynolds number than available in the laboratory, if necessary, is also given for each meter in ASME PTC 19.5. Differential pressure meters used in the measurement of Class 2 primary parameters and variables may use the empirical formulations for the discharge coefficient for differential pressure class meters if the uncertainty requirements are met and the meter is manufactured, installed, and operated in strict accordance with ASME PTC 19.5.

For a differential pressure meter to be used as a Class 1 instrument, it shall be manufactured, calibrated, installed, and operated in strict accordance with ASME PTC 19.5. The calculation of the flow shall also be done in accordance with that Code. The documentation of factory measurements, manufacturing requirements, dimensional specifications of the installation including upstream and downstream disturbances, and of the start-up procedures, shall be examined to validate compliance with the requirements of ASME PTC 19.5. Details shall be documented as suggested in (a) through (m) below.

(a) piping straight-length requirements upstream and downstream of the primary element and between the flow conditioner (if used) and the primary element

(b) piping and flow-element diameters and roundness, and locations of roundness measurements

(c) piping smoothness

(d) internal smoothness of flow nozzle or venturi element

(e) smoothness and flatness of upstream face of orifice plate

(f) dimensions and machining tolerances for all dimensions of primary element given in ASME PTC 19.5

(g) sharpness of orifice plate edge

(h) thickness of orifice plate required

(i) inspection for assurances of no burrs, nicks, wire edges, etc.

(j) location, size, and manufacturing requirements of pressure taps, including machining and dimensional tolerances

(k) location of temperature measurement

(l) eccentricity of primary element and piping

(m) type and manufacturing requirements of flow conditioner, if used

Class 1 primary parameters and variables shall be measured with a minimum of two sets of differential pressure taps, each with independent differential pressure measurement devices. The two sets of pressure taps should be separated by 90 deg or 180 deg. In addition, the meter for the throat tap flow nozzle should be manufactured with four sets of differential pressure taps located 90 deg apart, and the taps should be individually measured. Further, the flow calculation should be done separately for each pressure tap pair, and averaged. An investigation shall be conducted if the results differ from each tap-set calculation by more than the flow-measurement uncertainty. In cases where the metering run is installed downstream of a bend or tee, the pairs of single taps should be installed so that their axes are perpendicular to the plane of the bend or tee. Differential pressure meters should be assembled, calibrated (if applicable), and left intact for the duration of the test since manufacture. Once manufactured and calibrated (if applicable), the flow meter assembly should not be disassembled at the primary element flanges. If it is necessary to disassemble the section for inspection or other means prior to the test, provisions for the accurate realignment and reassembly, such as pins, shall be built into the section to replicate the precise position of the flow element when it was manufactured and calibrated (if applicable), or the empirical formulation shall be used in the calculation of flow. In addition, gaskets or seal rings (if used) shall be inserted in such a way that they do not protrude at any point

Table 4-5.3.1-1 Units and the Conversion Factor for Mass Flow Through a Differential Pressure Class Meter

Units in General Flow Equation						
					Values of Constants	
Unit Type	Mass Flow Rate, q_m	Meter Geometry, *d* or *D*	Fluid Density, ρ_f	Differential Pressure, Δp	Proportionality Constant, g_c	Units Conversion Constant, N
SI Units	$\frac{kg}{s}$	m	$\frac{kg}{m^3}$	p_a	1.0 dimensionless	1.0 dimensionless
U.S. Customary Units	$\frac{lbm}{hr}$	in.	$\frac{lbm}{ft^3}$	$\frac{lbf}{in.^2}$	32.174056 $\frac{lbm-ft}{lbf-s^2}$	$n \equiv 300.0$ $\frac{ft^2}{s^2}\left(\frac{in.^2}{ft^2}\bullet\frac{sec^2}{hr^2}\right)^{0.5}$

GENERAL NOTE: $N \equiv kg\text{-}m/s^2$, and $p_a \equiv N/m^2$. Therefore, $p_a \equiv kg/m\text{-}s^2$.

inside the pipe or across the pressure tap or slot when corner tap orifice meters are used.

The general equation of mass flow through a differential pressure class meter for liquids and gases, flowing at subsonic velocity from ASME PTC 19.5 is

$$q_m = N\frac{\pi}{4}d^2C_dE\sqrt{\frac{2\rho(\Delta p)g_c}{1-\beta^4}} \tag{4-5-1}$$

where

C_d = discharge coefficient
d = diameter of flow element (bore) at flowing fluid temperature
E = expansion factor
g_C = proportionality constant
N = units conversion factor for all units to be consistent
q_m = mass flow of liquid or gas
Δp = differential pressure
β = ratio of flow element (bore) and pipe diameters (d/D), both diameters at the flowing fluid temperature
ρ = fluid density

Table 4-5.3.1-1 provides the appropriate units and the conversion factor for eq. (4-5-1) in SI and U.S. Customary units.

The procedures for determining the discharge coefficient and expansion factor for the various devices are given in ASME PTC 19.5. Note that because the discharge coefficient is dependent on Reynolds number, which in turn is dependent on flow, both the sizing of and calculation of flow through these meters involve iteration. For a properly constructed differential pressure meter, the discharge coefficient is a function of the Reynolds number of flow, and the diameters of the flow element and the pipe for the range of flows found in power plants. Discharge coefficients for flow nozzle and venturi meters are in the order of 1.0, as compared to typical discharge coefficients of orifice meters in the order of 0.6.

Due to the repeatability of hydraulic laboratory calibration data for differential pressure meters of like type and size, relationships of C versus R_D are available for each type of differential pressure meter. Empirical formulations for discharge coefficient are based on studies of the results of large numbers of calibrations. Application of the empirical formulations for discharge coefficient may be used for primary variables if uncertainty requirements are met. In some cases it is preferable to perform a hydraulic laboratory calibration of a specific differential pressure meter to determine the specific C versus R_D relationship for that meter. To meet the uncertainty requirements of this Code for Class 1 primary parameters and variables, the meter shall be calibrated to determine the specific C versus R_D relationship for that meter.

The expansion factor is a function of the diameters of the flow element and the pipe, the ratio of the differential pressure to the static pressure, and the isentropic exponent of the gas or vapor. It is used for compressible flows; in this case, commonly gas. It corrects the discharge coefficient for the effects of compressibility. This means that a hydraulic calibration of a differential pressure flow meter is equally as valid for compressible flow application as in incompressible flow application with trivial loss of accuracy. This is a strong advantage of differential pressure meters in general because laboratory determination of compressible flow is generally less accurate than of incompressible flow. The value of E for liquid flow measurement is unity, since it is incompressible.

The systematic uncertainty of the empirical formulation of the discharge coefficient and the expansion factor in the general equation for each of the recommended differential pressure meters is presented in ASME PTC 19.5 and repeated in Table 4-5.3.1-2 for convenience. It should be noted that the tabulated uncertainty values have analytical constraints on pipe Reynolds numbers, bore diameters, and beta ratios. These values assume that the flow-measurement device is manufactured, installed, and operated as specified in ASME PTC 19.5

Table 4-5.3.1-2 Summary Uncertainty of Discharge Coefficient and Expansion Factor

Differential Pressure Meter	Uncertainty of Empirical Discharge Coefficient, C_d, for an Uncalibrated Flow Element	Uncertainty of Expansion Factor, E [Note (1)]
Orifice	0.6% for $0.2 \le \beta \le 0.6$ β% for $0.6 \le \beta \le 0.75$	$\frac{4(\Delta p)}{p_1}$
Venturi	0.7% for $0.3 \le \beta \le 0.75$	$\frac{(4+100\beta^8)(\Delta p)}{p_1}$
Flow nozzle, wall taps	1.0% for $0.2 \le \beta \le 0.5$	$\frac{2(\Delta p)}{p_1}$
Flow nozzle, throat taps	Not recommended without calibration.	$\frac{2(\Delta p)}{p_1}$

NOTE:
(1) Pressure and differential pressure are the same units.

and herein. In using the empirical formulations, the uncertainty of the discharge coefficient is by far the most significant component of the flow-measurement uncertainty, and is the dominant factor in the uncertainty analysis, assuming that the process and differential pressure instrumentation used in conjunction with the meter is satisfactory. Among differential pressure meters, orifice-metering runs are usually the choice in Performance Test Code work on an accuracy basis when using the empirical formulation for the discharge coefficient.

The total measurement uncertainty of the flow contains components consisting of the uncertainty in the determination of fluid density, flow element (bore) and pipe diameter, and of pressure, temperature, and differential pressure measurement uncertainty in addition to the components caused by the uncertainty in C_d and E. Reference ASME PTC 19.5 for the methodology in the determination of the systematic uncertainty.

4-5.3.1.1 Orifice Meters

4-5.3.1.1.1 Application. Recommended flow measurements by orifice meters are for liquid in pipes greater than 8 cm (3 in.), and low-pressure steam.

In accordance with ASME PTC 19.5, three types of tap geometries are available and include flange taps, D and D/2 taps, and corner taps. This Code recommends that only flange taps or corner taps be used for primary variable measurements with orifice meters.

The lip-like upstream side of the orifice plate that extends out of the pipe, called the tag, shall be permanently marked with the following information:

− identification as the upstream side
− measured bore diameter to five significant digits
− measured upstream pipe diameter to five significant digits if same supplier as orifice plate
− instrument, or orifice, identifying number

4-5.3.1.1.2 Calibration. Water calibration of an orifice meter does not increase the measurement uncertainty when the meter is used in gas measurements. The uncertainty of the expansion factor of fundamental flow (eq. 4-5-1) is the same whether or not the orifice is water or air calibrated. The procedure for curve fitting, including extrapolation, if necessary, and evaluating the curve for the coefficient of discharge shall be conducted in compliance with ASME PTC 19.5.

4-5.3.1.2 Flow Nozzle Meters

4-5.3.1.2.1 Application. Flow nozzle meters in an ASME PTC 51 test may be used for high-pressure steam flows, and for liquid flow in pipes at least 10 cm (4 in.).

In accordance with ASME PTC 19.5, three types of ASME primary elements are recommended: low-beta ratio flow nozzles, high-beta ratio flow nozzles, and throat tap flow nozzles. Other flow nozzles may be used if equivalent level of care be taken in their fabrication and installation and if they are calibrated in a laboratory with the same care and precision as required in ASME PTC 19.5 and herein.

As detailed in ASME PTC 19.5, the flow section is comprised of the primary element; the diffusing section, if used; the flow conditioner; and the upstream and downstream piping lengths.

4-5.3.1.2.2 Calibration. At least 20 calibration points should be run over the widest range of Reynolds numbers possible that applies to the Performance Test. The procedure for determining whether the calibration curve parallels the theoretical curve shall be conducted in accordance with ASME PTC 19.5. The procedure for fitting, including extrapolation, if necessary, and evaluating the curve for the coefficient of discharge shall be conducted in compliance with ASME PTC 19.5.

4-5.3.1.3 Venturi Meters

4-5.3.1.3.1 Application. Venturi meters in an ASME PTC 51 test may be used for high-pressure steam flows, and for liquid flow in pipes at least 10 cm (4 in.).

In accordance with ASME PTC 19.5, the ASME (classical Herschel) venturi is the recommended type of primary element. Other venturis may be used if equivalent level of care be taken in their fabrication and installation and if they are calibrated in a laboratory with the same care and precision as required in ASME PTC 19.5 and herein. The convergent cone of a venturi is effective as a flow conditioner for the throat section. As such, the upstream length requirements for venturi meters are commonly less than alternative differential pressure class meters for the same upstream conditions.

4-5.3.1.3.2 Calibration. In accordance with ASME PTC 19.5, due to similar design considerations, ASME venturi meters commonly maintain the same physics of the flow as the throat tap flow nozzles. As such, similar to flow nozzle meters, at least 20 calibration points should be run over the widest range of Reynolds numbers possible that applies to the Performance Test. The procedure for fitting, including extrapolation, if necessary, for the coefficient of discharge, shall be conducted in compliance with ASME PTC 19.5.

4-5.3.2 Mechanical Meters. In this subsection, the application and calibration requirements for the use of turbine and positive displacement meters are presented. Turbine meters are presented first, and the section on positive displacement meters follows. Turbine meters are commonly classified as inference meters as they measure certain properties of the fluid stream and "infer" a volumetric flow, while positive displacement meters are commonly classified as direct meters as they measure volumetric flow directly by continuously separating (isolating) a flow stream into discrete volumetric segments and counting them.

A fundamental difference between differential pressure meters and mechanical meters is the flow equation derivation. The flow calculations of differential pressure meters may be based on fluid flow fundamentals utilizing the First Law of Thermodynamics derivation where deviations from theoretical expectation may be assumed under the discharge coefficient. Thus, one can manufacture, install, and operate a differential pressure meter of known uncertainty. Conversely, mechanical meter operation is not rooted deeply in fundamentals of thermodynamics and has performance characteristics established by design and calibration. Periodic maintenance, testing, and recalibration is required because the calibration will shift over time due to wear, damage, or contamination.

All mechanical meters used in the measurement of Class 1 or Class 2 primary parameters and variables shall be laboratory calibrated. These calibrations shall be performed on each meter using the fluid, operating conditions, and piping arrangements as nearly identical to the test conditions as practical. If flow straighteners or other flow-conditioning devices are used in the test, they shall be included in the meter piping run when the calibration is performed.

4-5.3.2.1 Turbine Meters

4-5.3.2.1.1 Application. Recommended applications of turbine meters by this Code are liquid flow rates in pipes less than 8 cm (3 in.).

The turbine meter is an indirect volumetric meter. Its main component is an axial turbine wheel turning freely in the flowing fluid. The turbine wheel is set in rotation by the fluid at a speed that is directly proportional to the average velocity of the fluid in the free cross section of the turbine meter. The speed of the turbine wheel is therefore directly proportional to the volumetric flow rate of the flow, with the number of revolutions proportional to the volume that has passed through the meter. There are two basic turbine meter designs: electromagnetic and mechanical.

The electromagnetic-style meter has two moving parts: the rotor and bearings. The rotor velocity is monitored by counting pulses generated as the rotor passes through a magnetic flux field created by a pickup coil located in the measurement module. A meter factor, or *K* factor, is determined for the meter in a flow calibration laboratory by counting the pulses for a known volume of flow and is normally expressed as pulses per acf. This *K* factor is unique to the meter and defines its accuracy.

The mechanical-style meter uses a mechanical gear train to determine the rotor's relationship to volume. The gear train is commonly comprised of a series of worm gears, drive gears, and intermediate gear assemblies that translate the rotor movement to a mechanical counter. In the mechanical-style meter, a proof curve is established in a flow calibration laboratory and a combination of change gears is installed to shift the proof curve to 100%.

Turbine meter performance is commonly defined by rangeability, linearity, and repeatability. Rangeability is a measure of the stability of the output under a given set of flow conditions and is defined as the ratio of the maximum meter capacity to the minimum capacity for a set of operating conditions during which the meter maintains its specified accuracy. Linearity is defined as the total deviation in the meters indication over a stated flow range and is commonly expressed by meter manufacturers to be within ±0.5% over limited flow ranges. High-accuracy meters have typical linearities of ±0.15% for liquids and ±0.25% for gases, usually specified over a 10:1 dynamic range below maximum rated flow. Repeatability is defined as the ability of the meter to indicate the same reading each time the same condition exist and is normally expressed as ±0.1% of reading for liquids and ±0.25% for gases. Accuracy shall be expressed as a composite statement of repeatability and linearity over a stated range of flow rates.

Turbine meters are susceptible to overregistration due to contaminants, positive swirl, nonuniform velocity profile, and pulsations. In gas flow, contaminants can build on internal meter parts and reduce the flow area, which results in higher-velocity fluid, a faster-moving rotor, and a skewed rotor exit angle. The increased velocity and the altered exit angle of the fluid cause the rotor to overregister. For all fluids, positive upstream swirl may be caused by a variety of conditions that may include out-of-plane elbows, insufficient flow conditioning, partially blocked upstream filters, or damaged internal straightening vanes. The positive swirl causes the fluid flow to strike the rotor at an accentuated angle, causing the rotor to overregister. In cases where there is a distortion of the velocity profile at the rotor inlet introduced by upstream piping configuration, valves, pumps, flange misalignments, and other obstructions, the rotor speed at a given flow will be affected. For a given average flow rate, generally, a nonuniform velocity profile results in a higher rotor speed than a uniform velocity profile. In pulsating flow, the fluid velocity increases and decreases, resulting in a cyclical acceleration and deceleration of the rotor causing a net measurement overregistration. Dual-rotor turbine meters with self-checking and self-diagnostic capabilities are recommended to aid measurement accuracy to detect and adjust for mechanical wear, fluid friction, and upstream swirl. Additionally, dual-rotor meters' electronics and flow algorithms detect and make partial adjustments for severe jetting and pulsation. ASME PTC 19.5 should be consulted for guidance for flow disturbances that may affect meter performance and standardized tests to assess the effects of such disturbances.

4-5.3.2.1.2 Calibration. In accordance with ASME PTC 19.5, an individual calibration shall be performed on each turbine meter at conditions as close as possible to the test conditions under which the meter is to operate. This shall include using the fluid, operating conditions (temperature and pressure), and piping arrangements as nearly identical to the test conditions as is practical with calibration data points that are taken at flow rates that surround the range of expected test flows. The orientation of the turbine meter will influence the nature of the load on the rotor bearings, and thus, the performance of the meter at low flow rates. For optimum accuracy, the turbine meter should be installed in the same orientation in which it was calibrated. The turbine meter calibration report shall be examined to confirm the uncertainty as calibrated in the calibration medium.

As the effect of viscosity on the turbine meter calibration, or *K* factor, is unique, turbine meters measuring liquid flow rate shall be calibrated at two kinematic viscosity points surrounding the test fluid viscosity. Each kinematic viscosity point shall have three different calibration temperatures that encompass the liquid temperature expected during the test. It is recommended that a universal viscosity curve (UVC) be developed to establish the sensitivity of the meter's *K* factor to a function of the ratio of the output frequency to the kinematic viscosity. The universal viscosity curve reflects the combined effects of velocity, density, and absolute viscosity acting on the meter. The latter two effects are combined into a single parameter by using kinematic viscosity.

The result of the calibration shall include

− the error at the minimum flow and all the flowing flow rates that are above the minimum flow; 0.1/0.25/0.4/0.7 of the maximum flow

− the name and location of the calibration laboratory

− the method of calibration (bell prover, sonic flow nozzles, critical flow orifice, master meters, etc.)

− the estimated uncertainty of the method, using ASME PTC 19.1

− the nature and conditions (pressure, temperature, viscosity, specific gravity) of the test fluid

− the position of the meter (horizontal, vertical flow up, vertical flow down)

In presenting the calibration data, either the relative error or its opposite, the correction; or the volumetric efficiency or its reciprocal, the meter factor, shall be plotted versus the meter bore Reynolds number (the meter's bore shall be measured accurately as part of the calibration process).

4-5.3.2.2 Positive Displacement Meters

4-5.3.2.2.1 Application. This Code recommends positive displacement meters for liquid flows for all size pipes, but in particular for pipes less than 8 cm (3 in.). There are many designs of positive displacement meters, including wobble plate, rotating piston, rotating vanes, and gear or impellor types. All of these designs measure volumetric flow directly by continuously separating (isolating) a flow stream into discrete volumetric segments and counting them. As such, they are often called volumeters. Because each count represents a discrete volume of fluid, positive displacement meters are ideally suited for automatic batching and accounting. Unlike differential pressure class meters and turbine meters, positive displacement meters are relatively insensitive to piping installations and otherwise poor flow conditions; they in fact are more of a flow disturbance than practically anything else upstream or downstream in plant piping.

Positive displacement meters provide high accuracy (±0.1% of actual flow rate in some cases) and good repeatability (±0.05% of reading in some cases), and accuracy is not significantly affected by pulsating flow unless it entrains air or gas in the fluid. Turndowns as high as 100:1 are available, although ranges of 15:1 or lower are more common.

Use of positive displacement meters is recommended without temperature compensation. The effects of temperature on fluid density can be accounted for by calculating the mass flow based on the specific gravity at the flowing temperature.

(SI Units)

$$q_{mh} = sg \times q_v \tag{4-5-2}$$

(U.S. Customary Units)

$$q_{mh} = 8.337 \times sg \times q_v \times 60 \tag{4-5-3}$$

where

q_{mh} = mass flow, kg/s (lbm/hr)
q_v = volume flow, l/s (gal/min)
sg = specific gravity at flowing temperature, dimensionless

4-5.3.2.2.2 Calibration. The recommended practice is to calibrate these meters in the same fluid at the same temperature and flow rate as is expected in their intended performance test environment or service. If the calibration laboratory does not have the identical fluid, the next best procedure is to calibrate the meter in a similar fluid over the same range of viscosity−pressure drop factor expected in service. This recommendation implies duplicating the absolute viscosity of the two fluids.

4-6 AIR-FLOW MEASUREMENT

4-6.1 Introduction

Due to the large ducts handling airflows associated with this Code, often the only practicable method of direct air-flow measurement is the velocity traverse method. This method shall be considered the primary method for measuring airflows and is the only direct measurement method discussed by this Code.

An alternate direct measurement method is that of the calibrated gas turbine bell mouth method. In this approach, the gas turbine bell mouth has been calibrated at a laboratory and the airflow is determined from pressure drop measurements across the bell mouth. Typically the calibration information is the sole property of the gas turbine manufacturer and access to the calibration information or the use of this device is not always available to parties for an inlet air-conditioning equipment test. This method is acceptable if the calibration information is available to the parties of the test and the measurement unceraínty meets the requirements of this Code.

Other methods of determining airflow are analytical methods. These methods include, but are not limited to, calculation of airflow using exhaust gas composition, gas turbine energy balance, and heat-recovery steam generator energy balance minus the gas turbine/duct burner fuel flow input. These analytical methods may be permitted if it can be shown that the uncertainty of the method is at least equal to that of the velocity traverse method. The calculation of airflow using exhaust gas composition is discussed in para. 5-2.5.6. For application of the gas turbine energy balance method and the heat-recovery steam generator energy balance method, please refer to ASME PTC 22 and ASME PTC 4.4, respectively.

4-6.2 Air-Flow Measurement by Traverse

4-6.2.1 Introduction. This subsection presents requirements and guidance regarding the measurement of airflow by traverse in support of ASME PTC 51 testing. It also discusses specification, calibration, and application of air-flow measurement devices.

Since air mass−flow measurement planes associated with ASME PTC 51 tests are not conducive to the application of direct mass-flow measurement devices, air mass flow must be treated as a variable that is a function of the parameters of velocity, pressure, temperature, and humidity. In the velocity traverse method, the duct is subdivided into a number of elemental areas and, using a suitable probe, the velocity, incident angle, and temperature is measured at a point in each elemental area over a selected measurement plane area. The total flow is then obtained by combining the contributions of each elemental area. Within the framework of the velocity traverse method, many different techniques have been proposed: Gauss, Tchebycheff, log-lineaer, and equal area, among others. For guidance on these methods, please refer to ASME PTC 19.5. This Code does not require one particular method be used over another. Each method has its benefits and problems depending on the flow stream being analyzed. Therefore, this Code has elected to allow the user to select the best method for their application. Proper use of the measurement instrument by following the manufacturer's guidelines and specifications for the instrument shall be followed so as to limit the overall test uncertainty.

Mass flow rate as shown by computer printout or flow computer shall not be acceptable without showing intermediate information and the data used for the calculations. As example, in the case of a differential pressure class meter, required intermediate information includes the pitot calibration coefficient and incident angles. Data includes static and differential pressures, and temperature. For the case of a mechanical meter, required intermediate information includes the meter constant(s) used in the calculation, and how it is determined from the calibration curve of the meter. Data includes frequency, temperature, and static pressure. Regardless of the flow measurement devices, analysis methods and the intermediate information used in the calculation of the air mass flow is required.

Since the characteristics of measurement planes will change from test to test, this Code has elected to provide general guidance on the methods that lead to accurate determination of airflow by traverse. It will be up to the user of the Code to determine which methods are applicable to their flow-traversing situation.

4-6.2.2 Required Uncertainty. The required uncertainty shall depend upon the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussion on measurement classification and instrumentation categorization, respectively.

If not otherwise specified by this Code, Class 1 primary velocities shall be determined with air-velocity measurement devices that have a systematic uncertainty of no more than ±3% of reading. Devices used to determine Class 1 primary parameters and variables shall have a laboratory calibration performed unless the device can demonstrate a systematic uncertainty lower than ±3% without calibration.

Class 2 primary velocities shall be measured with air-velocity measurement devices that have a systematic uncertainty of no more than 6% of reading. Secondary parameters and variables can be measured with any type of flow-measurement device.

Uncertainty requirements for the measurements of pressure, temperature, and humidity are given in paras. 4-2.2, 4-3.2, and 4-4.2, respectively.

Class 1 primary flow measurements determined by velocity traverse shall have a total uncertainty of no more than 5%. Class 2 primary flow measurements determined by velocity traverse must have a total uncertainty of no more than 10%.

As a general rule, uncertainty of flow measurement can be decreased by either increasing the number of points in the traverse plane or by using more sophisticated mathematical techniques (e.g., interpolation polynomials, boundary layer corrections) [6, 7, 8, 9]. It is more in line with the requirements of field testing as well as more realistic in light of the varied distributions of velocity that may actually occur in the field, to obtain the desired uncertainty of flow measurement by specifying measurements at a relatively large number of points rather than by relying on assumed velocity distributions or unsubstantiated assumptions regarding such things as boundary layer effects.

4-6.3 Recommended Flow-Measurement Devices

Differential pressure meters (pitot, venturi, and multidirectional), mechanical meters (propeller/vane), and thermal meters (hotwire and resistance) are the classes of meters recommended in this Code for the following specific applications covered herein.

Table 4-6.3-1 provides a sample list of instruments that measure air-flow velocity, typical application ranges, and associated uncertainty. However, since air-flow measurement technology will change over time, this Code does not limit the use of other air-flow measurement devices not covered in this Code, not currently available, or not currently reliable. If such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

The user of this Code must be careful in the selection of air-velocity measurement devices to ensure that they meet the requirements of the measurement. Economic, application, and uncertainty considerations should be taken into account when determining the most appropriate flow-measurement device.

4-6.3.1 Differential Pressure Devices. There are a number of acceptable differential pressure devices that may be used for determining point velocities. These devices, when used in conjunction with a suitable manometer or differential pressure transmitter, provide an accurate means to determine flow velocity from the measurement of differential pressue through the application of Bernoulli's equation.

Depending on the pitot-static tube design, a calibration coefficient shall be used as a premultiplying factor, or a characteristic curve(s) shall be employed to correct the measurement to give the actual value. However, in some cases, the design of the probe selected inherently lends itself to a discharge coefficient of unity. Examples of this are the N.P.L. tapered head ($0.995 < K < 0.996$), the N.P.L. hemispherical head ($0.993 < K < 0.995$), and the N.P.L. modified ellipsoidal head ($0.994 < K < 1.002$).

It is required that all differential pressure devices used in the measurement of Class 1 velocity measurements be laboratory calibrated with exception to standard pitot-static tubes. Standard pitot-static tubes are considered primary instruments and need not be calibrated provided that they are maintained and free of damage, debris, or warpage. Calibrated probes should be handled with care because large scratches or nicks near the pressure taps shall invalidate the calibration. If the device is viewed to be damaged, it should be recalibrated or replaced. Any secondary elements (differential pressure transmitters, manometers, etc.) utilized with differential pressure devices shall also be calibrated. Please refer to para. 4-2.3.3 for the calibration requirements of the secondary elements.

Nondirectional probes may be used only in applications where preliminary tests with directional probes gives good evidence that the average of the absolute values of either yaw angle or pitch angle does not exceed 5 deg with exception of the Kiel style, which can be used when the yaw or pitch angle does not exceed 15 deg.

A five-hole probe (Fig. 4-6.3.1-1) is generally required to determine pitch angles as well as yaw angles. In operation, a five-hole probe is inserted in the proper port to the proper depth for each traverse point. The probe should be rigid enough over its inserted length to avoid any droop or bending. The reference line on the probe should be used to orient the probe in such a way that when the total pressure hole is pointing upstream perpendicular to the measuring plane, the indicated yaw angle is zero. The probe is then rotated about its own axis until a null balance is obtained across the taps of the static pressure holes. The angle of probe rotation from the zero yaw reference direction is measured with an appropriate indicator and is reported as the yaw angle. Without changing the angularity of the probe, the pressure difference across the taps for the fourth and fifth holes shall also be recorded and used with the indicated velocity

Table 4-6.3-1 Air-Velocity Measurement Devices

Class of Device	Examples Within Class	Typical Velocity Range	Typical Uncertainty
Differential pressure	Standard pitot-static tubes (nondirectional) N.P.L tapered head standard N.P.L. hemispherical head standard N.P.L. modified ellipsoidal head standard ASHRAE spherical head standard ASHRAE blunt head Prandtl Stauscheibe (S-type)	1 m/s to 50 m/s (3.3 ft/sec to 164 ft/sec) [Note (1)] 50 m/s (164 ft/sec) and above [Note (2)]	1% to 5% of reading
	Shielded head (nondirectional) Kiel style	1 m/s to 50 m/s (3.3 ft/sec to 164 ft/sec) [Note (1)] 50 m/s (164 ft/sec) and above [Note (2)]	1% to 5% of reading
	Directional (yaw/pitch) Claw type Angle-tube, Prism, Spherical } # Holes { 3-hole, 5-hole, 7-hole Fechheimer	1 m/s to 50 m/s (3.3 ft/sec to 164 ft/sec) [Note (1)] 50 m/s (164 ft/sec) and above [Note (2)]	1% to 5% of reading
Mechanical anemometer	Turbine-type meters (nondirectional) Deflecting vane Revolving (rotating) vane Revolving (rotating) propeller	0.5 m/s to 30 m/s (1.6 ft/sec to 98 ft/sec)	2% to 5% of reading

GENERAL NOTES:
(a) This table provides only samples of the instruments under each class given and is not intended to be an all-inclusive list of instruments allowed under this Code.
(b) N.P.L. = National Physical Laboratory
(c) ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers

NOTES:
(1) Achievable with use of a micromanometer or special-range pressure transmitter
(2) Achievable with use of a standard manometer or pressure transmitter

pressure and the pitch pressure coefficient to determine pitch angle. Measurements of indicated velocity pressure and static pressure or indicated velocity pressure and total pressure shall be recorded with the probe in the proper null-balance position (note that a null balance can be obtained at four different positions but only one is correct. Incorrect null positions usually correspond to negative velocity pressures). When a directional probe cannot be nulled, velocity pressure shall be recorded as zero.

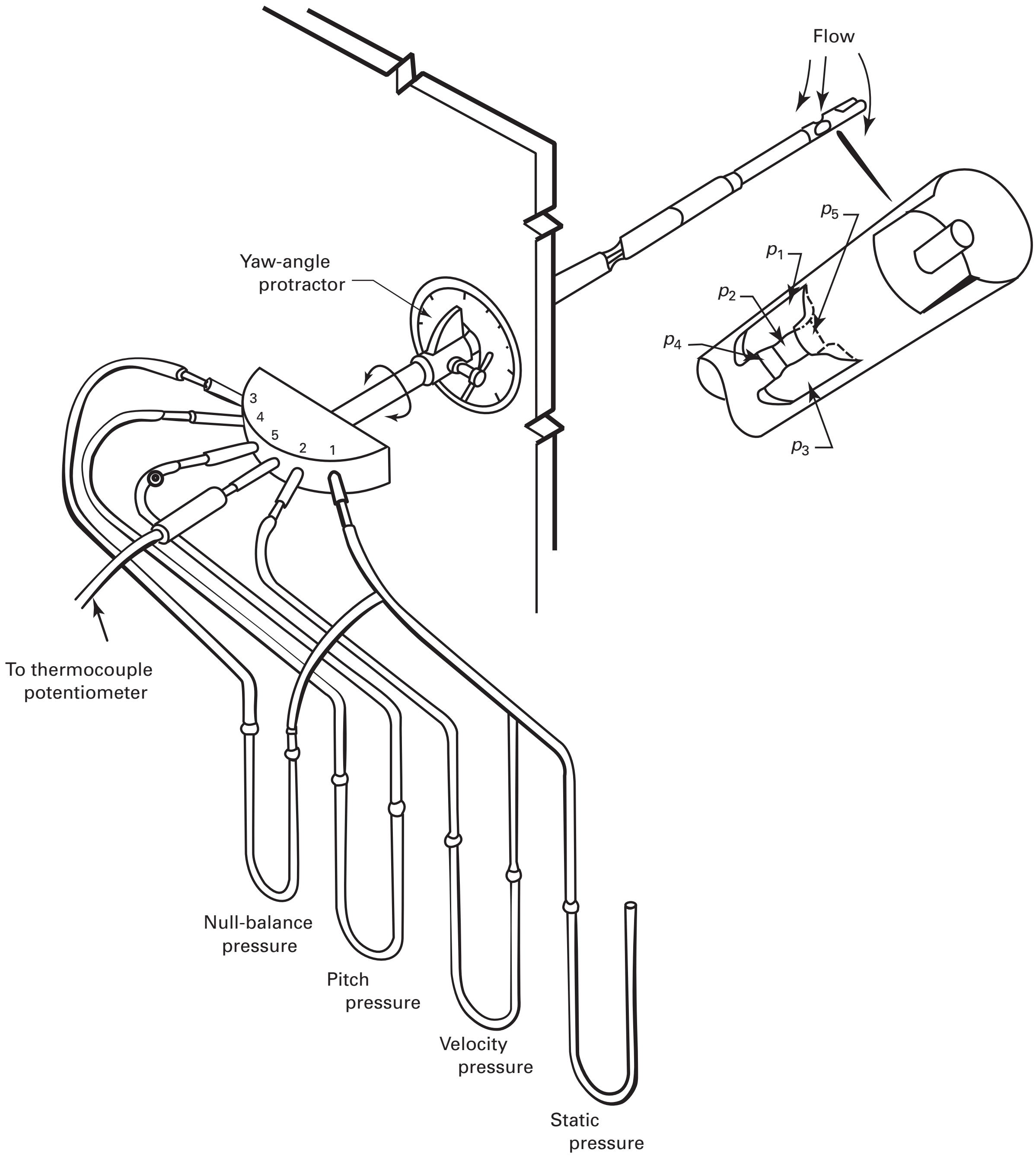
A three-hole probe (Fig. 4-6.3.1-2) is operated in a similar manner except that the pitch pressure difference is omitted.

4-6.3.2 Mechanical Anemometers. As with the differential pressure devices, mechanical anemometers come in a variety of configurations to determine measurements of point velocities. When properly used, these devices enable the user to determine suitable flow velocities within the uncertaninty required for Code-level testing.

Due to their aerodynamic nature and mechanical operation, all mechanical anemometers used in the measurement of Class 1 or Class 2 primary velocity measurements shall be laboratory calibrated. Calibrated mechanical anemometers should be handled with care because damage to the primary element (dings, scratches, warping, etc.) will invalidate the calibration. Likewise, if the device is used in dusty or corrosive environments, buildup on the rotating element will lead to loss of calibration. If the device is viewed to be damaged or dirty, it should be recalibrated or replaced.

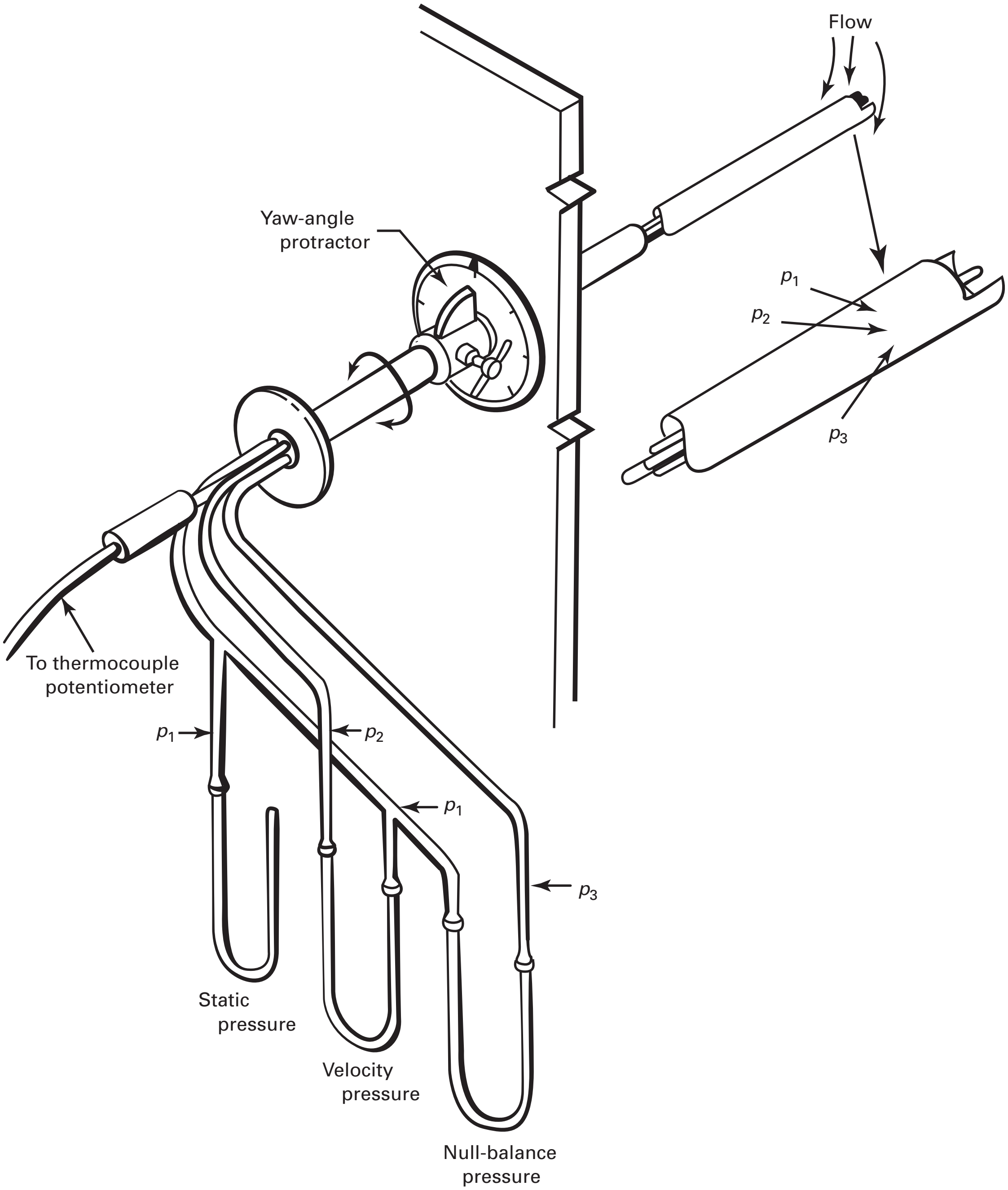
As with other nondirectional air-measuring equipment, the revolving anemometer is subject to errors due to incident angles (angles of attack). Vane anemometers are more susceptible to incident angle than to propeller anemometers since the vane anemometer is equipped with a shroud around the rotating element. Vane anemometers can expect to have a 1% error for ±10 deg, while propeller anemometers can expect to have a 1% error for ±20 deg. Mechanical anemometers may be used only in applications where preliminary tests with directional probes give good evidence that the average of the absolute values of either yaw angle or pitch angle do not exceed 5 deg for vane anemometers and 10 deg for propeller-style anemometers. Mechanical meters are also susceptible to overregistration due to contaminants, positive swirl, nonuniform velocity profile, and pulsations. ASME PTC 19.5

Fig. 4-6.3.1-1 Five-Hole Probe



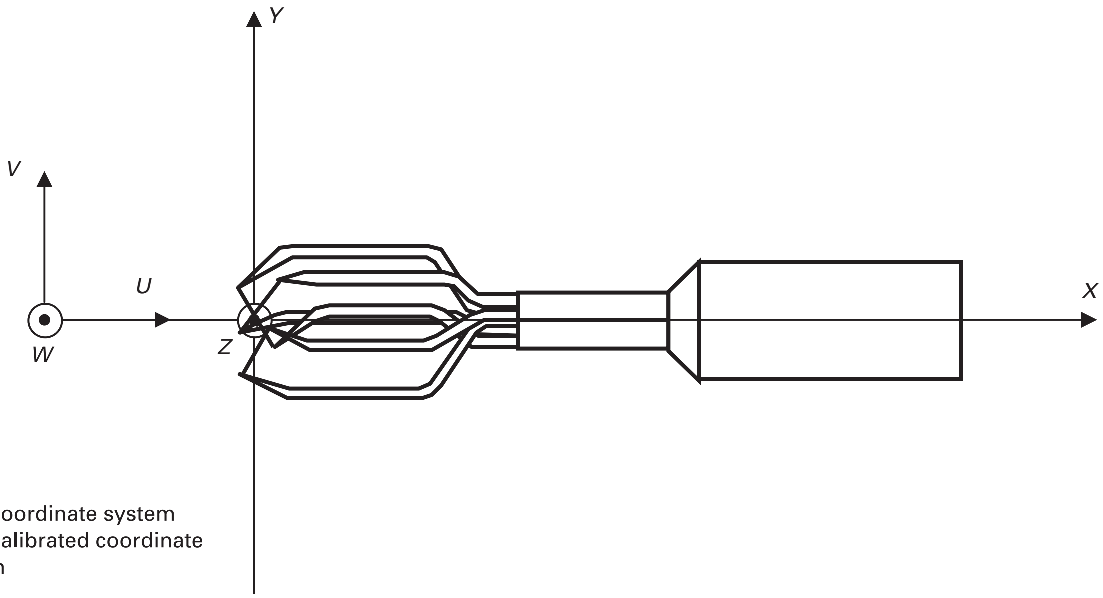
GENERAL NOTE: U-tubes are shown, but inclined manometers or other transducers can be used.

Fig. 4-6.3.1-2 Three-Hole Probe



GENERAL NOTE: U-tubes are shown, but inclined manometers or other transducers can be used.

Fig. 4-6.3.3-1 Directional Thermal Anemometer: Triaxial Probe (Three Wire)



should be consulted for guidance for flow disturbances that may affect meter performance and for standardized tests to assess the effects of such disturbances.

Due to the effects that variations of air density have on the accuracy of the measurement, temperature compensation equipped devices are recommended.

4-6.3.3 Thermal Anemometers. At the core of this type of device is typically an exposed hot wire, film, RTD, thermistor element, thermocouple junction, etc., that is either heated up by a constant current or maintained at a constant temperature. In either case, the heat lost to fluid convection is a function of the fluid velocity. By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with convective theory. Thermal anemometers must employ calibration curve(s) to correlate the measurement of voltages to velocities.

All thermal anemometers used in the measurement of Class 1 or Class 2 primary velocity measurements shall be laboratory calibrated. Calibrated thermal anemometers should be handled with care because damage to the primary element will invalidate the calibration. Likewise, if used in dusty or corrosive environments, buildup on the primary element will lead to loss of calibration. If the device is viewed to be damaged or dirty, it should be recalibrated or replaced.

Due to their principle of operation, thermal anemometers used in the measurement of Class 1 or Class 2 primary velocity measurements shall be equipped with an ambient temperature-sensing RTD or thermistor so that the indicated air velocity is temperature compensated to reference temperature related to standard calibration condition.

Nondirectional thermal anemometers may be used only in applications where preliminary tests with directional probes give good evidence that the average of the absolute values of either yaw angle or pitch angle does not exceed 15 deg.

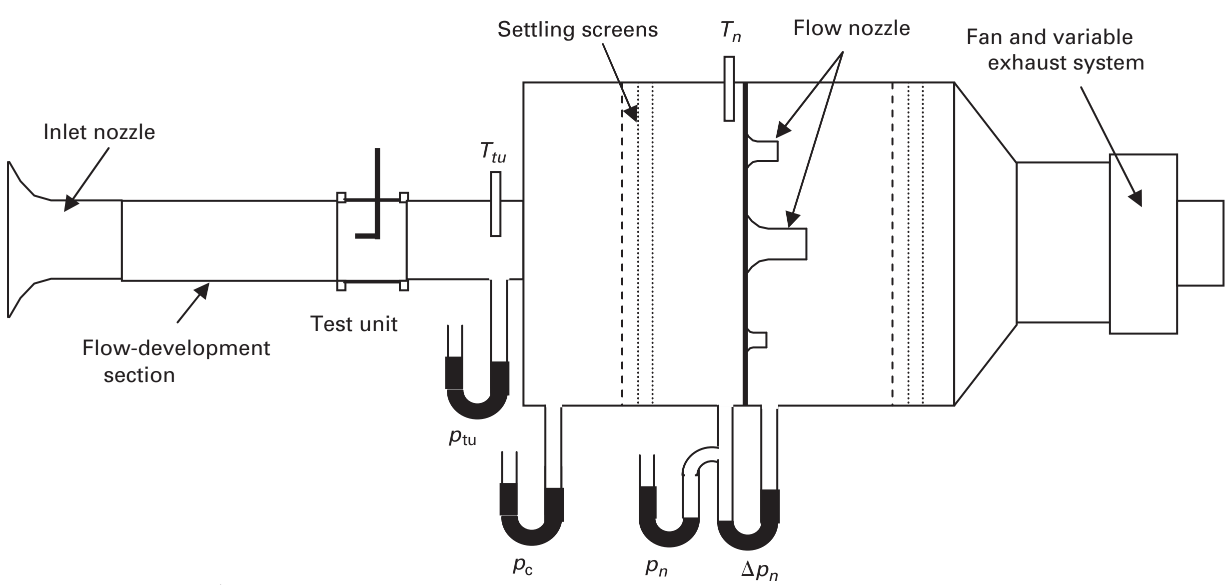
Thermal anemometers equipped with three wires are generally required to determine pitch angles as well as yaw angles. In operation, a directional thermal anemometer (Fig. 4-6.3.3-1) is inserted in the proper port to the proper depth for each traverse point. The anemometer should be rigid enough over its inserted length to avoid any droop or bending. The reference line on the probe should be used to orient the probe in such a way that the reference line is pointing upstream perpendicular to the measuring plane. The measurement of voltage over the three wires can then be used with the calibration curves to determine the pitch and yaw angles associated with the particular traverse point.

4-6.4 Flow-Measurement Device Calibration

All flow-measurement devices, with exception to the standard pitot-static tube, shall be calibrated. Calibration may be carried out in a free-stream flow nozzle jet (Fig. 4-6.4-1), ASME flow chamber (Fig. 4-6.4-2), or a wind tunnel (Fig. 4-6.4-3). The calibration reference may be a standard pitot-static tube or laser doppler velocimeter (preferred) or a previously calibrated reference device of another type. The reference and the test probe shall each be mounted so that they can be placed in the stream alternately, and their positions in the stream shall be the same and firmly held. In wind tunnel applications where the

Fig. 4-6.4-1 Free-Stream Flow Nozzle Jet

Fig. 4-6.4-2 ASME Flow Chamber



GENERAL NOTE: tu = test unit.

flow profile can be demonstrated identical for the reference and test probe-mounting locations, simultaneous mounting calibration is acceptable. Independent of the type calibration flow stream, the probe blockage (reference + standard) shall be less than 5% of the cross-sectional area. Preferably, the probe/device blockage should be as small as possible. The flow should be adjusted to produce at least 10 equally spaced calibration points. For nondirectional devices, the calibration shall include data on oblique flow up to 10 deg off the meter axis for the purpose of compensation of incident angles. All calibration devices shall be used in applications within their calibration range. The calibration curve may not be extrapolated. For directional devices, the directional calibrations shall be conducted with a rotational unit outfitted with a protractor scale that shall have a demonstrated accuracy of ±2 deg for measurement of yaw and pitch angles.

4-6.4.1 Calibration of Differential Pressure Devices. When calibrating nondirectional probes, the probe shall be aligned perpendicular with the stream to eliminate yaw- or pitch-angle influence. The probe shall be scribed with a reference line to indicate that the total pressure hole is pointing upstream perpendicular to the measurement plane.

When calibrating directional probes, such as a five-hole probe, the probe shall be aligned with the stream to eliminate yaw by null-balancing. The probe shall be scribed with a reference line to indicate when the total pressure hole is pointing upstream perpendicular to the measuring plane and corresponds to the null-balanced position of the probe and the zero-degree point on the probe's affixed protractor. The protractor scale with which the probe is equipped can be checked against any high-quality protractor used as a reference.

Pitch angles are determined from a pressure measurement obtained with a pressure indicator connected across the fourth and fifth holes of a five-hole probe. The probe shall be precision aligned at various pitch angles and the pressure difference across the taps for the fourth and fifth holes recorded. The flow should be set at several values for each position of the probe, and each time, the pressure difference across the yaw taps should be nulled.

A calibration function that represents pitch angle as a function of the pitch pressure coefficient, C_Φ (≡ pitch pressure difference/indicated velocity pressure), and Reynolds number may be derived. See Fig. 4-6.4.1-1. For probes of highly angular shape, such as the prismatic five-hole probe, the relationship of the pitch angle to the pitch pressure coefficient may be expected to be independent of Reynolds number for values of Reynolds number above roughly 10^4. For such probes, Reynolds number effects may be ignored.

Static pressure indication shall be from the appropriate static pressure hole(s) of the reference probe and test probe and not from wall taps (Fig. 4-6.4-3 Wind Tunnel), nor shall it be assumed equal to ambient pressure (free jet). The test probe and reference probe shall be connected to appropriate indicators so that the indicated static pressure, p_{si}, indicated total pressure, p_{ti}, and differential, indicated velocity pressure, p_{vi}, can each be recorded for each probe. When calibrating directional probes, the static pressure from each static pressure hole should be observed and any differences noted. The static pressure hole that is used to obtain indicated velocity pressure during the calibration should be noted and the same hole used for subsequent tests.

Probe calibration shall be expressed in terms of a probe total pressure coefficient, K_t, and a probe velocity coefficient, K_v. The probe total pressure coefficient is calculated from the test data by

$$K_t = \frac{(p_{ti})_{\text{ref}}}{(p_{ti})_{\text{test}}}$$

The probe velocity pressure coefficient is calculated from the test data by

$$K_v = \frac{\left(\dfrac{K_{v,\text{ref}}}{1+K_{v,\text{ref}}\beta_{\text{ref}}}\right)\left(\dfrac{(p_{vi})_{\text{ref}}}{(p_{vi})_{\text{test}}}\right)}{1-\dfrac{\beta_{\text{test}}K_{v,\text{ref}}}{1+K_{v,\text{ref}}\beta_{\text{ref}}}\left(\dfrac{(p_{vi})_{\text{ref}}}{(p_{vi})_{\text{test}}}\right)} \quad (4\text{-}6\text{-}1)$$

where

$$\beta = \pm\frac{(1-\varepsilon_p)}{4(1-\varepsilon_p)-3}(C_D)\left(\frac{S_p}{C}\right) \quad (4\text{-}6\text{-}2)$$

and

$$(1-\varepsilon_p) = 1-\left[\frac{K_{v,\text{ref}}}{2k}\right]\left[\frac{(p_{vi})_{\text{ref}}}{(p_{si})_{\text{ref}}}\right] \quad (4\text{-}6\text{-}3)$$

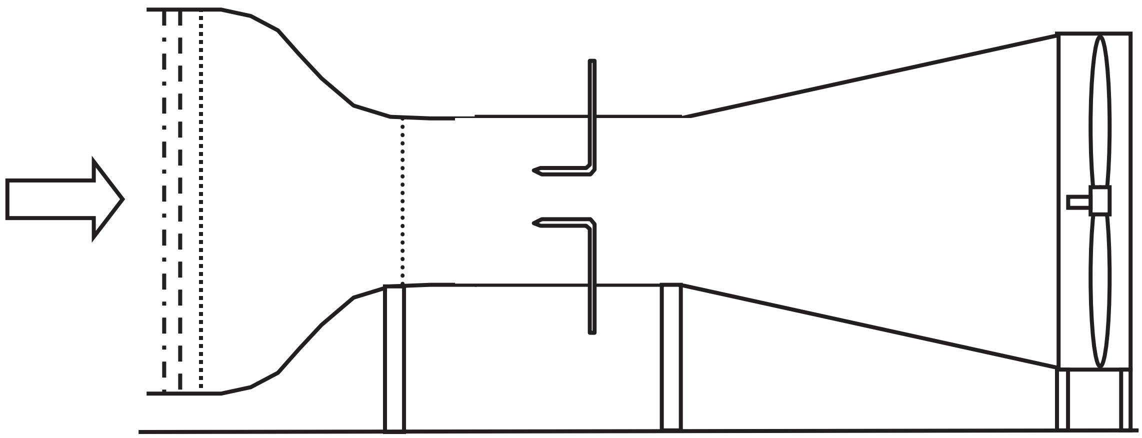
NOTE: It is recognized that C_D is usually not known to a high degree of accuracy. Lacking specific information, $C_D \approx 1.2$ for probes of cylindrical shape. For a closed wind tunnel, β will be positive; for a free jet, β will be negative.

The equation for K_v includes a correction for probe blockage derived from the analysis presented in refs. [10] and [11]. If the reference probe is a pitot-static tube, $K_{v,\,ref} = 1$, and the blockage of both the reference probe and the test probe is negligible, $S_p/C < 0.0005$, the equation for K_v assumes the simplified form.

$$K_v = \frac{(p_{vi})_{\text{ref}}}{(p_{vi})_{\text{test}}} \quad (4\text{-}6\text{-}4)$$

Generally, the probe total pressure coefficient and the probe velocity pressure coefficient are functions of a Reynolds number for nondirectional and three-hole probes and functions of the pitch pressure coefficient, C_Φ, and a Reynolds Number for five-hole probes. For probes of highly angular shape, such as the prismatic five-hole probe, the coefficients may be expected to be independent of the Reynolds number for values of a Reynolds number above roughly 10^4. For such probes, Reynolds number effects on the coefficients may be ignored.

Fig. 4-6.4-3 Wind Tunnel



4-6.4.2 Mechanical Anemometer Calibration. When calibrating mechanical anemometers, the primary element shall be aligned perpendicular with the stream to eliminate yaw- or pitch-angle influence. The anemometer shall be scribed with a reference line to indicate that the primary element is pointing upstream, perpendicular to the measurement plane. Calibrations shall be presented in the form of a calibration curve or table showing corrections to the indicated air speeds that shall be applied throughout the range for which the instrument is calibrated. Considerable care shall be taken to provide a suitable steady and uniform airstream for the purposes of calibration of this class of device.

4-6.4.3 Thermal Anemometer Calibration. Calibration of thermal anemometers establishes a relation between the thermal anemometer output and the flow velocity by exposing the probe to a set of known velocities, v, and then recording the voltages, E. A curve fit through the points (E, v) represents the transfer function to be used when converting data records from voltages into velocities. Temperature shall be recorded during calibration to formulate a temperature correction from calibration-to-measurement temperature variation.

Multisensor probes are required to be directionally calibrated. This calibration provides the individual directional sensitivity coefficients (yaw angle and pitch angle) for the sensors that are used to decompose calibration velocities into velocity components. Directional calibration is required only once in a probe's lifetime, as it depends only on the geometry that will not change in use. If the probe geometry is compromised, it shall be recalibrated (see Fig. 4-6.4.1-1 for a typical calibration of a five-hole probe).

Directional calibration of X-probes requires a rotation unit where the probe can be rotated on an axis through the crossing point of the wires perpendicular to the wire plane. The yaw angle coefficients for wires 1 and 2 shall be used to decompose the calibration velocities for wire 1 and 2, respectively, into the directional components of the measured velocity. The coordinate system shall be defined with respect to the wires of the probe, and the probe shall be calibrated against velocity for calculation of the yaw-angle coefficients.

Directional calibration of triaxial probes requires a rotation unit where the probe axis can be tilted with respect to the flow and thereafter rotated 360 deg around its axis. The directional sensitivity of triaxial probes is characterized by a yaw and a pitch for each sensor. The probe coordinate system shall be defined with respect to the sensor orientation, and the probe shall be calibrated agains velocity for calculation of the yaw-angle coefficients.

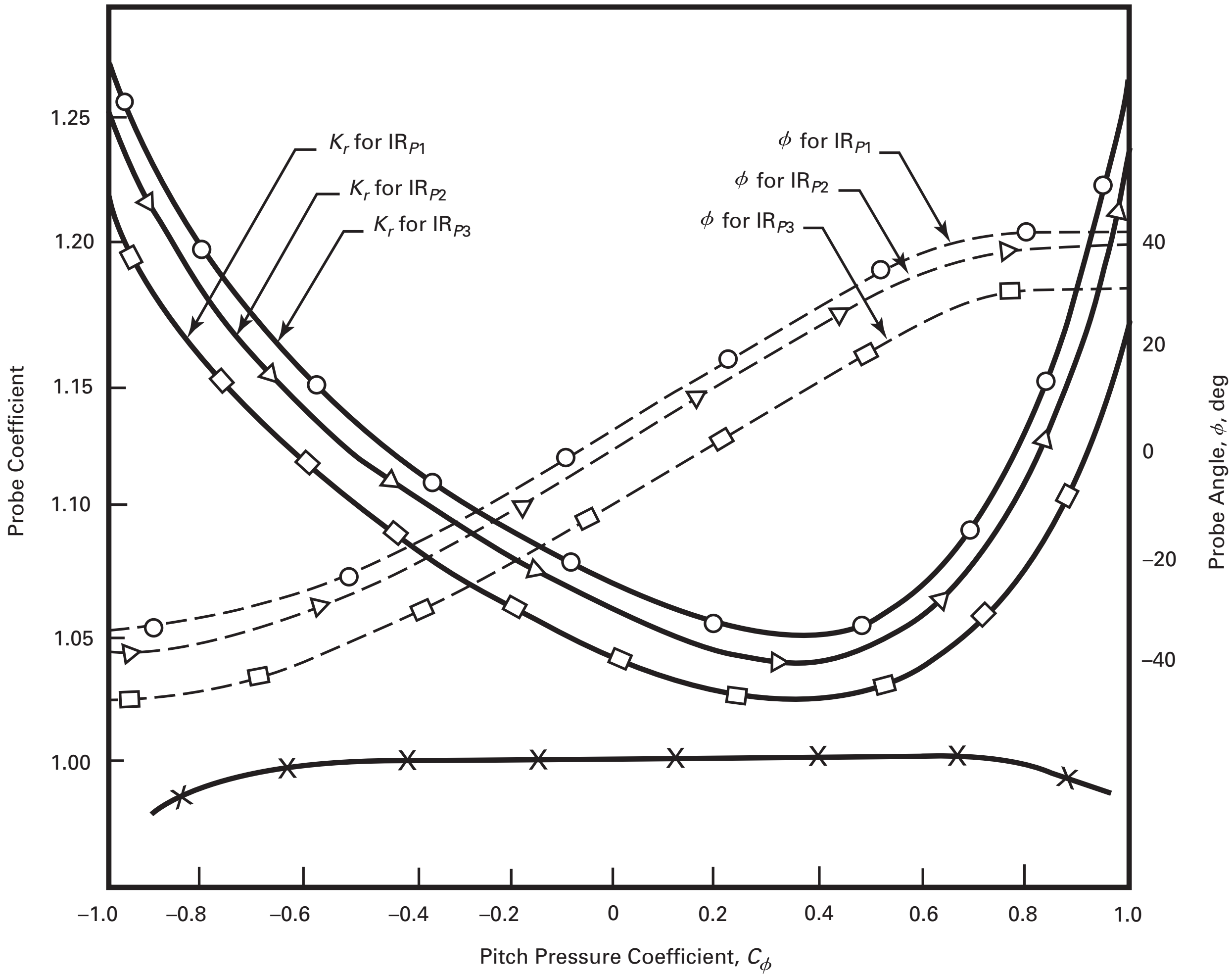
4-6.5 Traverse Planes

Gas turbine inlet air-conditioning equipment has at least two traverse planes, the inlet and the outlet. Either plane or both can be used as the traverse plane. The preferred location is upstream due to ease of access and reduced chance of accidental injection of foreign objects by the gas turbine since this measurement plane is upstream of the inlet filters. However, since the inlet is typically very large, this measurement plane requires a larger number of traverse points. In some applications, the downstream plane may be preferential due to smaller areas and increased velocity.

Only one traverse plane is required to determine flow rate, but if both the inlet plane and the outlet plane qualify, each should be used. If neither plane qualifies, an alternate plane further downstream (gas turbine exhaust, stack exhaust, etc.) shall be traversed and the fuel flow mass and secondary flows (if present) shall be subtracted.

4-6.5.1 Qualified Velocity-Traverse Planes. To qualify for a velocity traverse for purposes of determining air-flow rate, a plane shall meet the following specifications:

Fig. 4-6.4.1-1 Typical Calibration Curve for a Five-Hole Probe



GENERAL NOTE: Actual calibration curves may exhibit discontinuities.

– There shall be no internal supports or other internal obstructions within the plane.

– The profile of a person standing near the probe to support it may cause flow disturbances greater than acceptable. If other, nondisturbing supports are not available, all such test points shall be gathered using a wand of 1.1 m (4 ft) min. length.

– A preliminary velocity traverse shall show that the flow is reversed or essentially stagnant at no more than 15% (preferably 0%) of the elemental areas.

– There shall be no sudden change in either cross-sectional area or duct direction.

4-6.5.2 Determination of Sampling Grid. Measurements shall be taken at centroids of elemental areas determined by Gauss, Tchebycheff, log-lineaer, or equivalent method. The reason for providing a choice in the travese pattern is that the sensor locations are different for each method and physical and installation constraints found in the field may dictate the choice of traverse pattern.

For circular ducts, a minimum of 5 sensors per radius, or 10 per diameter, is required. For rectangular ducts, a minimum of 5 traverse lines with 5 traverse points each, for a total of 25 points, is required. It is required to perform a pretest uncertainty analysis simultaneously with the instrumentation and test design to ensure that sufficient grid points are selected to achieve the measurement uncertainty requirements of this Code. The number of points may have to be increased beyond the required minimums above to achieve the uncertainty requirements. Refer to ASME PTC 19.5 for more information about determination of sampling grids.

4-6.5.3 Orientation of Traverse Ports. Depending upon access and size of the duct, traverse ports fabricated into the duct walls may be necessary. Yaw and pitch are the two angles necessary to orient the velocity vector with respect to the nominal direction of flow (normal to the measurement plane). It is desirable, when measuring both yaw and pitch, to measure the larger angle by rotating the probe as explained in para. 4-6.3.1. For this reason, the traverse ports should be located in the duct wall or walls to orient the probes accordingly.

For measurement planes of circular cross section, the traverse ports should be oriented so that the probe stem will be inserted radially.

For measurement planes of rectangular cross section, the traverse ports should generally be oriented so that the probe stem is parallel to flow. In any case, the parties should agree in advance to the orientation of the traverse ports.

4-6.5.4 Handheld Devices. This Code does not exclude the use of handheld devices for implementation of the velocity-traverse method. These devices may be used if the combined device and person blockage is less than 5% of the cross-sectional area. Further, the sensing element shall be held perpendicular to the flow direction from the user's torso by 0.6 m (2 ft) to avoid blockage influence of the user.

4-7 HIGH-VOLTAGE ELECTRICAL MEASUREMENT

4-7.1 Introduction

This subsection presents requirements and guidance regarding electrical measurements of greater than 480 V at 60 Hz or 460 V at 50 Hz.

The scope of this subsection includes

− the measurement of polyphase (three-phase) alternating-current (AC), real (active) and reactive power

− the measurement of direct-current (DC) power

For additional requirements and instructions, see ref. [12].

4-7.2 Required Uncertainty

The required uncertainty is dependent on the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussions about measurement classification and instrumentation categorization, respectively.

Class 1 primary parameters and variables shall be measured with 0.1% or better accuracy class power metering, 0.3% or better accuracy class (metering-type) current transformers, and 0.3% or better accuracy class (metering-type) voltage transformers.

Class 2 primary parameters and variables should be measured with 0.5% or better accuracy class power metering, 0.3% or better accuracy class (metering-type) current transformers, and 0.3% or better accuracy class (metering-type) voltage transformers.

Secondary parameters and variables can be measured with any type of power measurement device.

4-7.3 Electrical-Metering Equipment

There are five types of electrical-metering equipment that may be used to measure electrical energy.

− watt meters

− watt-hour meters

− var meters

− var-hour meters

− power factor meters

Single or polyphase metering equipment may be used. However, if polyphase metering equipment is used, the output from each phase shall be available or the meter shall be calibrated three phase. These meters are described below.

The warm-up time of electrical-metering equipment shall be in accordance with the manufacturer's recommendations to ensure instrument specifications are met. Electrical-metering equipment with various measurement range settings should be selected to minimize the reading error while encompassing the test conditions. The systematic uncertainty associated with digital power analyzers that use some form of digitizing technique to convert an analog signal to digital-form accuracy specifications shall consider influence quantities including, but not limited to, environmental effects such as ambient temperature, magnetic fields, electric fields, and humidity, power factor, crest factor, digital/analog output accuracy, timer accuracy (integration time), and long-term stability.

The leads to the instruments shall be arranged so that inductance or any other similar cause will not influence the readings. Inductance may be minimized by utilizing twisted and shielded pairs for instrument leads. The whole arrangement of instruments should be checked for stray fields. Additionally, the lead wires shall have insulation resistance appropriate for their ratings.

To minimize the voltage drop in the voltage circuit, wire gauge shall be chosen considering the length of the wiring, the load on the voltage transformer circuit, and the resistance of the safety fuses. The errors due to wiring resistance (including fuses) shall always be taken into account, either by voltage-drop measurement or by calculation.

Extreme care shall be exercised in the transportation of calibrated portable instruments. The instruments should be located in an area as free of stray electrostatic and magnetic fields as possible. Where integrating meters are used, a suitable timing device shall be provided to accurately determine the real power during the test time period.

To reduce the effect of instrumental loss on measurement accuracy, power-metering equipment should be selected that uses a separate source of power and that has high-impedance voltage inputs (i.e., 2.4 MΩ) and low-impedance current inputs (i.e., 6 mΩ).

4-7.3.1 Watt Meters. Watt meters measure instantaneous active power. The instantaneous active power shall be measured frequently during a test run and averaged over the test-run period to determine average power (kilowatts) during the test. Should the total active electrical energy (kilowatt-hours) be desired, the average power shall be multiplied by the test duration in hours.

Watt meters measuring a Class 1 primary variable shall have a systematic uncertainty equal to or less than 0.2% of reading. Metering with a systematic uncertainty equal to or less than 0.5% of reading shall be used for the measurement of Class 2 primary variables. There are no metering accuracy requirements for measurement of secondary variables. The output from the watt meters shall be sampled with a frequency high enough to attain an acceptable random uncertainty. This is a function of the variation of the power measured. A general guideline is a frequency of not less than once each minute.

4-7.3.2 Watt-Hour Meters. Watt-hour meters measure active energy (kilowatt-hours) during a test period. The measurement of watt-hours shall be divided by the test duration in hours to determine average active power (kilowatts) during the test period.

Watt-hour meters measuring a Class 1 primary variable shall have an uncertainty equal to or less than 0.2% of reading. Metering with an uncertainty equal to or less than 0.5% of reading shall be used for measurement of Class 2 primary variables. There are no metering accuracy requirements for measurement of secondary variables.

The resolution of the watt-hour meter output is often so low that high inaccuracies can occur over a typical test period. Often watt-hour meters have an analog or digital output with a higher resolution that may be used to increase the resolution. Some watt-hour meters have a pulse type output that may be summed over time to determine an accurate total energy during the test period. For disk-type watt-hour meters with no external output, the disk revolutions can be counted during a test to increase resolution.

Some electronic watt-hour meters also display blinking lights or LCD elements that correspond to disk revolutions that can be timed to determine the generator electrical output. In such cases, much higher resolution can be achieved usually by timing a discrete repeatable event (e.g., a certain number of blinks of an LCD or complete rotations of a disk) rather than counting the number of events in a fixed amount of time (e.g., number of rotations of a disk in 5 min).

4-7.3.3 Var Meters. Var meters measure instantaneous reactive power. The var measurements are typically used on four-wire systems to calculate power factor as discussed in para. 4-6.3.2. The instantaneous reactive power shall be measured frequently during a test run and averaged over the test-run period to determine average reactive power (kilovars) during the test. Should the total reactive electrical energy (kilovar-hours) be desired, the average power shall be multiplied by the test duration in hours.

Var meters measuring a Class 1 or Class 2 primary variable shall have a systematic uncertainty equal to or less than 0.5% of range. There is no metering accuracy requirements for measurement of secondary variables. The output from the var meters shall be sampled with a frequency high enough to attain an acceptable random uncertainty. This is a function of the variation of the power measured. A general guideline is a frequency of not less than once each minute.

4-7.3.4 Var-Hour Meters. Var-hour meters measure reactive energy (kilovar-hours) during a test period. The measurement of var-hours shall be divided by the test duration in hours to determine average reactive power (kilovars) during the test period.

Var-hour meters measuring a Class 1 or Class 2 primary variable shall have an uncertainty equal to or less than 0.5% of range. There are no metering accuracy requirements for measurement of secondary variables.

The resolution of var-hour meter output is often so low that high inaccuracies can occur over a typical test period. Often var-hour meters have an analog or digital output with a higher resolution that may be used to increase the resolution. Some var-hour meters also have a pulse-type output that may be summed over time to determine an accurate total energy during the test period. For disk-type var-hour meters with no external output, the disk revolutions can be counted during a test to increase resolution.

4-7.3.5 Power Factor Meters. Power factor may be measured directly using three-phase power factor transducers when balanced load and frequency conditions prevail. Power factor transducers shall have a systematic uncertainty equal to or less than 0.01 PF of the indicated power factor.

4-7.4 Electrical-Metering Equipment Calibration

4-7.4.1 Watt and Watt-Hour Meter Calibration. Watt and watt-hour meters, collectively referred to as power meters, are calibrated by applying power through the test power meter and a watt meter or watt-hour meter standard simultaneously. This comparison should be conducted at several power levels (at least five) across the expected power range. The difference between the test and standard instruments for each power level should be calculated and applied to the power measurement data from the test. For test points between the calibration power levels, a curve fit or linear interpolation should be used. The selected power levels should be approached in an increasing and decreasing manner. The calibration data at each power level should be averaged to minimize any hysteresis effect. Should polyphase metering equipment be used, the output of each phase shall be available or the meter shall be calibrated with all three phases simultaneously.

When calibrating watt-hour meters, the output from the watt meter standard should be measured with frequency high enough to reduce the random error during calibration so the total uncertainty of the calibration process meets the required level. The average output can be multiplied by the calibration time interval to compare against the watt-hour meter output.

Watt meters should be calibrated at the electrical line frequency of the equipment under test, i.e., do not calibrate meters at 60 Hz and use on 50 Hz equipment.

Watt meter standards should be allowed to have power flow through them prior to calibration to ensure the device is adequately "warm." The standard should be checked for zero reading each day prior to calibration.

4-7.4.2 Var and Var-Hour Meter Calibration. To calibrate a var or var-hour meter, one shall either have a var standard or a watt meter standard and an accurate phase-angle measuring device. Also, the device used to supply power through the standard and test instruments shall have the capability of shifting phase to create several different stable power factors. These different power factors create reactive power over the calibration range of the instrument.

Should a var meter standard be employed, the procedure for calibration outlined above for watt meters should be used. Should a watt meter standard and phase-angle meter be used, simultaneous measurements from the standard, phase-angle meter, and test instrument should be taken. The var level shall be calculated from the average watts and the average phase angle.

Var meters should be calibrated at the electrical line frequency of the equipment under test, i.e., do not calibrate meters at 60 Hz and use on 50 Hz equipment. Var meters are particularly sensitive to frequency and should be used within 0.5 Hz of the calibration frequency.

When calibrating var-hour meters, the output from the var meter standard or watt meter/phase-angle meter combination should be measured with frequency high enough to reduce the random error during calibration so the total uncertainty of the calibration process meets the required level. The average output can be multiplied by the calibration time interval to compare against the var-hour meter output.

Should polyphase metering equipment be used, the output of each phase shall be available or the meter shall be calibrated with all three phases simultaneously.

4-7.5 Instrument Transformers

Instrument transformers are used for the purpose of

(a) reducing the voltages and currents to values that can be conveniently measured, typically to ranges of 120 V and 5 A, respectively

(b) insulating the metering instruments from the high potential that may exist on the circuit under test

Instrument transformer practice is described in detail in ref. [13].

The impedances in the transformer circuits shall be constant during the test. Protective relay devices or voltage regulators shall not be connected to the instrument transformers used for the test. Normal station instrumentation may be connected to the test transformers if the resulting total burden is known and is within the range of calibration data.

Instrument transformers include voltage transformers and current transformers. The voltage transformers measure voltage from a conductor to a reference, and the current transformers measure current in a conductor.

The instrument transformers introduce errors when converting the high primary voltage or current to a low secondary voltage or current. These errors result in a variation of the true ratio from the marked ratio, and also the variation of the phase angle from the ideal (zero). The magnitude of the errors depends on

− the burden (number and kinds of instruments connected to the transformer)

− the secondary current (in the case of current transformers)

− the power factor of the device being measured (in the case of power measurement)

It is recommended to test near a power factor of unity to minimize the sensitivity of the measured power to the phase-angle errors arising from the power meter, α, current transformers, β, and voltage transformers, γ.

4-7.5.1 Voltage Transformers. Voltage transformers are used when measuring either phase-to-phase voltage or phase-to-neutral voltage. The voltage transformers serve to convert the line or primary voltage (typically very high in voltage) to a lower or secondary voltage safe for metering (typically 120 V for phase-to-phase systems and 69 V for phase-to-neutral systems). For this reason, the measured secondary voltage shall be multiplied by the appropriate turns ratio to calculate the primary voltage.

Voltage transformers are available in several metering accuracy classes. For the measurement of Class 1 or Class 2 primary variables, 0.3% or better accuracy class (metering-type) voltage transformers shall be used. In the case of Class 1 primary variable measurements, voltage transformers shall be calibrated for turns ratio and phase angle and operated within their rated burden range. The method of calibration should permit the determination of the turns ratio and phase angle to an uncertainty of ±0.1% and ±0.9 mrad (3 min), respectively. The calibration shall consist of ratio and phase-angle tests from 90% to 110% of rated primary voltage at rated frequency with zero burden, and with the maximum standard burden for which the transformer is rated at its best accuracy class. The magnitude of such corrections depend upon

− the burden (number and kinds of instruments connected to the transformer)

− the power factor of the device being measured (in the case of power measurement)

The ratio is usually from 0.1% to 0.3% below the nominal value for a small burden, while the phase angle is commonly negligible, being slightly leading. Voltage transformer ratio correction factors (RCF_c) shall be applied for the actual burdens that exist during the test. Actual volt-ampere burdens shall be determined either by calculation from lead impedances or by direct measurement. Reference [13] should be consulted for determining the associated equations in providing an analytical determination of the RCF_c. Corrections for voltage drop of the connecting lines should be determined and applied.

In using voltage transformers, care should be taken to avoid short-circuiting the secondary. The circuit may be opened whenever desired.

4-7.5.2 Current Transformers. Current transformers are used when measuring current in a given phase. Current transformers serve to convert line or primary current (typically very high) to lower or secondary metering current. For this reason, secondary current measurement shall be multiplied by the appropriate ratio to calculate the primary current.

Current transformers are available in several metering accuracy classes. For the measurement of Class 1 or Class 2 primary variables, 0.3% or better accuracy class (metering-type) current transformers shall be used. For primary variable measurements, current transformers should be calibrated for turns ratio and phase angle at zero external burden (0 VA) and at least one burden that exceeds the maximum expected during the test at 10% and 100% of rated primary current. Accuracy test results may be used from factory-type (design) tests in the determination of turns-ratio and phase-angle correction factors. Type tests are commonly performed on at least one transformer of each design group that may have a different characteristic in a specific test. Current transformers shall be operated within their rated burden range during the test and should be operated near 100% of rated current to minimize instrument error.

Near the rated current outputs, ratio and phase-angle correction factors for current transformers may be neglected due to their minimal impact on measurement uncertainty; however, if the ratio or phase-angle correction factor is expected to exceed 0.02% at actual test conditions, actual correction factors should be applied.

In using current transformers, care should be taken never to open the secondary circuit while current is in the primary winding because of the dangerously high voltage that may be developed and the excessive temperature rise that may ultimately take place due to high losses in the transformer. Also, current transformer cores may be permanently magnetized by inadvertent operation with the secondary circuit opened, resulting in a change in the ratio and phase-angle characteristics. If magnetization is suspected, the transformer should be removed as described in ref. [12], under "Nature of Deviations from Nominal Ratio in Current Transformers." When it is necessary to open the secondary circuit while current is in the primary winding, in order to change the instrument, for example, the secondary winding should be short-circuited, preferably at the transformer terminals.

4-7.6 Calculation of Corrected Average Power or Corrected Total Energy

The calculation method for average power or total energy should be performed in accordance with ref. [12] for the specific type of measuring system used. For Class 1 primary variables, power measurements shall be corrected for actual voltage transformer ratio and for phase-angle errors in accordance with the procedures of ref. [13].

The error for each phase is corrected by applying calibration data from the transformers and the power meter as follows:

$$PW_c = SW \times VTR \times CTR \times MCF \times VTRCF_c \times CTRCF_c \times PACF_c \times VTVDC \quad (4\text{-}7\text{-}1)$$

where

CTR = current transformer marked ratio

$CTRCF_C$ = current transformer ratio correction factor from calibration data (if applicable)

MCF = meter correction factor from calibration data (if applicable)

$PACF_C$ = phase-angle correction factor from calibration data

PW_c = corrected primary power

SW = measured secondary power

VTR = voltage transformer marked ratio

$VTRCF_C$ = voltage transformer ratio correction factor from calibration data

$VTVDC$ = voltage transformer voltage drop correction

The meter correction factor (MCF) is determined from calibration data. Each phase of the meter should be calibrated as a function of secondary current. The process should be done at a minimum of two different secondary voltages and at two different power factors. The actual MCF at test conditions may then be interpolated.

The phase-angle correction factor for each phase ($PACF_C$) accounts for the phase shift that occurs in the voltage transformer, γ, current transformer, β, and the power meter, α. The phase shifts of each transformer could have an offsetting effect. For example, if the current transformer shifts the current waveform to the right and the voltage transformer shifts the voltage waveform in the same direction, the power meter output is not affected by a phase shift. Each of the phase shifts should be determined from calibration data.

$$PACF_C = \frac{\cos(\theta - \alpha + \beta - \gamma)}{\cos(\theta)} = \frac{\cos(\theta - \alpha + \beta - \gamma)}{PF} \quad (4\text{-}7\text{-}2)$$

where

α = shift in the power meter phase angle

β = shift in the current transformer phase angle

θ = arccos (power factor)

γ = shift in the voltage transformer phase angle

4-7.7 Excitation-Power Electrical Measurement

If the measurement of the excitation power is required, the power supplied to the exciter may be determined by the following two methods:

(a) *Derivation from Breaker Currents*. Excitation power can be calculated from the current and voltage input to the exciter power transformer or breaker. Since this is a measure of the actual power, which comes off of the main generator bus, this is the preferred method of determining exciter power. The calculation is done as follows:

$$ExcLoss = \frac{\sqrt{3} \times V \times A \times PF}{1,000} \quad (4\text{-}7\text{-}3)$$

where

1,000 = conversion factor from watts to kW

A = average phase field current, amps, measured value

$ExcLoss$ = exciter power, kW

PF = power factor, measured or calculated value

V = average field voltage (volts), measured value

(b) *Derivation From Field Voltage and Current.* Power supplied to the exciter can also be estimated by calculating the power output by the exciter and by correcting for an assumed AC-to-DC conversion efficiency. The calculation is done as follows:

$$ExcLoss = \frac{FV \times FC}{1,000 \times ACDC} \quad (4\text{-}7\text{-}4)$$

where

1,000 = conversion factor from watts to kW

$ACDC$ = AC-to-DC conversion efficiency factor (typically 0.975), assumed value

$ExcLoss$ = exciter power, kW

FC = field current, DC amps, measured value

FV = field voltage, DC volts, measured value

4-8 INTERMEDIATE- AND LOW-VOLTAGE ELECTRICAL MEASUREMENT

4-8.1 Introduction

Auxiliary power consumption measurements are an important part of many inlet air-conditioning components addressed in this Test Code. Performance measurements can be made based on either the power delivered to the component as measured by the electrical consumption or by the power delivered by the component, in which case a motor efficiency shall be applied to the consumed power. Intermediate- and low-voltage motors are often used for driving small pumps, cooling fans, and ancillary equipment. For electric motors with constant speed drives, test measurements of the input power are made, and the output power is computed by multiplying input power by motor efficiency, provided the total measurement uncertainty meets the requirements of para. 4-1.2.

When readings are taken at a load center located a substantial distance from the motors, correction to the delivered power should be made by computation of voltage drop between the load center and motor.

4-8.2 Required Uncertainty

The required uncertainty depends on the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.2.3 for discussions about measurement classification and instrumentation categorization, respectively.

Class 1 primary parameters and variables shall be measured with 0.1% or better accuracy class power metering, 0.3% or better accuracy class (metering-type) current transformers, and 0.3% or better accuracy class (metering-type) voltage transformers.

Class 2 primary parameters and variables should be measured with 0.5% or better accuracy class power metering, 0.3% or better accuracy class (metering-type) current transformers, and 0.3% or better accuracy class (metering-type) voltage transformers.

Secondary parameters and variables can be measured with any type of power measurement device.

4-8.3 Power Measurement Equipment

The preferred instrument for determining power is a calibrated wattmeter. In some installations, including applications using more than 600 V, panel readings of bus voltage and motor amperage may be used.

4-8.4 Calculations

The unit for measuring the electrical horsepower (HP) input to a motor is the watt (W). For direct current, this is the product of the volts, E, and the amperes, I, measured at the motor terminals and is represented as $W = EI$.

Since 746 W are equivalent to 1 HP, the following formula represents the above relationship (see Table 4-8.4-1):

$$\text{Input HP} = \frac{\text{EI}}{746} \quad (4\text{-}7\text{-}5)$$

Refer to Table 4-8.4-2 for properties of conductors (with special reference to Table 4-8.4-3).

4-8.5 Measurement of Variable Frequency Drives

Some cooling components (e.g., foggers) may use electric motors with pulse width modulated variable

Table 4-8.4-1 Electrical Horsepower

For alternating current systems, using the symbols W = watts, E = average volts between terminals, I = average line current, and pf = power factor expressed as a decimal fraction. The formulas shown at right apply for input horsepower.	Single phase $HP = \frac{EI \times pf}{746}$ Two phase $HP = \frac{2EI \times pf}{746}$ Three phase $HP = \frac{\sqrt{3} \times EI \times pf}{746}$
To obtain fan driver output horsepower, multiply by the proper motor efficiency as follows:	Three phase output $HP = \frac{\sqrt{3} \times EI \times pf \times \eta_m}{746}$

Reprinted by permission of the Cooling Towers Institute.

frequency drives (VFDs) to control water flow supplied to the unit. For motors with VFDs, the VFD should be put in bypass mode if possible for the duration of the test. When the VFD is bypassed, the power measurement is identical to that for a standard electric motor with a constant speed shaft. When in service, both the motor efficiency and motor shaft speed are typically reduced through the use of a VFD.

If the VFD does not have a bypass or if the test must be conducted with the VFD in service, one of the following approaches shall be taken for the evaluation of the motor power:

(a) Some VFDs are equipped with a display of power delivered to the motor. The pretest uncertainty analysis should be used to confirm that the provided reading is accurate enough to comply with Code uncertainty requirements. Speed controller displays typically are accurate enough for the evaluation of the motor power.

(b) The power on the line side of the VFD shall be measured. The VFD manufacturer's guaranteed voltage drop across the unit shall be used to calculate the power input into the motor shaft. The motor efficiency shall be evaluated at the reduced power loading.

(c) The fan-motor power shall be measured with a true RMS wattmeter on the load side of the VFD, and the motor efficiency shall be evaluated at the reduced power loading. The wattmeter must have a sampling frequency that is at least twice the highest frequency component in the wave being sampled. Switching frequencies of pulsed width modulation drives can range from 2 kHz to 15 kHz. A low-pass filter should be connected between the measurement location (e.g., switch gear) and the meter. The cutoff frequency of the low-pass filter should correspond to the sampling frequency of the digital meter.

The use of a VFD lowers the motor output efficiency. The motor manufacturer should provide data for the expected motor efficiency at the reduced speed to be used for the calculations.

4-9 DROPLET CARRYOVER AND DROPLET SIZE

4-9.1 Introduction

This subsection presents guidance for evaluating and quantifying liquid droplets that are generated due to the operation of the gas turbine inlet air-conditioning equipment. Liquid droplets that escape Plane 2 are subject to ingestion by the turbine. Please note that the planes referenced herein are defined by Fig. 5-2-1. The evaluation of the liquid droplets in the sampling plane should be evaluated as part of the ASME PTC 51 test. The presence of droplets that puddle or wet the downstream ductwork and the equipment in the ductwork are indicative of a problem that can invalidate temperature measurements. The source of the droplets shall be investigated and addressed prior to executing this Test Code. The presence of large liquid droplets can be qualitatively evaluated using visual techniques. Quantitatively, evaluation utilizing sensitive paper, impaction, or hotwire measurements are not part of this Code and are covered in Nonmandatory Appendix B.

When discussing the evaluation of liquid particles, the terms "drops," "droplets," "aerosols," and "mist" are used. In the following, all liquid particles, irrespective of their size, will be called "droplets." This subsection presents requirements and guidance regarding the measurement of water droplets that cross over Plane 2. Techniques that meet the uncertainty requirements of this subsection may be used.

Because inlet air velocities are in the range of 7 m/s to 15 m/s (1,500 ft/min to 3,500 ft/min) at Plane 5, just upstream of the inlet bell mouth, visual observation of water droplets in the air stream is considered to be the most practical method to assess water carryover at this plane. Invasive methods may impose safety risks.

This Code does not define acceptable levels of water carryover, but provides a method based on observation to assess water carryover. Users should seek recommendations from the gas turbine OEM, fogging system manufacturers, and gas turbine user groups since compressor

Table 4-8.4-2 Properties of Conductors

		Concentric Lay Stranded Conductors		Bare Conductors		DC Resistance. ohms/m at 25°C (ohms/ft at 77°F) [Note (1)]		
						Copper		Aluminum [Note (4)]
Size AWG MCM	Area, Cir. mils	Number of Wires	Diameter of Each Wire, in.	Diameter, in.	Area [Note (2)], in.^{2}	Bare Cond.	Tin'd. Cond. [Note (3)]	
18	1620	Solid	0.0403	0.0403	0.0013	6.51	6.79	10.7
16	2580	Solid	0.0508	0.0508	0.0020	4.10	4.26	6.72
14	4110	Solid	0.0641	0.0641	0.0032	2.57	2.68	4.22
12	6530	Solid	0.0808	0.0808	0.0051	1.62	1.68	2.66
10	10380	Solid	0.1019	0.1019	0.0081	1.018	1.06	1.67
8	16510	Solid	0.1285	0.1285	0.0130	0.6404	0.659	1.05
6	26240	7	0.0612	0.184	0.027	0.410	0.427	0.674
4	41740	7	0.0772	0.232	0.042	0.259	0.269	0.424
3	52620	7	0.0867	0.260	0.053	0.205	0.213	0.336
2	66360	7	0.0974	0.292	0.067	0.162	0.169	0.266
1	83690	19	0.0664	0.332	0.087	0.129	0.134	0.211
0	105600	19	0.0745	0.372	0.109	0.102	0.106	0.168
00	133100	19	0.0837	0.418	0.137	0.0811	0.0843	0.133
000	167800	19	0.0940	0.470	0.173	0.0642	0.0668	0.105
0000	211600	19	0.1055	0.528	0.219	0.0509	0.0525	0.0836
250	250000	37	0.0822	0.575	0.260	0.0431	0.0449	0.0708
300	300000	37	0.0900	0.630	0.315	0.0360	0.0374	0.0590
350	350000	37	0.0973	0.681	0.364	0.0308	0.0320	0.0505
400	400000	37	0.1040	0.728	0.416	0.0270	0.0578	0.0442
500	500000	37	0.1162	0.813	0.519	0.0216	0.0222	0.0354
600	600000	61	0.0992	0.893	0.626	0.0180	0.0187	0.0295
700	700000	61	0.1071	0.964	0.730	0.0154	0.0159	0.0253
750	750000	61	0.1109	0.998	0.782	0.0144	0.0148	0.0236
800	800000	61	0.1145	1.030	0.833	0.0135	0.0139	0.0221
900	900000	61	0.1215	1.090	0.933	0.0120	0.0123	0.0197
1000	1000000	61	0.1280	1.150	1.039	0.0108	0.0111	0.177
1250	1250000	91	0.1172	1.289	1.305	0.00863	.00888	0.0142
1300	1500000	91	0.1284	1.410	1.561	0.00719	.00740	0.0118
1750	1750000	127	0.1174	1.526	1.829	0.00616	.00634	0.0101
2000	2000000	127	0.1255	1.630	2.087	0.00529	.00555	0.00885

Reprinted by permission of the Cooling Towers Institute.

GENERAL NOTES:
(a) The values given are taken from ref. [14 A]. The table as constructed is taken from ref. [14 B].

NOTES:
(1) The resistance values are applicable only to direct current. When conductors larger than No. 4/0 are used with alternating current, the multiplying factors in Table 4-8.4-3 should be used to compensate for skin effect.
(2) Area given is that of a circle having a diameter equal to the overall diameter of a stranded conductor.
(3) The values given are taken from ref. [15].
(4) The values given are taken from refs. [16] and [17].

Table 4-8.4-3 Multiplying Factors for Converting DC Resistance to 60-Hz AC Resistance

			Multiplying Factor			
			For Nonmetallic Sheathed Cables in Air or Nonmetallic Conduit		For Metallic Sheathed Cables or All Cables in Metallic Raceways	
Size			Copper	Aluminum	Copper	Aluminum
	3		1.	1.	1.	1.
	2		1.	1.	1.01	1.00
Up to	1	AWG	1.	1.	1.01	1.00
	0		1.001	1.000	1.02	1.00
	00		1.001	1.001	1.03	1.00
	000		1.002	1.001	1.04	1.01
	0000		1.004	1.002	1.05	1.01
	250	MCM	1.005	1.002	1.06	1.02
	300	MCM	1.006	1.003	1.07	1.02
	350	MCM	1.009	1.004	1.08	1.03
	400	MCM	1.011	1.005	1.10	1.04
	500	MCM	1.018	1.007	1.13	1.06
	600	MCM	1.025	1.010	1.16	1.08
	700	MCM	1.034	1.013	1.19	1.11
	750	MCM	1.039	1.015	1.21	1.12
	800	MCM	1.044	1.017	1.22	1.14
	1000	MCM	1.067	1.026	1.30	1.19
	1250	MCM	1.102	1.040	1.41	1.27
	1500	MCM	1.142	1.058	1.53	1.36
	1750	MCM	1.185	1.079	1.67	1.46
	2000	MCM	1.233	1.100	1.82	1.56

Reprinted by permission of the Cooling Towers Institute.

GENERAL NOTE: The procedure is as follows:
(a) Read DC resistance from Table 4-8.4-2 and multiplying factor from Table 4-8.4-3.
(b) Compute AC resistance in kohms: $\Omega AC = \Omega DC/1{,}000' \times \frac{ft}{1{,}000} \times f$
(c) Compute kilowatt loss:
Single phase: kW loss = $I^2 R/1{,}000'$
Two phase: kW loss = $2I^2 R/1{,}000$
Three phase: kW loss = $3I^2 R/1{,}000$
(d) Compute net kW input to motor:
Net kW input to motor = kW measured − kW loss
(e) Compute motor BHP:

$$\text{Motor BHP} = \frac{(\text{Net kW input to motor})(\text{Motor } \eta)}{0.746}$$

blade coatings and blade tolerance to erosion vary widely among gas turbines.

4-9.2 Required Uncertainty

Techniques shall be developed to assure accurate evaluation. The uncertainty of the water-droplet evaluation shall consider effects including, but not limited to, temperature distribution, relative humidity, air velocity, and droplet-size distribution.

Four possible sources of error are

− oversaturation or flooding of view ports

− nonrepresentative view-port locations (water carryover tends to be concentrated in specific locations)

− poor lighting

− droplet distribution outside of the visual range

4-9.3 Visual Observations

Visual observations are a simple method to make qualitative observations about the presence, relative size, and relative quantity of water droplets downstream of Plane 2. With well-placed view ports and good illumination, a fair amount of information can be obtained without accessing the plenum or ducts.

4-9.3.1 Calibration. Visual observations cannot be calibrated.

4-9.3.2 Conduct. Visual observations for water carryover should be made at 5 min intervals during the performance test run. For fogging systems, additional evaluations for water carryover should be made when ambient conditions require the system to be operated at reduced cooling levels. Water carryover is more likely to occur due to stratification of moisture in the inlet air as fewer fogging spray nozzle arrays are operated, increasing droplet evaporation times. Another indication of water carryover is the drainage of water from the ductwork. If possible, the flow rate of drain water from the duct should be monitored. The flow rate from the drain should be documented over a period of time when the system is operating at steady state. There is a delay characteristic of the system between the time when the droplets coalesce and when they reach the outlet of the drain. This data should be used for informational purposes only.

4-9.3.3 View Ports. View ports, if not already available in the inlet manifold, should be added to enable visual observations across the inlet air stream through the inlet struts, inlet guide vanes, and into the first stage of rotating blades. The preferred location is on the upstream side of the center shaft and should have at least a 120-deg view of the compressor inlet. Two view ports are recommended so that one can be used for making the visual observations and the second can be used for illuminating the inlet to avoid the glare that would restrict visual observation through a single-view port.

Additional view ports are recommended just downstream of the fogging spray nozzle arrays if the region of duct where they are installed is not accessible during gas turbine operation, and also on the downstream side of any inlet duct obstructions such as silencing panels, structural members, or trash screens where droplets may coalesce and shed back into the air stream as much larger droplets.

The inlet view ports should have a viewing area of no less than 64 cm^2 (9.5 $in.^2$) each. The view ports shall be rated for the design pressure of the inlet duct, which is generally negative, but should also be capable of withstanding positive pressure loadings associated with compressor surge.

Safe accessibility to the view ports during turbine and fogging system operation should be considered when selecting view-port locations.

4-9.3.4 Duct Illumination. A strong and uniform light source shall be used to illuminate the inlet manifold and bell mouth region so that the condition of the flow stream can be detected.

4-9.4 Visual Classification of Water Carryover

Visual observations of water carryover should be to classified as follows:

(a) dry — no signs of droplets or puddling water.

(b) light fog — occasional to steady but light streams of fog or droplets. Some wetting of the inlet bell mouth, inner cylinder, or nose cone and struts is visible (trickle of water may be flowing from the inlet manifold drain).

(c) heavy fog — steady stream of fog with a dense grey appearance is visible entering the compressor. More than 50% of the inlet bell mouth, inner cylinder or nose cone, and struts are wet. Some droplets may be observed being shed from inlet struts. A slow and steady stream of water may be flowing from the inlet.

(d) light rain — droplets are visible impacting on the bell mouth, struts, and inner cylinder or nose cone, and these components shall be mostly wetted. These droplets do not follow the air stream into the inlet like the fog. Water flow rates from the manifold drain may be equal to 1% to 2% of the system flow rate.

(e) heavy rain — large droplets are visible impacting the bell mouth, inner cylinder or nose cone, and struts. These droplets have the appearance of those encountered during a thunderstorm where droplet impact may have a white appearance as the droplets rebound from metal surfaces. Flow rates from the inlet manifold drain shall also be increased and steady.

4-10 DATA COLLECTION AND HANDLING

4-10.1 Introduction

This subsection presents requirements and guidance regarding the acquisition and handling of test data. Also presented are the fundamental elements that are essential to the makeup of an overall data acquisition and handling system.

This Code recognizes that technologies and methods in data acquisition and handling shall continue to change and improve over time. If new technologies and methods become available and are shown to meet the required standards stated within this Code, they may be used.

4-10.2 Data Acquisition Systems

4-10.2.1 Data Acquisition Systems. The purpose of a data acquisition system is to collect data and store it in a form suitable for processing or presentation. Systems may be as simple as a person manually recording data to as complex as a digital computer-based system. Regardless of the complexity of the system, a data acquisition system shall be capable of recording, sampling, and storing the data within the requirements of the test and allowable uncertainty set by this Code.

4-10.2.2 Manual System. In some cases, it may be necessary or advantageous to record data manually. It should be recognized that this type of system introduces additional uncertainty in the form of human error that should be accounted for accordingly. Further, manual systems may require longer periods of time or additional personnel for a sufficient number of samples to be taken due to the limited sampling rate. Care shall be taken with the selection of the test-period duration to allow for the manual methods to have sufficient number of samples to coincide with the requirements of the test. Data collection sheets should be prepared prior to the test. The data collection sheets should identify the test-site location, date, time, and type of data collected. The data collection sheets should also delineate the sampling time required for the measurements. Careful recording of the collection times with the data collected should be performed using a digital stopwatch or other sufficient timing device. The recording of data on the original data sheets shall be done clearly and permanently. Data from the original data sheets shall not be transcribed. If it becomes necessary to edit data sheets during the testing, all edits shall be made using ink, and all errors shall be marked through with a single line and initialed and dated by the editor.

4-10.2.3 Automated System. Automated data collection systems have a great deal of flexibility. Automated systems are beneficial in that they allow for the collection of data from multiple sources at high frequencies while recording the time interval with an internal digital clock. Rapid sampling rates serve to reduce test uncertainty and test duration. These systems can consist of a centralized processing unit or distributed processing to multiple locations in the plant.

Automated data acquisition systems shall be functionally checked after installation. As a minimum, a pretest data run should be performed to verify that the system is operating properly. Documentation on the setup, programming, channel lists, signal-conditioning, and operational accuracies, and lists of the equipment making up the automated system should be prepared and supplied in the test report.

4-10.3 Data Management

4-10.3.1 Automated Collected Data. All automated collected data should be recorded in appropriate engineering units and provided in electronic format to the official test parties immediately at the conclusion of the tests. After rigorous review of the data, faulty data readings or failed instruments may be removed from the instrument averages used to calculate performance parameters. All such corrections to the data shall be documented in the final test report. Distribution of the data in engineering units at the conclusion of the test limits the chance of such data being accidentally lost, damaged, or modified. At the conclusion of the test, all test parties should receive any available corrected data or calculated results from the test.

4-10.3.2 Manually Collected Data. All manually collected data recorded on data collection sheets shall be reviewed for completeness and correctness. Immediately after the test and prior to leaving the test site, photocopies of the data collection sheets should be made and distributed between the parties of the test to eliminate the chance of such data being accidentally lost, damaged, or modified.

4-10.3.3 Data Calculation Systems. The data calculation system should have the capability to average each input collected during the test and calculate the test results based on the average values. The system should also calculate the standard deviation and coefficient of variance of each instrument. The system should have the ability to locate and eliminate spurious data from being used in the calculation of the average. The system should also have the ability to plot the test data and each instrument reading over time to look for trends and outlying data.

4-10.4 Data Acquisition System Selection

4-10.4.1 Data Acquisition System Requirements. Prior to selection of a data acquisition system, it is necessary to have the test procedure in place that dictates the requirements of the system. The test procedure should clearly dictate the type of measurements to be made, number of data points needed, the length of the test, the number of samples required, and the frequency of data collection to meet the allowable test uncertainty set by this Code. This information shall serve as a guide in the selection of equipment and system design.

Each measurement loop should be designed with the ability to be loop calibrated and located where it can be checked for continuity and power supply problems. To prevent signal degradation due to noise, each instrument cable should be designed with a shield around the conductor, and the shield should be grounded on one end to drain any stray induced currents.

4-10.4.2 Temporary Automated Data Acquisition System. This Code encourages the usage of temporary automated data acquisition systems for testing purposes. These systems can be carefully calibrated and their proper operation confirmed in the laboratory and then transported to the testing area, thus providing traceability and control of the complete system. The temporary setup limits the instruments' exposure to the elements and avoids problems associated with construction and ordinary plant maintenance.

Site layout and ambient conditions shall be considered when determining the type and application of temporary systems. Instruments and cabling shall be selected to withstand or minimize the impact of any stresses, interference, or ambient conditions to which they may be exposed.

4-10.4.3 Existing Plant Measurement and Control System. This Code does not prohibit the use of the plant measurement and control system for Code testing. However, the system shall meet the requirements set forth in this Code. Caution should be applied with the use of these systems for performance testing by recognizing the limitations and restrictions of these systems.

Most distributed plant control systems apply threshold or dead-band restraints on data signals. This results in data that is only the report of the change in a parameter that exceeds a set threshold value. All threshold values shall be set low enough so that all data signals sent to the distributed control system during a test are reported and stored.

Most plant systems do not calculate flow rates in accordance with this Code, but rather by simplified relationships. This includes, for example, a constant discharge coefficient or even expansion factor. A plant-system indication of flow rate is not to be used in the execution of this Code, unless the fundamental input parameters are also logged and the calculated flow is confirmed to be in accordance with this Code and ASME PTC 19.5.

Section 5
Computation of Results

5-1 GENERAL CALCULATION METHODOLOGY

5-1.1 Introduction

This Code provides procedures for the calculation of the results, and for the correction of the results to base reference conditions as a measure of gas turbine inlet air-conditioning system performance. Performance variables, parameters, and test boundaries are described in subsection 5-1. Each type of inlet air-conditioning system is unique. Section 5 is divided into the following additional subsections:

5-2 Common Parameters and Variables
5-3 General Correction Methodology
5-4 Inlet Cooling Using Evaporative Media
5-5 Inlet Cooling Using Fogging
5-6 Inlet Cooling Using Chillers (Multiple Arrangements)
5-7 Inlet Heating Using Closed-Loop Heating Systems (Coils)
5-8 Inlet Heating Using Open-Loop Heating Systems (Compressor Bleed)

5-1.2 Use of Primary Parameters

In accordance with para. 4-1.2.2, only the data identified as primary parameters are used in the calculation of performance variables.

5-1.3 Review of Test Data

Prior to use in these calculations, test data shall be reviewed for outliers in accordance with subsection 3-5. The remaining data points shall be adjusted for calibrations, water legs, zero readings, and ambient effects.

5-1.4 Use of Bulk Average Value

Where an array of measurements is taken for a given test boundary plane, the parameter used in the calculations shall be the bulk average value, calculated as described later in this Section.

5-1.5 Use of Correction Parameters

If a correction parameter or variable does not influence the correction result by ±0.05%, then it may be neglected in the determination of the primary corrected parameter.

5-2 COMMON PARAMETERS AND VARIABLES

The following calculations refer to plane numbers based on the specific technology under test. A generic system boundary diagram, Fig. 5-2-1, is provided to identify the expected boundaries that will be encountered for an ASME PTC 51 test. System-specific figures are included in the applicable subsections later in this Section.

5-2.1 Inlet Conditions

Inlet conditions are dry-bulb temperature, T_{db1}; barometric pressure, $p_{\mathrm{baro}1}$; and relative humidity, RH_1, or wet-bulb temperature, T_{wb1} at Plane 1 as shown in the generic system boundary diagram, Fig. 5-2-1. Measurement frequency and locations shall be sufficient to account for stratification of incoming air conditions, which may be caused by equipment, vents, or both in close proximity. The number of locations and frequency of measurements required shall follow the guidance provided in Section 4, and be determined by the pretest uncertainty analysis.

5-2.2 Specific Humidity

Specific humidity at any test plane can be determined from psychrometric charts or ASHRAE formulations given dry-bulb temperature, barometric pressure, and wet-bulb temperature or relative humidity.

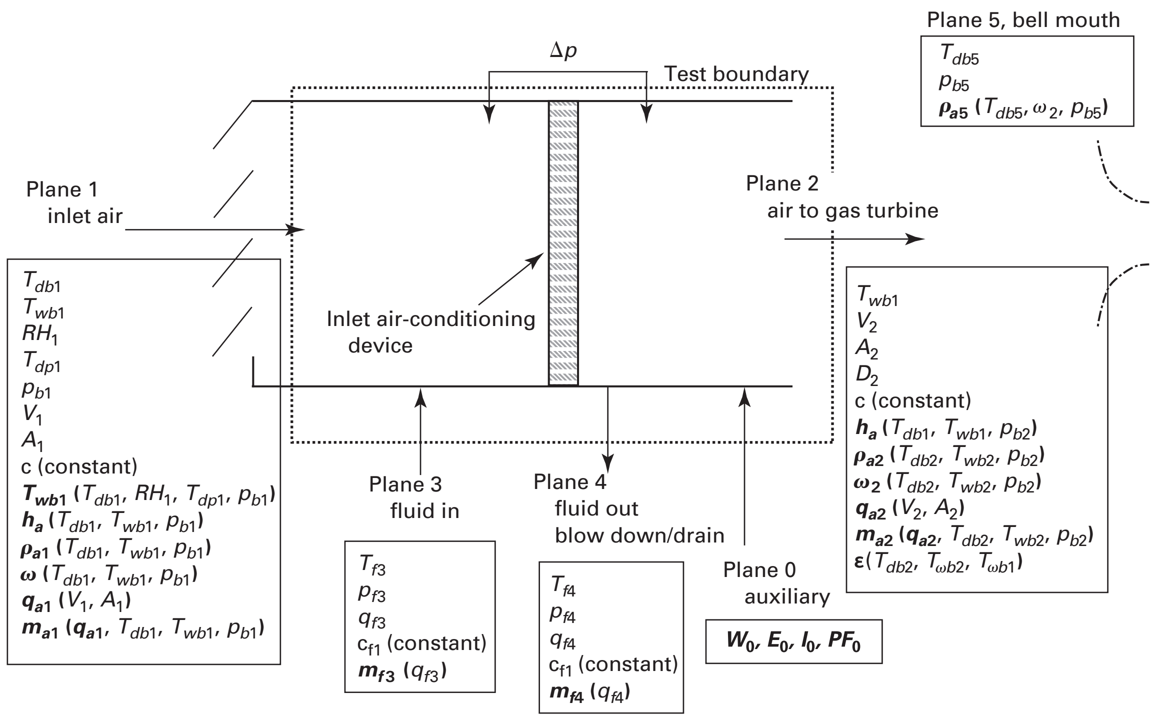
5-2.3 Flow-Weighted Averages

Flow-weighted average properties properly represent the mass and energy flows through the inlet air-conditioning system. Even though variations in inlet air properties are normally small enough to allow arithmetic averaging of the measurements alone, a method is presented here to account for cases in which flow properties require mass and/or volume weighting to account for stratification.

NOTE: The following nomenclature applies to eq. (5-2-1) through eq. (5-2-7):

ψ_j = yaw angle at point j, deg
ϕ_j = pitch angle at point j, deg
w_j = weighting factor, ratio
v_j = point velocity, m/s (ft/sec)

Fig. 5-2-1 Generic Test Boundary Diagram



GENERAL NOTES:
(a) Measured variables are shown in italics.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

5-2.3.1 Average Static Pressure, kPa (psi)

$$p_{st,ave} = \frac{\sum_{j=1}^{n}\left(p_{st,j} v_j w_j \cos\psi_j \cos\phi_j\right)}{\sum_{j=1}^{n}\left(v_j w_j \cos\psi_j \cos\phi_j\right)} \tag{5-2-1}$$

5-2.3.2 Average Density, kg/m^3 (lb/ft^3)

$$\rho_{ave} = \frac{\sum_{j=1}^{n}\left(\rho_j v_j w_j \cos\psi_j \cos\phi_j\right)}{\sum_{j=1}^{n}\left(v_j w_j \cos\psi_j \cos\phi_j\right)} \tag{5-2-2}$$

5-2.3.3 Average Temperature, °C (°F)

$$T_{ave} = \frac{\sum_{j=1}^{n}\left(T_j \rho_j v_j w_j \cos\psi_j \cos\phi_j\right)}{\sum_{j=1}^{n}\left(\rho_j v_j w_j \cos\psi_j \cos\phi_j\right)} \tag{5-2-3}$$

5-2.3.4 Average Specific Kinetic Energy, kJ/kg (Btu/lbm)

$$e_{k,ave} = \frac{\sum_{j=1}^{n}\left(\rho_j v_j^3 \cos^3\psi_j \cos^3\phi_j\right)}{2\sum_{j=1}^{n}\left(\rho_j v_j w_j \cos\psi_j \cos\phi_j\right) g_c K_1} \tag{5-2-4}$$

where

$e_{k,\text{ave}}$ = flow-weighted average specific kinetic energy

K_1 = conversion constant, 1 000 N·m/kJ (778.175 ft-lbf/Btu)

5-2.3.5 Kinetic Energy Correction Factor

$$\gamma_{ave} = \frac{2 g_c \rho^2 e_k A^2}{K_2 m^2} \tag{5-2-5}$$

where

A = area, m^2 (ft^2)

K_2 = conversion constant, 1 J/N·m (7.716×10^{-8} hr^2/sec^2)

m = mass flow rate, kg/s (lbm/hr)

5-2.3.6 Average Velocity Pressure

$$p_{v,ave} = \rho \cdot e_k \cdot K_2 \quad (5\text{-}2\text{-}6)$$

where

K_2 = conversion constant, 1 kPa-m^3/kJ (112,057.2 psi-ft^3/Btu)

5-2.3.7 Average Total Pressure, kPa (psia)

$$p_{t,ave} = p_{st,ave} + p_{v,ave} + p_{baro} \quad (5\text{-}2\text{-}7)$$

NOTE: If $p_{\text{st,ave}}$ is already in absolute pressure, p_{baro} does not need to be included in this equation.

5-2.4 Offset of the Compressor Inlet Dry-Bulb Temperature for Use in Temperature Differential Calculations

Before initiating the system test, any offsets in downstream temperature due to influences other than the inlet air-conditioning system shall be determined. This is accomplished by comparing the temperature readings at Planes 1 and 2 with the gas turbine running and no inlet air-conditioning equipment in operation such that the downstream temperature reading is being impacted while taking the T_2 measurements.

If the offset, ΔT_{1-2} (with inlet air-conditioning system out of service), is greater than 0.5°C (1°F), sources of this difference shall be identified prior to testing. If the sources of this difference are external to the inlet air-conditioning equipment and cannot be removed during testing, this differential shall be accounted for when determining equipment performance by substituting $T_{db2,\text{adj}}$ for $T_{db2,\text{meas}}$ in applicable correction calculations, and the following equation applies:

$$T_{db2,adj} = T_{db2} + \Delta T_{1-2} \quad (5\text{-}2\text{-}8)$$

where

T_{db2} = measured dry-bulb temperature (Plane 2)
$T_{db2,\text{adj}}$ = Plane 2 dry-bulb temperature adjusted for measured temperature offset
ΔT_{1-2} = $T_{db2} - T_{db1}$ (determined with inlet air-conditioning equipment out of service)

As regards the change in difference between the offset due to change in airflow (the effect due to airflow being different in the narrow range), it is small and can be ignored. Enthalpy plays a more important role.

5-2.5 Air Mass Flow Rate

Air mass flow rate entering the inlet air-conditioning equipment (m_1) may be determined using any method that meets uncertainty requirements, including the following.

5-2.5.1 Mass Flow Rate by Velocity Traverse. This method involves the use of a velocity traverse to measure the air velocity directly. Using velocity profile and air density, a calculated value for air mass flow rate can be determined. See Section 4 for more information on this measurement technique.

When the flow rate of the fluid (air, exhaust gases, etc.) is determined by velocity traverse, the mass flow rate is obtained using eq. (5-2-9) [18], with weighting factor added]:

$$m = \sum_{j=1}^{n} m_j = A \cdot C1 \cdot \frac{1}{n} \cdot \sum_{j=1}^{n} \left(\rho_j v_j w_j \cos\psi_j \cos\phi_j \right) \quad (5\text{-}2\text{-}9)$$

where

C1 = time conversion constant, 1 s/s (3,600 sec/hr)
m = mass flow rate, kg/s (lbm/hr)
v_j = point velocity at point j, m/s (ft/sec)
ϕ_j = pitch angle at point j, deg
ψ_j = yaw angle at point j, deg
w_j = weighting factor at point j, ratio

The weighting factor, w_j, is dependent upon the traversing method used. ASME PTC 19.5 recommends using either the Gauss, Tchebycheff, or the log-linear traversing methods. The weighting factors associated with these methods are tabularized in ASME PTC 19.5. For the equal area traversing method, the weighting factor is equal to unity.

The point velocity, v_j, of the airflow into or out of the inlet air-conditioning system is determined by using an air-flow measurement device as described in Section 4 of this Code.

5-2.5.2 Mass Flow Rate by Equipment Energy Balance. In this method, mass flow rate is calculated utilizing an energy balance of the inlet air-conditioning system:

$$q_{3-4} = q_{1-2} + \text{losses} \quad (5\text{-}2\text{-}10)$$

where

q_{1-2} = $q_1 - q_2$
q_{3-4} = $q_3 - q_4$
q_i = $m_i \times h_i$

and

h_i = $f(p_i, T_i, c_i)$ (including ω_i if medium is air)
losses = 0 = radiative heat losses (assumed small and not easily obtained)

5-2.5.3 Mass Flow Rate by Calibrated Flow Coefficient at the Bell Mouth. The inlet airflow (at Plane 5 of Fig. 5-2-1) can be calculated by measuring the air properties at the inlet to the compressor bell mouth annulus section. This method is an option for gas turbines that have a calibrated bell mouth flow coefficient available.

This method may be used for other gas turbines as well; however, the lack of a calibrated flow coefficient will add additional uncertainty to the airflow calculation that must be considered for this method to be a valid airflow calculation technique.

The calibrated bell mouth flow coefficient may be obtained by means of a factory test (usually conducted by the equipment manufacturer), in which the actual airflow to the turbine is measured under laboratory conditions using flow-measurement devices in accordance with ASME PTC 19.5. The inlet air total temperature and humidity, inlet air total pressure, and inlet air static pressure are also measured simultaneously during the factory test.

The bell mouth flow coefficient is then calculated by comparing the factory-measured airflow to the airflow calculated using the method described below. The uncertainty of the calculated flow coefficient shall be specified based on an uncertainty analysis of the factory test. The basis for the bell mouth annulus area used in the airflow calculation, and the measurement locations of the inlet air conditions relative to the bell mouth of the gas turbine shall also be specified as part of the bell mouth flow coefficient calibration report.

To maintain the validity of the calibrated flow coefficient during subsequent calculations of the inlet airflow, it is critical that the bell mouth annulus area specified during the factory test is used for the calculations, and the measurement locations for the inlet air properties used in the calculations are consistent with the measurement locations used during the factory test.

To calculate the gas turbine inlet air mass flow rate from the calibrated flow coefficient, the following equation is used:

$$m_2 = \frac{C_f \cdot A \cdot p_t \cdot K}{\sqrt{T_t}} \cdot \sqrt{\left(\frac{g_c \times k}{R}\right)} \cdot M_5 \cdot \left[1 + \left(\frac{k-1}{2}\right) \cdot M_5^2\right]^{\left(\frac{k+1}{2\times(1-k)}\right)} \tag{5-2-11}$$

where

A = compressor bell mouth throat annulus area, m^2 (ft^2)

C_f = compressor bell mouth flow coefficient, nondimensional

g_c = gravitational constant, 1 kg-m/N-s^2 (32.174 lbm-ft/lbf-sec^2)

K = unit conversion factor, 1 (12 in./ft)

k = ratio of specific heats, C_p/C_v, defined below, nondimensional

M_5 = compressor bell mouth throat Mach number, defined below, nondimensional

m_2 = inlet airflow at Plane 2, kg/s (lbm/hr)

p_t = compressor inlet total pressure, kPa (psia)

R = gas constant, defined below, kJ/kg-K (Btu/lbm-R)

T_t = compressor inlet total temperature, K (R)

For moist air (assuming all water is in vapor form)

$$k = k_{da,5} * \frac{1}{1+\omega_5} + k_{w,5} * \frac{\omega_5}{1+\omega_5} \tag{5-2-12}$$

where

$k_{da,5}$ = 1.400 (dry air) (1.400) at Plane 5

$k_{w,5}$ = 1.327 (water vapor) (1.329) at Plane 5

ω_5 = specific humidity at Plane 5, kg_w/kg_{da} (lb_w/lb_{da})

$$R = R_{da,5} \times \frac{1}{1+\omega_5} + R_{w,5} \times \frac{\omega_5}{1+\omega_5} \tag{5-2-13}$$

where

$R_{da,5}$ = 0.2870 kJ/kg-K (dry air) (0.06855 Btu/lbm-R) at Plane 5

$R_{w,5}$ = 0.4615 kJ/kg-K (water vapor) (0.1102 Btu/lbm-R) at Plane 5

ω_5 = specific humidity at Plane 5, kg_w/kg_{da} (lb_w/lb_{da})

and

$$M_5 = \sqrt{\left(\frac{2}{k-1}\right) \times \left[\left(\frac{p_t}{p_s}\right)^{\frac{k-1}{k}} - 1\right]} \tag{5-2-14}$$

where

k = ratio of specific heats, C_p/C_v

p_s = compressor bell mouth static pressure, kPa (psia)

p_t = compressor inlet total pressure, kPa (psia)

5-2.5.4 Mass Flow Rate by Gas Turbine Energy Balance. The inlet airflow may be calculated using an energy balance of the gas turbine, following the methods described in ASME PTC 22 (also requires parameters to be acquired utilizing the methods described in ASME PTC 22).

5-2.5.5 Mass Flow Rate by HRSG Energy Balance. The inlet airflow may be determined using an energy balance of the heat recovery steam generator (HRSG) to determine gas turbine exhaust gas flow.

The inlet airflow at Plane 2 may then be calculated by mass balance around the gas turbine as the gas turbine exhaust gas flow minus any injection flows (such as fuel, water, steam, or air) between Plane 2 and the measurement plane. Methods described in ASME PTC 4.4 shall be followed (also requires parameters to be acquired utilizing the methods described in ASME PTC 4.4).

5-2.5.6 Mass Flow Rate by Stack Exhaust Composition. In this method, measured excess oxygen at the unit exhaust stack and stoichiometric combustion calculations are used to determine the inlet airflow at Plane 2.

The calculation uses an iterative process to solve for the inlet airflow based on the following measurements: specific humidity of the inlet air, water flow added to or removed from the inlet air-conditioning device, fuel flow, fuel chemical composition, injection fluid (for NOx control or power augmentation) and exhaust gas oxygen and/or carbon dioxide concentration. Because this is an iterative process, it is best to use a spreadsheet program for performing these calculations to take advantage of circular calculation or goal seek tools.

The accuracy of the measurements of fuel flow, fuel composition, and exhaust gas concentrations of oxygen and/or carbon dioxide will have the greatest effect on the calculated airflow, and measurement of these parameters should be carefully reviewed and evaluated in pretest and posttest uncertainty analyses. The readings of exhaust gas constituents such as oxygen are often available from continuous emission monitors located in the gas turbine exhaust stream. Users of this method are required to evaluate the stratification of oxygen levels in the measurement plane since exhaust gas oxygen and carbon dioxide readings can be stratified near the turbine exhaust or in simple cycle stacks. This is less of an issue in combined cycle applications where the emission probe is installed downstream of the heat recovery steam generators, which effectively mixes the exhaust gas and reduces stratification. The use of duct burners should be avoided during the test, but if necessary their fuel flow can be included in the calculation, as long as the impact to uncertainty is included in the posttest uncertainty analysis.

Environmental Protection Agency test results from initial plant commissioning or annual recertification testing of gas turbine emissions and continuous emissions monitoring (CEM) system should include an evaluation of oxygen content variation at the plane where the emission probe is located [19]. This input can be used as a basis for the sampling error if an exhaust traverse is not performed during the ASME PTC 51 test as long as there is no substantial change in operating configuration between the EPA test and the inlet air-conditioning system test.

5-2.5.6.1 Calculations. The calculations begin with an estimated value of compressor inlet air mass flow rate and calculation of inlet air composition.

m_a = initial estimate of compressor inlet air mass flow (5-2-15)

The composition of dry air is given as

Element	Vol%	Wt%
Nitrogen (N_2)	78.03	75.46
Oxygen (O_2)	20.99	23.19
Argon (Ar)	0.98	1.35

GENERAL NOTE: Values provided in this table are taken from ref. [20].

Moist air composition, on a weight percentage basis, is then calculated based on the inlet specific humidity measured during the performance test.

The composition of moist air is

Element	Percent by Weight of Moist Air
Nitrogen (N_2)	Wt% N_{2dry} / $(1 + \omega)$
Oxygen (O_2)	Wt% O_{2dry} / $(1 + \omega)$
Argon (Ar)	Wt% Ar_{dry} / $(1 + \omega)$
Water (H_2O)	$\omega / (1 + \omega)$
Total	100%

If the inlet air-conditioning equipment is increasing or decreasing the specific humidity of the inlet air at the exit of the equipment (e.g., at the compressor inlet or Plane 2), it will be necessary to adjust the specific humidity by further iterating on the calculations after the air-flow estimate is calculated.

In those cases, specific humidity will become

$$\omega_2 = \omega + (m_w / m_a) \tag{5-2-16}$$

The mass flow of the air elements is next calculated by taking the product of mass flow of air and the weight percent of the element.

$m_{Element}$	Percent by Weight of Air Mass Flow	Percent by Weight of Moist Air
m_{N2}	$m_a \times$ Wt% N_2	Wt% N_{2dry} / $(1 + \omega)$
m_{O2}	$m_a \times$ Wt% O_2	Wt% O_{2dry} / $(1 + \omega)$
m_{Ar}	$m_a \times$ Wt% Ar	Wt% Ar_{dry} / $(1 + \omega)$
m_w	$m_a \times$ Wt% H_2O	$\omega / (1 + \omega)$
Total	. . .	100%

Next, the fuel composition must calculated, breaking it down to an elemental basis from the fuel analysis. For example, methane, which has a composition of CH_4, has a carbon weight percent of 74.87% and hydrogen weight percent of 25.13%.

The complete analysis of the fuel is to be broken down into the following elements, noting that water can remain as a molecule since the conversion from elements back to water can be easily handled:

Fuel Element	Percent by Weight in Fuel
Carbon (C)	_____
Hydrogen (H_2)	_____
Sulfur (S)	_____
Nitrogen (N_2)	_____
Oxygen (O_2)	_____
Water (H_2O)	_____
Total	100%

The mass flow of the fuel elements is calculated by taking the product of the fuel elements and the measured mass flow rate of the fuel.

Fuel Element	Percent by Weight of Fuel Mass Flow
Carbon (C)	____
Hydrogen (H_2)	____
Sulfur (S)	____
Nitrogen (N_2)	____
Oxygen (O_2)	____
Water (H_2O)	____
Total	Verify = measured fuel flow

If an injection fluid such as water, steam, or nitrogen are injected into the combustion system of for emission control or power augmentation, that fluid stream should be accounted for as well.

Injection Element	Percent by Weight of Fuel Mass Flow
Nitrogen (N_2)	____
Steam or water (H_2O)	____

Next, the oxidation of combustible materials is calculated converting carbon to carbon dioxide, hydrogen to water, and so on.

Fuel Element	Oxidation Reaction	Calculated Mass of Oxidized Molecule
Carbon (C)	$C + O_2 = CO_2$	$m_{CO2} = 3.6641 \times m_C$
Hydrogen (H_2)	$4\,H + O_2 = 2\,H_2O$	$m_{H2O} = 8.9370 \times m_H$
Sulfur (S)	$S + O_2 = SO_2$	$m_{SO2} = 1.9981 \times m_S$
Oxygen consumed (O_2)	. . .	$m_{O2} = m_{CO2} + m_{H2O} + m_{SO2} - (m_C + m_H + m_S)$

The composition of the exhaust gas on a mass basis is then calculated by combining the air, fuel, and injection flows as follows:

Exhaust Gas Composition	Calculated Mass Flow
Oxygen (O_2)	$m_{O2,a} - m_{O2,cons}$
Carbon dioxide (CO_2)	m_{CO2}
Water (H_2O)	$m_{H2O,a} + m_{H2O,inj} + m_{H2O,ox}$
Sulfur dioxide (SO_2)	m_{SO2}
Nitrogen (N_2)	$m_{N2,a} + m_{N2,inj}$
Argon (Ar)	$m_{Ar,a}$
Total mass flow	m_{exh} = Sum of above cells

This mass analysis is then used to calculate weight percent of the exhaust gas composition.

Exhaust Gas Composition	Percent by Weight of Exhaust Gas
Oxygen (O_2)	$\text{Wt\% } O_{2},_{exh} = m_{O2,exh} / m_{exh} \times 100$
Carbon dioxide (CO_2)	$\text{Wt\% } CO_{2},_{exh} = m_{CO2} / m_{exh} \times 100$
Water (H_2O)	$\text{Wt\% } H_2O,_{exh} = m_{H2O} / m_{exh} \times 100$
Sulfur dioxide (SO_2)	$\text{Wt\% } SO_{2},_{exh} = m_{SO2} / m_{exh} \times 100$
Nitrogen (N_2)	$\text{Wt\% } N_{2},_{exh} = m_{N2} / m_{exh} \times 100$
Argon (Ar)	$\text{Wt\% } Ar,_{exh} = m_{Ar} / m_{exh} \times 100$
Total	100%

This composition should be used to calculate the molecular weight of the exhaust gas.

$$\text{Mole weight of exhaust gas} = \frac{(100 \times \Sigma \text{Wt\% of exhaust molecule})}{(\text{mole weight of exhaust molecule})} \tag{5-2-17}$$

Volume percent is calculated from the known weight percent of the individual molecules and the molecular weight of the exhaust gas.

Exhaust Gas Composition	Percent by Volume of Exhaust Gas
Oxygen (O_2)	$\text{Vol\% } O_{2exh} = \text{Wt\%} O_{2exh} / 31.9988 \times$ mole weight of exhaust gas
Carbon dioxide (CO_2)	$\text{Vol\% } CO_{2exh} = \text{Wt\% } CO_{2exh} / 44.0098 \times$ mole weight of exhaust gas
Water (H_2O)	$\text{Vol\% } H_2O_{exh} = \text{Wt\% } H_2O_{exh} / 18.0152 \times$ mole weight of exhaust gas
Sulfur dioxide (SO_2)	$\text{Vol\% } SO_{2exh} = \text{Wt\% } SO_{2exh} / 64.0588 \times$ mole weight of exhaust gas
Nitrogen (N_2)	$\text{Vol\% } N_{2exh} = \text{Wt\% } N_{2exh} / 28.0134 \times$ mole weight exhaust gas
Argon (Ar)	$\text{Vol\% } Ar_{exh} = \text{Wt\% } Ar_{exh} / 39.948 \times$ mole weight of exhaust gas
Total	100%

The final required correction, prior to iterating on the inlet airflow and inlet air specific humidity, is to convert the oxygen and carbon dioxide values to a dry basis for comparison to the exhaust gas measurement values. Conversion to dry values is calculated as follows:

$$\text{dry \%Vol} = \text{moist \%Vol} / [1 - (\text{Vol\% } H_2O / 100)] \tag{5-2-18}$$

Exhaust Gas Composition	Conversion to Dry Values by Percent Volume of Exhaust Gas
Oxygen (O_2)	$\text{Vol\% } O_{2exh} / [1 - (\text{Vol\% } H_2O/100)]$
Carbon dioxide (CO_2)	$\text{Vol\% } CO_{2exh} / [1 - (\text{Vol\% } H_2O/100)]$

5-2.5.7 Mass Flow Rate of Dry Air. The mass flow rate of dry air crossing a plane can be calculated from the total mass flow and the specific humidity at that plane, as follows:

$$m_{da,i} = m_i \;/\; (1 + \omega_i) \tag{5-2-19}$$

where

m_i = mass flow rate of moist air crossing Plane i
ω_i = specific humidity of the air at Plane i

5-2.6 Inlet Air Temperature Differential

The change in inlet air temperature brought about by the inlet air-conditioning equipment is a primary test variable for each type of equipment covered in this document. The temperature differential across the inlet air-conditioning system is the difference between the average dry bulb temperatures at Planes 1 and 2.

Inlet air temperature change due to inlet air-conditioning equipment (ΔT):

$$\Delta T = T_{db1} - T_{db2} \tag{5-2-20}$$

where

T_{db1} = dry-bulb temperature at Plane 1
T_{db2} = dry-bulb temperature at Plane 2

5-2.7 Auxiliary Energy Consumption

Auxiliary energy consumption may either be electrical or thermal in nature.

5-2.7.1 Electrical Auxiliary Consumption. The equipment power consumption should be measured at each source point to the inlet air-conditioning equipment. Each motor control center (MCC) should be monitored and recorded following methods described in Section 4. Equipment may include, but is not limited to, pumps, fans, control panels, compressors, and evaporators. The following equation applies for each electrical auxiliary energy source:

Single-phase source

$$kW_j = \frac{I_j \cdot E_j \cdot PF}{1000} \tag{5-2-21}$$

where

E_j = electric voltage for source j
I_j = electric current for source j
kW_j = power consumption for source j
PF = power factor

Three-phase source

$$kW_j = \frac{I_j \cdot E_j \cdot PF \cdot \sqrt{3}}{1000} \tag{5-2-22}$$

where

E_j = electric voltage for source j
I_j = electric current for source j
kW_j = power consumption for source j
PF = power factor

5-2.7.2 Thermal Auxiliary Consumption. Thermal energy consumption of the equipment, if available, shall be determined from the measured flow, pressure, and temperature of the fluid, following the guidelines presented in Section 4. If the working fluid is steam, then consumption shall be determined using the current ASME Steam Table formulations for enthalpy. The following equation applies:

$$q_{3-4} = (m_3 \times h_3) - (m_4 \times h_4) + \text{losses} \tag{5-2-23}$$

where

h_3 = enthalpy of fluid entering equipment
h_4 = enthalpy of fluid exiting equipment
losses = radiative heat losses, assumed zero
m_3 = steam flow rate from Plane 3 to Plane 4
q_{3-4} = heat consumption from Plane 3 to Plane 4

NOTES:
(1) Radiation losses are not easily obtained and in most cases can be assumed small enough to be insignificant.
(2) $m_3 = m_4$

5-3 GENERAL CORRECTION METHODOLOGY

5-3.1 Introduction

Calculations for correcting test results to the base reference conditions are included in each subsection.

5-3.2 Generic Correction Formula

Once results for the tests are determined at test-measured conditions, these results should be corrected to a base reference set of conditions. The following equation is the generic correction formula that shall be applied to each test-run result, following the guidance provided in each subsection herein:

$$F_{\text{corr}} = F_{\text{meas}} \times \Pi\alpha_0 \times \Pi\alpha_1 \times \Pi\alpha_2 \times \Pi\alpha_3 \times \Pi\alpha_4 \times \Pi\alpha_5 \tag{5-3-1}$$

where

F_{corr} = generic performance factor or test result, corrected to base reference conditions
F_{meas} = generic performance factor or test result, as determined for test measured conditions
α_X = correction factor at Plane X, as defined by pretest agreement [see subpara. 3-1.2 (o)].
$\Pi\alpha_0$ = product of correction factors at Plane 0
$\Pi\alpha_1$ = product of correction factors at Plane 1
$\Pi\alpha_2$ = product of correction factors at Plane 2
$\Pi\alpha_3$ = product of correction factors at Plane 3
$\Pi\alpha_4$ = product of correction factors at Plane 4
$\Pi\alpha_5$ = product of correction factors at Plane 5

NOTE: This is the generic correction equation, based on test boundary of Fig. 5-2-1.

5-3.3 Variation in Correction Factors

Correction factors at each plane vary depending on the inlet air-conditioning equipment and test conditions.

The applicability for each technology is discussed in the applicable subsections below.

5-3.4 Replacement of Humidity Correction

Due to the potential multivariant behavior of corrections for wet-bulb temperature, this correction may be replaced with specific humidity at the election of the Code user.

5-4 INLET COOLING USING EVAPORATIVE MEDIA

5-4.1 Introduction

Subsection 5-4 applies to cooling systems designed to use the latent heat of vaporization of water to remove sensible heat from the GT compressor inlet air by passing the inlet air stream across a wetted media. Figure 5-4.1-1 is a test boundary diagram identifying the most common planes of reference required for evaporative coolers.

5-4.2 Test Goals

Subsections 5-1 through 5-3 should be reviewed prior to the use of subsection 5-4. The most common test goals for evaporative cooling are described in paras. 5-4.2.1 through 5-4.2.8.

5-4.2.1 Measured Evaporative Cooler Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The temperature of the air leaving the evaporative cooler, commonly referred to as the "measured exit temperature" (also referred to as the "GT inlet air at Plane 2," or "compressor inlet temperature") may be measured directly. The measurement technique employed should ensure that no moisture accumulates on the temperature element(s).

5-4.2.2 Corrected Evaporative Cooler Exit Dry-Bulb Temperature, $T_{db2,corr.}$ The measured temperature of the air leaving the evaporative cooler that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine corrected exit temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αp_1 = multiplicative correction for inlet air pressure at Plane 1
αm_1 = multiplicative correction for air mass flow at Plane 1
αT_{w3} = multiplicative correction for inlet water temperature at Plane 3

Therefore, the correction equation for exit dry-bulb temperature becomes

$$T_{db2,corr} = T_{db2,meas} \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha p_1 \times \alpha m_1 \times \alpha T_{w3} \quad (5\text{-}4\text{-}1)$$

5-4.2.3 Measured Evaporative Effectiveness, $\varepsilon_{meas.}$ The evaporative effectiveness calculated at tested conditions, commonly known as "measured effectiveness," is calculated using the following equation:

$$\varepsilon_{meas} = (T_{db1,meas} - T_{db2,meas}) \,/\, (T_{db1,meas} - T_{wb1,meas}) \quad (5\text{-}4\text{-}2)$$

where

T_{db1} = dry-bulb temperature at Plane 1
T_{db2} = dry-bulb temperature at Plane 2
T_{wb1} = wet bulb temperature at Plane 1

5-4.2.4 Corrected Evaporative Effectiveness, $\varepsilon_{corr.}$ The calculated evaporative effectiveness corrected to base reference conditions is commonly known as "corrected effectiveness." To determine corrected effectiveness, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αp_1 = multiplicative correction for inlet air pressure at Plane 1
αm_1 = multiplicative correction for air mass flow at Plane 1
αT_{w3} = multiplicative correction for inlet water temperature at Plane 3

Therefore, the correction equation for evaporative effectiveness becomes

$$\varepsilon_{corr} = \varepsilon_{meas} \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha p_1 \times \alpha m_1 \times \alpha T_{w3} \quad (5\text{-}4\text{-}3)$$

5-4.2.5 Measured Water Consumption, $m_{w1-2.}$ The measured water consumption through evaporation is calculated using the following equation:

$$m_{w1-2} = m_{w3} - m_{w4} \quad (5\text{-}4\text{-}4)$$

where

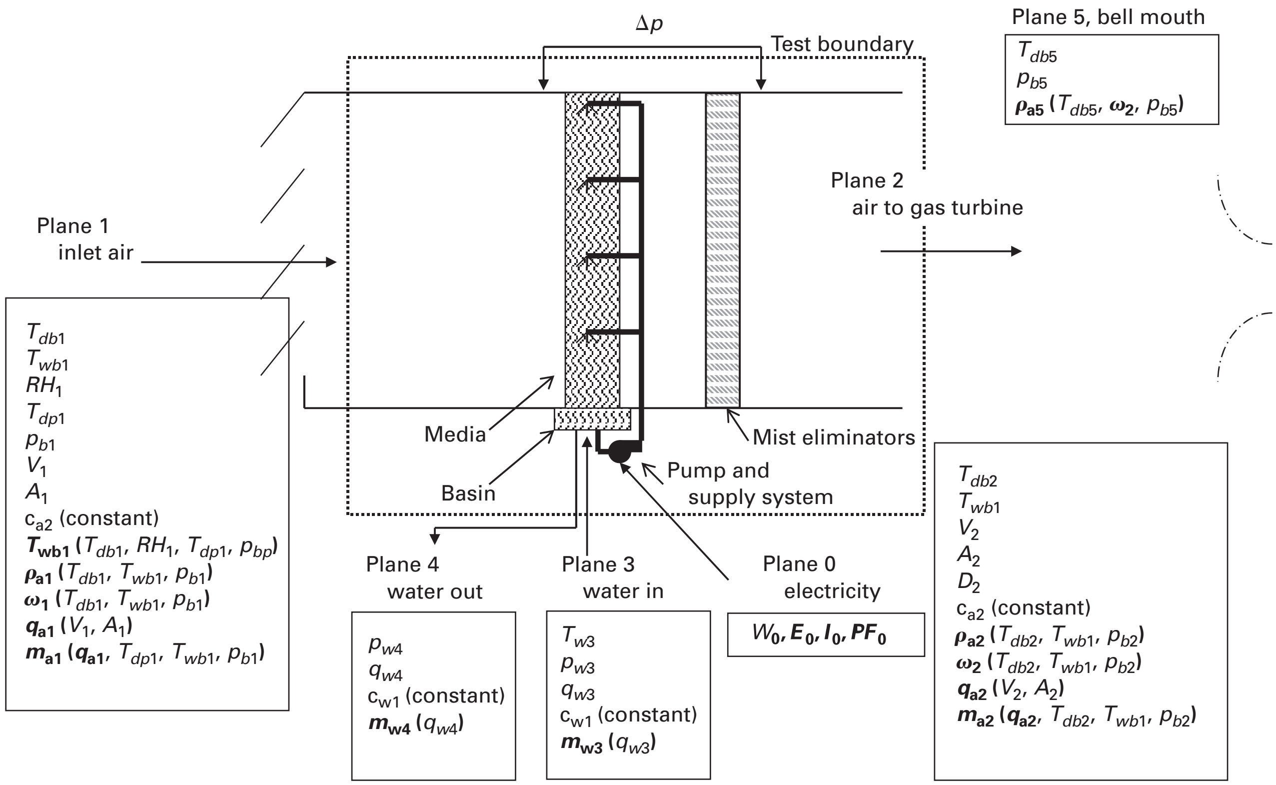
m_{w3} = the mass flow rate of the water entering the system at Plane 3
m_{w4} = the mass flow rate of the water discharge at Plane 4

Note that the water evaporated may not be the same as the water consumed because not all the water gets evaporated; some of it is collected in the basin and other surfaces and therefore wasted. The water evaporated can be calculated using the following equation:

$$m_{w2} - m_{w1} = m_{da1}(\omega_2 - \omega_1) \quad (5\text{-}4\text{-}5)$$

m_{da1} = the mass flow of dry air entering the evaporative cooling system at Plane 1
$m_{w2} - m_{w1}$ = the water mass flow rate evaporated
ω_1 = specific humidity of the air at Plane 1
ω_2 = specific humidity of the air at Plane 2

Fig. 5-4.1-1 Evaporative Cooler Test Boundary Diagram



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

5-4.2.6 Corrected Water Consumption, $m_{w2} - m_{w1,corr.}$ Water consumption corrected to base reference conditions is commonly called "corrected water consumption." For a given air-flow rate, corrected water consumption is a function of the wet-bulb depression and cooling effectiveness.

$\alpha(T_{db1} - T_{wb1})$ = multiplicative correction for web-bulb depression at Plane 1
$\alpha\varepsilon_{corr}$ = multiplicative correction for cooling effectiveness

Therefore, the correction equation for water consumption becomes

$$(m_{w2} - m_{w1})_{corr} = (m_{w2} - m_{w1})_{meas} \times \alpha(T_{db1} - T_{wb1}) \times \alpha\varepsilon_{corr} \quad (5\text{-}4\text{-}6)$$

5-4.2.7 Measured Pressure Drop, $\Delta p_{1-2,meas.}$ Measured pressure drop of the GT compressor inlet air across the equipment (Plane 1 to Plane 2) is calculated as follows:

$$\Delta p_{1-2,meas} = p_{1,meas} - p_{2,meas} \quad (5\text{-}4\text{-}7)$$

5-4.2.8 Corrected Pressure Drop, $\Delta p_{1-2,corr.}$ Measured pressure drop corrected to base reference conditions is commonly known as "corrected pressure drop." Corrected pressure drop is calculated as follows:

$$\Delta p_{1-2,corr} = \Delta p_{1-2,meas} \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha p_1 \times \alpha m_1 \quad (5\text{-}4\text{-}8)$$

where

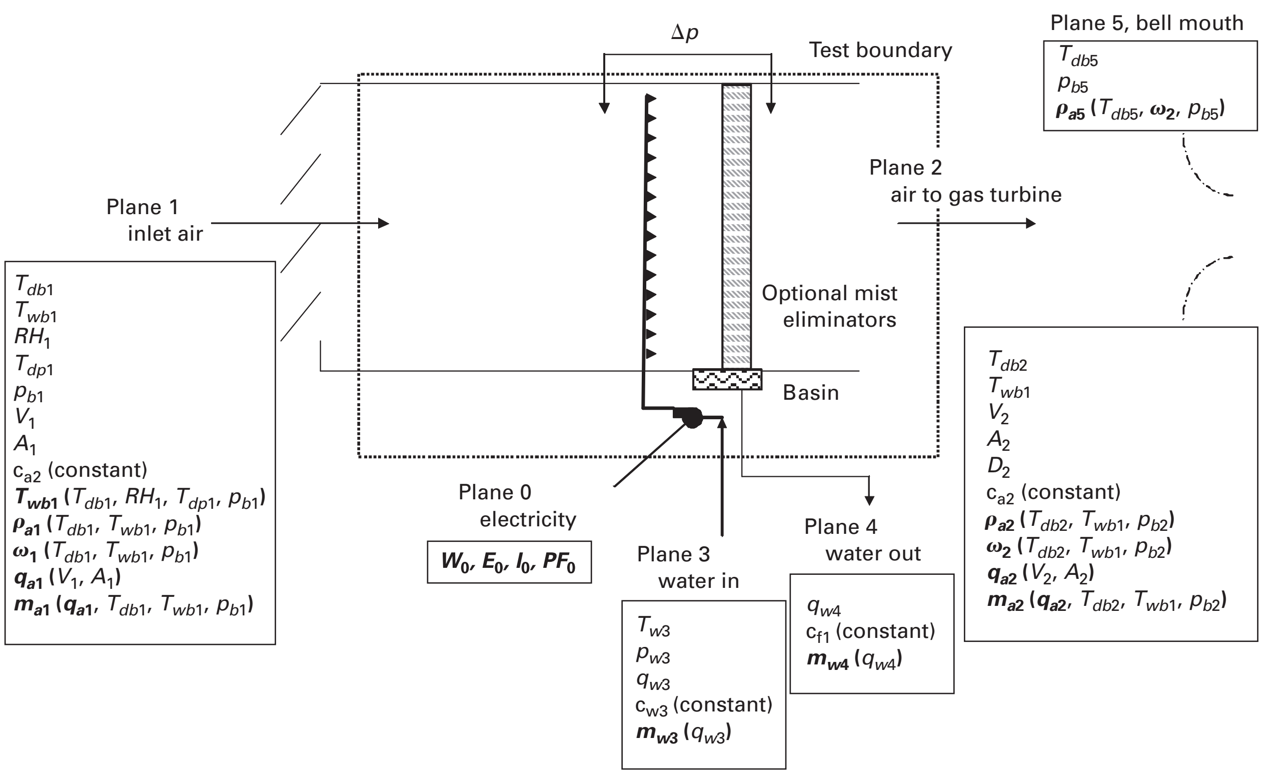
αm_1 = multiplicative correction for air mass flow at Plane 1
αp_1 = multiplicative correction for inlet air pressure at Plane 1
αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
$\Delta p_{1-2,meas}$ = measured pressure drop

5-5 INLET COOLING USING FOGGING

5-5.1 Introduction

Subsection 5-5 applies to cooling systems designed to use the latent heat of vaporization of water to remove sensible heat from the GT compressor inlet air by injecting finely atomized water droplets directly into

Fig. 5-5.1-1 Inlet Fogger Test Boundary Diagram



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

the inlet air stream. Figure 5-5.1-1 is a test boundary diagram identifying the most common planes of reference required for inlet foggers.

5-5.2 Test Goals

Subsections 5-1 through 5-3 should be reviewed prior to the use of subsection 5-5. The most common test goals for cooling by fogging are described in paras. 5-5.2.1 through 5-5.2.8.

5-5.2.1 Measured Fogger Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The temperature of the air leaving the fogger, commonly known as "measured exit temperature" (also referred to as the "GT inlet air at Plane 2," or "compressor inlet temperature") may be measured directly following the guidance provided in subsection 4-3.

5-5.2.2 Corrected Fogger Exit Dry-Bulb Temperature, $T_{db2,corr.}$ Fogging systems are often designed to provide stepped reductions in cooling based on the evaporative cooling potential, or wet-bulb depression (the difference between T_{db1} and T_{wb1}). These systems often have a control temperature set point that is offset from the wet-bulb temperature to promote evaporation and minimize water carryover. Refer to Fig. 5-5.2.2-1 for a sample fogging system curve showing system cooling capability versus potential cooling level.

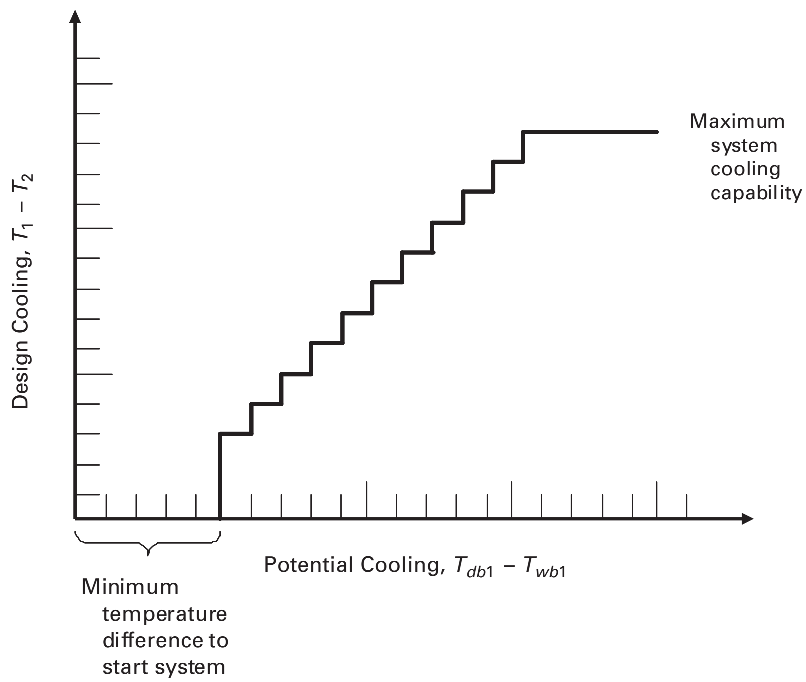
If a more advanced control algorithm is used to control the amount of cooling, which may take inlet air temperature, barometric pressure, or other parameters into account, then the manufacturer shall provide correction factors to adjust measured results to the guarantee point conditions using corrections such as:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
$\alpha\omega_1$ = multiplicative correction for specific humidity at Plane 1
αp_1 = multiplicative correction for inlet air pressure at Plane 1
αm_1 = multiplicative correction for air mass flow at Plane 1

In that case, the correction equation for exit dry-bulb temperature becomes

$$T_{db2,\mathrm{corr}} = T_{db2,\mathrm{meas}} \times \alpha T_{db1} \times \alpha\omega_1 \times \alpha p_1 \times \alpha m_1 \quad (5\text{-}5\text{-}1)$$

Fig. 5-5.2.2-1 Sample Fogging System Design Curve for System Cooling Capability vs. Potential Cooling Level



GENERAL NOTES:
(a) Test objective 1 is to verify that the amount of cooling is consistent with the number of stages designed to be operating.
(b) The test presumes that if $T_{db1} - T_{db2}$ is less than design cooling, the system will continue to follow the design curve.

5-5.2.3 Measured Water Consumption, $m_{w1-2,meas.}$ Water consumption for a fogging system shall be determined as follows:

$$m_{w1-2,\text{meas}} = m_{w3} - m_{w4} \tag{5-5-2}$$

where

m_{w3} = water mass flow rate into the system at Plane 3
m_{w4} = water mass flow rate out of the system via drains at Plane 4

5-5.2.4 Corrected Water Consumption, $m_{w1-2,corr.}$ To be a meaningful test of the system, the system must be operated near the full system capacity (75% cooling or greater). If the system is tested at less than full cooling capacity, the system has the capability of injecting more water into the air than defined on the expected flow curve. Therefore, the design water flow versus degrees of cooling shall be verified to extrapolate the test results to the full system cooling capability. If more cooling zones or water flow are used at the partial system capacity, the full system flow may not provide the projected amount of cooling. Refer to Fig. 5-5.2.4-1 for a sample curve showing system water flow verses expected inlet air cooling.

If a more advanced control algorithm is used to control the amount of cooling, which may take inlet air temperature, barometric pressure, or other parameters into account, then the manufacturer shall provide correction factors to adjust measured water flow expected or guaranteed water flow rate using the corrections such as

αT_{db1} = multiplicative corrections for dry-bulb temperature at Plane 1
$\alpha\omega_1$ = multiplicative corrections for specific humidity at Plane 1
αp_1 = multiplicative corrections for inlet air pressure at Plane 1
αm_1 = multiplicative corrections for air mass flow at Plane 1

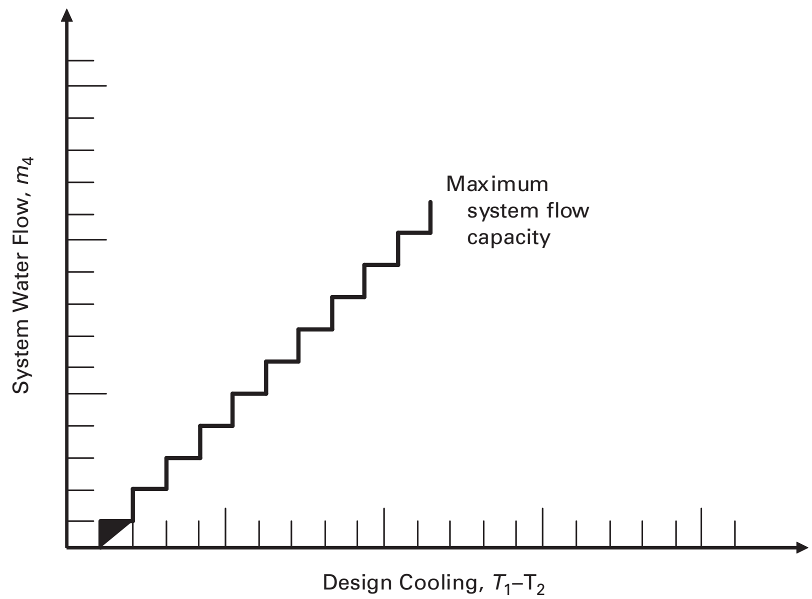
Therefore, the correction equation for fogger water consumption becomes:

$$m_{w1-2,\text{corr}} = m_{w1-2,\text{meas}} \times \alpha T_{db1} \times \alpha\omega_1 \times \alpha p_1 \times \alpha m_1 \tag{5-5-3}$$

5-5.2.5 Measured Fogger Performance Factor, $FPF_{meas.}$ The fogger performance factor is a measure of the how well the fogger functions in cooling and humidifying the air. The term "effectiveness" is not used here because of its definition being rooted in and associated with evaporative coolers. While effectiveness may be calculated for a fogging system, it will vary over time as ambient conditions change and the fogging control system adjusts spray flow accordingly.

Therefore, the term "fogging performance factor," or *FPF*, is used. The fogging performance factor relates the amount of water used to cool the inlet air to the target temperature, to the amount of water used to cool the air to saturation as defined in equations below.

Fig. 5-5.2.4-1 Sample Fogging System Design Curve for Water Flow vs. Expected Inlet Air Cooling



GENERAL NOTE: Test objective 2 is to ensure that the amount of water flow is consistent with design such that if an intermediate point is the test point, the system will not run of short of water at the design point.

$$FPF = \%\ \text{saturation cooling} / \%\ \text{saturation flow} \quad (5\text{-}5\text{-}4)$$

where

$$\%\ \text{saturation cooling} = (T_{db1} - T_{db2}) / (T_{db1} - T_{wb1}) \quad (5\text{-}5\text{-}5)$$

$$\%\ \text{saturation flow} = (m_{w3} - m_{w4}) / (m_{w2,sp}) \quad (5\text{-}5\text{-}6)$$

This results in

$$FPF_{meas} = [(T_{db1} - T_{db2}) \times (m_{w2,sp})] / [(T_{db1} - T_{wb1}) \times (m_{w3} - m_{w4})] \quad (5\text{-}5\text{-}7)$$

where

m_{w3} = water mass flow rate into the system at Plane 3
m_{w4} = water mass flow rate out of the system via drains at Plane 4
$m_{w2,sp}$ = theoretical water mass flow rate required to bring temperature at Plane 2 to set-point temperature
FPF_{meas} = fogging performance factor at measured conditions
T_{db1} = measured dry-bulb temperature at Plane 1
T_{db2} = measured dry-bulb temperature at Plane 2
T_{wb1} = measured wet-bulb temperature at Plane 1

and

$$m_{w2,sp} = m_{da1} \times (\omega_{2,sp} - \omega_1) \quad (5\text{-}5\text{-}8)$$

where

m_{da1} = mass flow rate of dry air at Plane 1
ω_1 = specific humidity at Plane 1
$\omega_{2,sp}$ = specific humidity at Plane 2, once set point has been reached

NOTE: For systems controlled to the entering wet-bulb temperature, T_{wb1}, the mass flow required to reach the set point will be equal to the mass flow required for saturation, or $m_{w2,sp} = m_{2,sat}$.

A fogger performance factor, FPF, of 1.0 would indicate that the actual water input into the air would all be evaporated and the air temperature would be reduced to the saturated or set-point temperature. There would be no drain flow and no carryover. However, in practical systems, this will not normally be the case. For example, for a system that is controlled to cool the system to the inlet wet-bulb temperature, T_{wb1}, saturation cooling is 100%. But the measured water flow rate required to cool the airflow to T_{wb1} is 10% more than theoretically calculated to produce that cooling. Then saturation flow = 110%. For this example

$$FPF = 1.0/1.1 \times 100 = 90.5\%$$

5-5.2.6 Corrected Fogger Performance Factor, $FPF_{corr.}$ To determine the fogging performance factor, FPF, corrected to base reference conditions, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for inlet air pressure at Plane 1
αm_1 = multiplicative corrections for air mass flow at Plane 1

$\alpha\omega_1$ = multiplicative corrections for specific humidity at Plane 1

Therefore, the correction equation for fogging performance factor becomes

$$FPF_{\text{corr}} = FPF_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha\omega_1 \quad (5\text{-}5\text{-}9)$$

5-5.2.7 Carryover Flow. The measured water consumption can be compared to the water consumption theoretically required (either for 100% saturation or saturation to set-point temperature, as determined above) to determine carryover. Carryover is in the form of water droplets at Plane 2, which have no expectation of being evaporated prior to being ingested by the compressor. The carryover flow rate is calculated as follows:

$$m_{co,\text{meas}} = m_{w3} - m_{w2} - m_{w4} \quad (5\text{-}5\text{-}10)$$

where

$m_{co,meas}$ = measured mass of water not evaporated, but carried over into the GT compressor inlet (Plane 2)

m_{w2} = water mass flow rate at Plane 2

m_{w3} = water mass flow rate into the system at Plane 3

m_{w4} = water mass flow rate leaving system at Plane 4

5-5.2.8 Corrected Carryover Flow. To determine carryover flow for a fogger system, corrected to base reference conditions, the following correction factors apply:

αT_{db1} = multiplicative corrections for dry-bulb temperature at Plane 1

αp_1 = multiplicative corrections for inlet air pressure at Plane 1

αm_1 = multiplicative corrections for air mass flow at Plane 1

$\alpha\omega_1$ = multiplicative corrections for specific humidity at Plane 1

αm_4 = multiplicative corrections for water mass drain flow at Plane 4

Therefore, the correction equation for fogger carryover becomes

$$m_{co,\text{corr}} = m_{co,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha\omega_1 \times \alpha m_4 \quad (5\text{-}5\text{-}11)$$

5-6 INLET COOLING USING CHILLERS (MULTIPLE ARRANGEMENTS)

Subsection 5-6 applies to chilling systems that are designed to extract heat from the GT inlet air stream with no mass transfer at the gas turbine inlet via thermal or electrical means. An example would be homogenous chilling fluid channeled through a set of coils in the inlet system that extracts heat from the GT inlet air, but no mixing of the chilling fluid and the GT inlet air occurs.

However, other parts of the chilling system may involve secondary heat and mass transfer ("secondary" in that the primary heat transfer is considered to be with the gas turbine inlet air stream, for the purposes of this Code), such as with a cooling tower or secondary heat exchanger. Using the inlet coil example described in the previous paragraph, the working fluid passing through the coils may or may not subsequently be passed through a secondary heat dump (e.g., a heat exchanger or cooling tower) where heat and mass transfer may occur.

When verifying the performance of such a system, it may be necessary or desirable to verify the performance of the system with respect to different test boundaries. Examples may include differing scopes of supply, a desire to verify the performance of the individual components or subsystems within the chiller, etc.

Therefore, subsection 5-6 provides the calculation methodology for multiple test boundary and test goal configurations for a closed-loop inlet chilling system. The specific test boundary cases to be addressed are defined as

- chiller inlet air coil loop
- primary cooling loop
- primary cooling and chiller loops
- entire chilling system

The discussion for each of these four test boundary cases begins with a diagram defining the test boundary, the streams crossing the test boundary, and the plane for each of those streams. Methods for determining the test goals follow the test boundary diagrams.

Paragraph 5-6.1 is devoted to calculating common parameters for chiller systems. The individual test boundary discussions follow these common calculations.

5-6.1 Calculation of Common Parameters and Intermediate Results for Inlet Cooling by Closed Coils (Mechanical/Thermal Refrigeration Systems)

5-6.1.1 Calculated Coil Net Heat Load. The heat load on the inlet air-conditioning coil can be determined by the heat balance on the working-fluid side of the coils and by the heat balance on the inlet air side of the coils. Both methods should be used to reduce the uncertainty of the final calculated coil heat load.

5-6.1.2 Heat Balance on Working-Fluid Side. The coil heat load can be determined by heat balance on the working fluid as follows:

$$q_{4-3} = m_{f3} \cdot \left(h_{f4} - h_{f3}\right) \quad (5\text{-}6\text{-}1)$$

where

h_{f3} = the enthalpy of the working fluid at Plane 3, kJ/kg (Btu/lb)

h_{f4} = the enthalpy of the working fluid at Plane 4, kJ/kg (Btu/lb)

m_{f3} = the mass flow rate of the working fluid entering the coil (Plane 3), kg/h (lb/hr)

q_{4-3} = the heat load on the coil based on the energy change from Plane 3 (working fluid inlet) to Plane 4 (working fluid outlet or return), kJ/h (Btu/hr)

5-6.1.3 Heat Balance on Inlet Air Side. The coil net heat load can also be determined by heat balance on the inlet air side of the coil as follows:

$$q_{2-1} = m_{da1} \cdot (h_{da2} - h_{da1}) + m_{w-vap,2} h_{w-vap,2} - m_{w-vap,1} h_{w-vap,1} + m_{w-liq,6} h_{w-liq,6} \quad (5\text{-}6\text{-}2)$$

where

q_{2-1} = the heat load on the coil based on energy change in the airflow entering the air-conditioning system (Plane 1), to the airflow delivered to the gas turbine compressor inlet (Plane 2), kJ/h (Btu/hr)

h_{da1} = the enthalpy of the dry air at Plane 1, kJ/kg (Btu/lb)

h_{da2} = the enthalpy of the dry air at Plane 2, kJ/kg (Btu/lb)

$h_{w\text{-}liq,6}$ = the enthalpy of the water as a liquid at Plane 6, kJ/kg (Btu/lb)

$h_{w\text{-}vap,1}$ = the enthalpy of the water as a vapor at Plane 1, kJ/kg (Btu/lb)

$h_{w\text{-}vap,2}$ = the enthalpy of the water as a vapor at Plane 2, kJ/kg (Btu/lb)

m_{da1} = the mass flow rate of the dry air at Plane 1, kg/h (lb/hr)

$m_{w\text{-}liq,6}$ = the mass flow rate of water leaving the system in liquid form, via the condensate drains (Plane 6), kg/h (lb/hr)

$m_{w\text{-}vap,1}$ = the mass flow rate of water vapor at Plane 1, kg/h (lb/hr)

$m_{w\text{-}vap,2}$ = the mass flow rate of water vapor at Plane 2, kg/h (lb/hr)

5-6.1.4 Chiller Heat Load. The chiller heat load (gross load) is similar to the coil heat load, using temperatures measured at the chiller inlet and outlet instead of temperatures local to the coil itself.

$$q_{4-3,gross} = m_{f3} \cdot \left(h_{f4'} - h_{f3'}\right) \quad (5\text{-}6\text{-}3)$$

where

$h_{f3'}$ = the enthalpy of the working fluid exiting the chiller at Plane 3, kJ/kg (Btu/lb)

$h_{f4'}$ = the enthalpy of the working fluid returning to the chiller at Plane 4, kJ/kg (Btu/lb)

m_{f3} = the mass flow rate of the working fluid exiting the chiller at Plane 3, kg/h (lb/hr)

$q_{4-3,\text{gross}}$ = the heat load at the chiller based on the energy change from Plane 3 to Plane 4, kJ/h (Btu/hr)

The prime (′) on the plane identifiers indicates that the temperature basis for the enthalpies is measured as close to the supply and return lines of the chiller package as possible. This is in contrast to the net heat load, which is based on temperatures measured as close to the coil as possible.

5-6.2 Chiller Inlet Air Coil Loop

5-6.2.1 Test Boundary for Chiller Inlet Air Coil Loop. Figure 5-6.2.1-1 shows the test boundary for the chiller inlet air coil loop. The assumption is that the coil piping is carrying the primary working fluid (coolant) for heat transfer with the GT inlet air. This test boundary includes only that part of the chiller system that directly contacts (and cools) the GT inlet air.

5-6.2.2 Test Goals. Subsections 5-1 through 5-3 should be reviewed prior to the use of para. 5-6.2. The most common test goals for closed-coil cooling are decribed in paras. 5-6.2.2.1 through 5-6.2.2.12.

5-6.2.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured dry-bulb temperature at Plane 2 is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the chiller inlet air coil (Plane 2).

5-6.2.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,corr.}$ The measured temperature of the air leaving the coil that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine corrected exit coil temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αX_{f3} = multiplicative correction for working-fluid composition at Plane 3

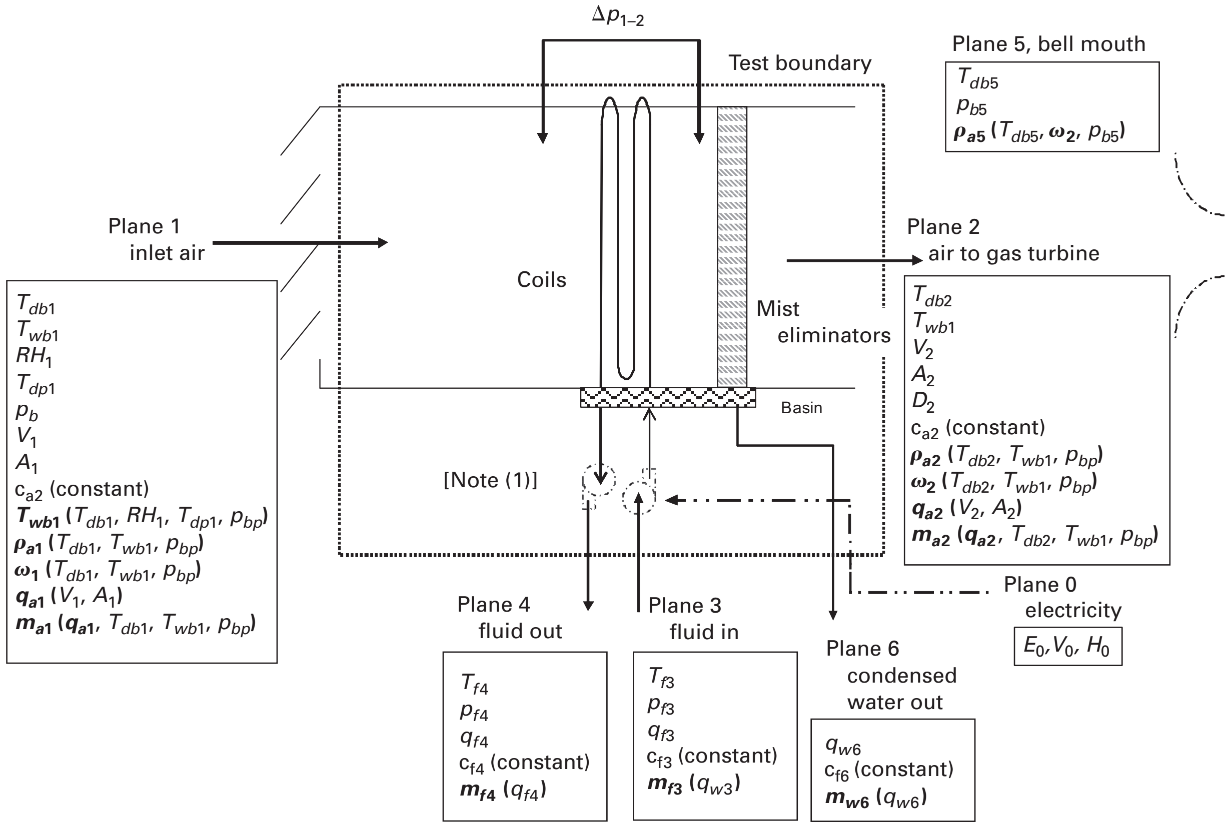
αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation for coil exit temperature becomes

$$T_{db2,\text{corr}} = T_{db2,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha T_{f3} \times \alpha X_{f3} \times \alpha m_{f3} \quad (5\text{-}6\text{-}4)$$

5-6.2.2.3 Measured Temperature Difference, $\Delta T_{2-1,meas.}$ The measured air temperature difference across the coil (Plane 1 to Plane 2) is determined following the guidelines provided in this Code. The measured

Fig. 5-6.2.1-1 Inlet Chiller Test Boundary Diagram: Coils Only



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

NOTE:
(1) Pump(s) may or may not be included with the coils.

air temperature difference is the bulk average temperature difference across the chiller inlet air coil.

5-6.2.2.4 Corrected Temperature Difference, $\Delta T_{2-1,corr.}$ For corrected temperature difference across the chiller inlet air coil, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αX_1 = multiplicative correction for air composition Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3
αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3
αX_{f3} = multiplicative correction for working-fluid composition at Plane 3

Therefore, the correction equation becomes:

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha X_3 \quad (5\text{-}6\text{-}5)$$

5-6.2.2.5 Measured Pressure Drop, $\Delta p_{2-1,meas.}$ The measured pressure drop of the air across the chiller inlet air coil (Plane 1 to Plane 2) is determined following the guidelines provided in this Code. The measured air pressure drop across the chiller inlet air coil is the bulk average air pressure difference across the chiller inlet air coil.

5-6.2.2.6 Corrected Pressure Drop, $\Delta p_{2-1,corr.}$ For the corrected air pressure drop, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation becomes

$$\Delta p_{2-1,\text{corr}} = \Delta p_{2-1,\text{meas}} \times \alpha m_1 \times \alpha m_{f3} \qquad (5\text{-}6\text{-}6)$$

5-6.2.2.7 Measured Temperature Difference, $\Delta T_{4-3,\text{meas}}$, of the Primary Working Fluid. The measured primary working-fluid temperature difference across the chiller inlet air coil (Plane 4 to Plane 3) is determined following the guidelines provided in this Code. The measured primary working-fluid temperature difference is the bulk average primary working-fluid temperature difference across the chiller inlet air coil.

5-6.2.2.8 Corrected Temperature Difference, $\Delta T_{4-3,\text{corr}}$, of the Primary Working Fluid. For the corrected temperature difference of the primary working fluid, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_3 = multiplicative correction for working-fluid pressure at Plane 3

αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

αX_3 = multiplicative correction for working-fluid composition at Plane 3

Therefore, the correction equation becomes

$$\Delta T_{4-3,\text{corr}} = \Delta T_{4-3,\text{meas}} \times \alpha T_1 \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_3 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha X_3 \qquad (5\text{-}6\text{-}7)$$

5-6.2.2.9 Measured Pressure Drop, $\Delta p_{4-3,\text{meas}}$, of the Primary Working Fluid. The measured pressure drop of the primary working-fluid across the chiller inlet air coil (Plane 4 to Plane 3) is determined following the guidelines provided in this Code. The measured primary working-fluid pressure drop across the chiller inlet air coil is the bulk average primary working-fluid pressure difference across the chiller inlet air coil.

5-6.2.2.10 Corrected Pressure Drop, $\Delta p_{4-3,\text{corr}}$, of the Primary Working Fluid. For corrected primary working-fluid pressure drop, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αX_3 = primary working-fluid composition correction to primary working-fluid temperature difference at Plane 3

αm_{f3} = primary working-fluid mass flow correction to primary working-fluid temperature difference at Plane 3

Therefore, the correction equation becomes

$$\Delta p_{4-3,\text{corr}} = \Delta p_{4-3,\text{meas}} \times \alpha m_1 \times \alpha X_3 \times \alpha m_{f3} \qquad (5\text{-}6\text{-}8)$$

5-6.2.2.11 Measured Efficiency, η_{meas}, and Load, q_{meas}, of the Chiller Inlet Air Coil. The measured efficiency and load of the chiller inlet air coil are determined following the guidelines provided previously in this Code. The measured efficiency and load of the chiller inlet air coil are taken from the bulk average parameters across the chiller inlet air coil. The measured efficiency of the chiller inlet air coil is calculated as follows:

$$\eta_{\text{meas}} = (T_{db,1} - T_{db,2}) / (T_{db,1} - T_{f3}) \qquad (5\text{-}6\text{-}9)$$

5-6.2.2.12 Corrected Efficiency, η_{corr}, and Load, q_{corr}, of the Chiller Inlet Air Coil. For corrected chiller efficiency or load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet bulb temperature at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_2 = multiplicative correction for barometric pressure at Plane 2

αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation for efficiency becomes

$$\eta_{\text{corr}} = \eta_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \qquad (5\text{-}6\text{-}10)$$

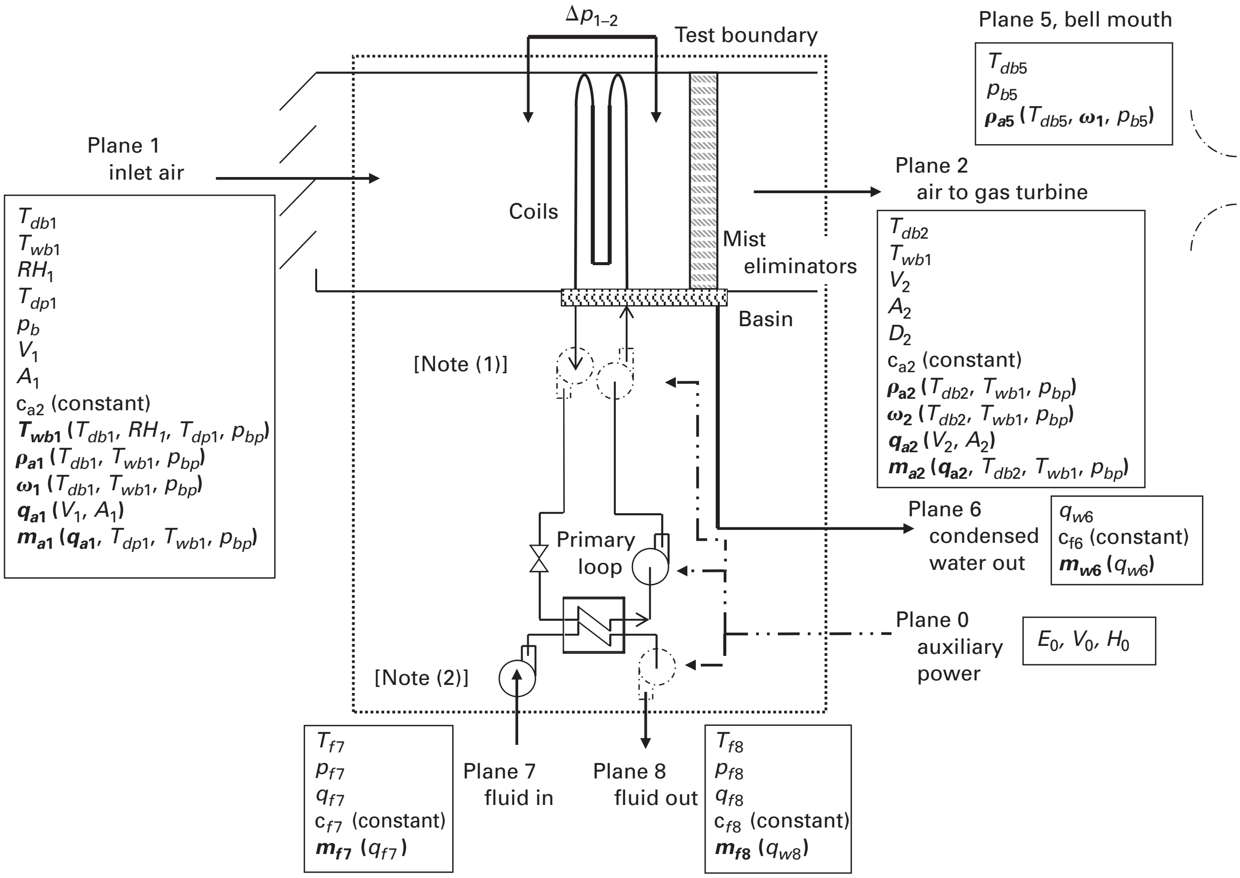
and the correction equation for load becomes

$$q_{\text{corr}} = q_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \qquad (5\text{-}6\text{-}11)$$

5-6.3 Chiller Primary Cooling Loop

5-6.3.1 Test Boundary for the Chiller Primary Cooling Loop. Figure 5-6.3.1-1 shows the test boundary for the chiller primary cooling loop. This test boundary includes

Fig. 5-6.3.1-1 Inlet Chiller Test Boundary Diagram: Coils and Primary Cooling Loop



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

NOTES:
(1) Pump(s) may or may not be included with the coils.
(2) Pump(s) may or may not be included on heat exchanger intake (Plane 7) and/or discharge (Plane 8).

the mechanical equipment associated with the movement of the primary working fluid (coolant) between its primary heat sink and the GT inlet air, in addition to the scope included in the chiller inlet air coil loop, as described in para. 5-6.2. In this case, Planes 7 and 8 refer to the secondary working fluid — which cools the primary working fluid (coolant) — as the primary working fluid is entirely contained within, and does not cross, this test boundary.

The assumptions are that the secondary fluid is sent through piping for heat transfer with the primary working fluid (coolant), and that the GT inlet air is exchanging heat with the chiller inlet air coil (containing the primary working fluid).

5-6.3.2 Test Goals. Subsections 5-1 through 5-3 should be reviewed prior to the use of para. 5-6.3.

5-6.3.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured air dry-bulb temperature at Plane 2 is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the chiller inlet air coil (Plane 2).

5-6.3.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,corr.}$ The measured temperature of the air leaving the test boundary that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine the corrected exit temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f7} = multiplicative correction for working-fluid temperature at Plane 7
αX_{f7} = multiplicative correction for working-fluid composition at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7

Therefore, the correction equation becomes

$$T_{db2,\text{corr}} = T_{db2,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha T_{f7} \times \alpha X_{f7} \times \alpha m_{f7} \quad (5\text{-}6\text{-}12)$$

5-6.3.2.3 Measured Temperature Difference, $\Delta T_{2-1,\text{meas.}}$ The measured temperature difference of the GT inlet air across the primary cooling loop (Plane 2 to Plane 1) is determined following the guidelines provided in this Code. The measured air temperature difference is the bulk average temperature difference across the primary cooling loop.

5-6.3.2.4 Corrected Temperature Difference, $\Delta T_{2-1,\text{corr.}}$ For the corrected temperature difference of the GT inlet air, the following correction factors apply:

αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f7} = multiplicative correction for working-fluid temperature at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7
αX_7 = multiplicative correction for working-fluid composition at Plane 7

Therefore, the correction equation becomes

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f7} \times \alpha m_{f7} \times \alpha X_7 \quad (5\text{-}6\text{-}13)$$

5-6.3.2.5 Measured Pressure Drop, $\Delta p_{2-1,\text{meas.}}$ The measured pressure drop of the GT inlet air across the primary cooling loop (Plane 1 to Plane 2) is determined following the guidelines provided in this Code. The measured pressure drop of the GT inlet air across the primary cooling loop is the bulk average GT inlet air pressure difference across the primary cooling loop.

5-6.3.2.6 Corrected Pressure Drop, $\Delta p_{2-1,\text{corr.}}$ For the corrected pressure drop of the GT inlet air, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7

Therefore, the correction equation becomes

$$\Delta p_{2-1,\text{corr}} = \Delta p_{2-1,\text{meas}} \times \alpha m_1 \times \alpha m_{f7} \quad (5\text{-}6\text{-}14)$$

5-6.3.2.7 Measured Temperature Difference, $\Delta T_{8-7,\text{meas,}}$ of the Secondary Working Fluid. The measured temperature difference of the secondary working fluid across the primary cooling loop (Plane 8 to Plane 7) is determined following the guidelines provided in this Code. The measured secondary working-fluid temperature difference is the bulk average secondary working-fluid temperature difference across the primary cooling loop.

5-6.3.2.8 Corrected Temperature Difference, $\Delta T_{8-7,\text{corr,}}$ of the Secondary Working Fluid. For the corrected temperature difference of the secondary working fluid, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_7 = multiplicative correction for working-fluid pressure at Plane 7
αT_{f7} = multiplicative correction for working-fluid temperature at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7
αX_7 = multiplicative correction for working fluid composition at Plane 7

Therefore, the correction equation becomes

$$\Delta T_{8-7,\text{corr}} = \Delta T_{8-7,\text{meas}} \times \alpha T_1 \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_7 \times \alpha T_{f7} \times \alpha m_{f7} \times \alpha X_7 \quad (5\text{-}6\text{-}15)$$

5-6.3.2.9 Measured Pressure Drop, $\Delta p_{8-7,\text{meas,}}$ of the Secondary Working Fluid. The measured pressure drop of the secondary working fluid across the primary cooling loop (Plane 8 to Plane 7) is determined following the guidelines provided in this Code. The measured secondary working-fluid pressure drop across the primary cooling loop is the bulk average secondary working-fluid pressure difference across the primary cooling loop.

5-6.3.2.10 Corrected Pressure Drop, $\Delta p_{8-7,\text{corr,}}$ of the Secondary Working Fluid. For the corrected pressure drop of the secondary working fluid, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1
αX_7 = multiplicative correction for working-fluid composition at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7

Therefore, the correction equation becomes

$$\Delta p_{8-7,\text{corr}} = \Delta p_{8-7,\text{meas}} \times \alpha m_1 \times \alpha X_7 \times \alpha m_{f7} \quad (5\text{-}6\text{-}16)$$

5-6.3.2.11 Measured Efficiency/Load, η_{meas} / q_{meas} Inlet Primary Cooling Loop. The measured primary cooling loop load (Plane 2 to Plane 1 or Plane 4 to Plane 3) is determined following the guidelines provided in this Code. The measured primary cooling loop efficiency and load are taken from the bulk average parameters across the primary cooling loop. The measured primary cooling loop efficiency is determined from the following:

$$\eta_{\text{meas}} = (T_{db,1} - T_{db,2}) \,/\, (T_{db,1} - T_{f7}) \quad (5\text{-}6\text{-}17)$$

5-6.3.2.12 Corrected Inlet Primary Cooling Loop Efficiency/Load (η_{corr} / q_{corr}). For the corrected chiller efficiency/load of the primary cooling loop, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f7} = multiplicative correction for working-fluid temperature at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7
αX_7 = multiplicative correction for working fluid composition at Plane 7

Therefore, the correction equation for efficiency becomes

$$\eta_{\text{corr}} = \eta_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f7} \times \alpha m_{f7} \times \alpha X_7 \quad (5\text{-}6\text{-}18)$$

and the correction equation for load becomes

$$q_{\text{corr}} = q_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f7} \times \alpha m_{f7} \times \alpha X_7 \quad (5\text{-}6\text{-}19)$$

5-6.3.2.13 Measured Auxiliary Load, $AUX_{0,meas.}$ The measured auxiliary load of the primary cooling loop (Plane 0) is determined following the guidelines provided in this Code. The measured primary cooling loop auxiliary load is the auxiliary load across the primary cooling loop.

5.6.3.2.14 Corrected Auxiliary Load, $AUX_{0,corr.}$ For the corrected primary cooling loop auxiliary load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f7} = multiplicative correction for working-fluid temperature at Plane 7
αm_{f7} = multiplicative correction for working-fluid mass flow rate at Plane 7

Therefore, the correction equation becomes

$$AUX_{0,\text{corr}} = AUX_{0,\text{meas}} \times \alpha m_1 \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha m_{f7} \times \alpha T_7 \quad (5\text{-}6\text{-}20)$$

5-6.4 Primary Cooling + Chiller Loop

5-6.4.1 Test Boundary for the Primary Cooling + Chiller Loop. Figure 5-6.4.1-1 shows the test boundary for the primary cooling + chiller loop. This test boundary includes the chiller and its associated equipment, including secondary heat exchanger(s), as well as the equipment included in the scope of both the chiller inlet air coil loop and the primary cooling loop, as described in paras. 5-6.2 and 5-6.3, respectively. In this case, Planes 9 and 10 refer to the heat rejection fluid — which cools the secondary working fluid — as both the secondary working fluid and the primary working fluid are entirely contained within (and do not cross) this test boundary. The assumptions are that the fluid is sent through piping for heat transfer with the secondary working fluid, and that the GT inlet air is exchanging heat with the chiller inlet air coil (containing the primary working fluid).

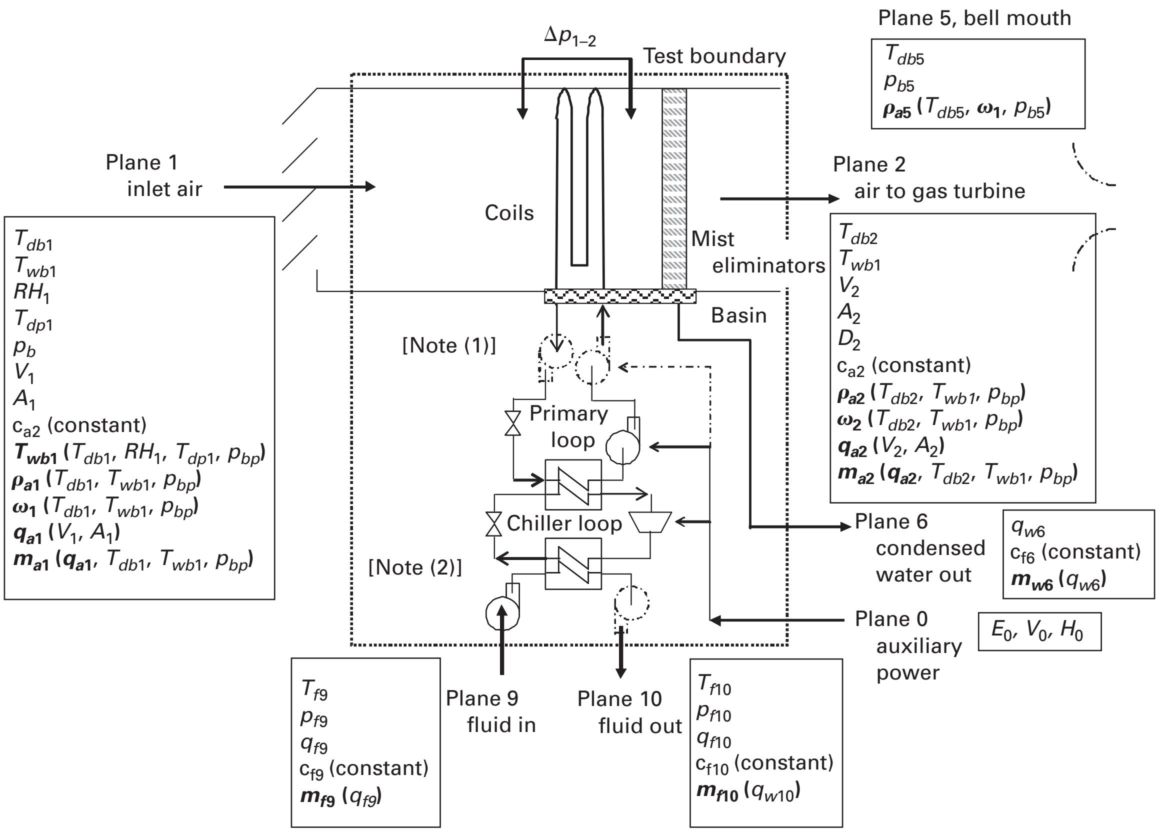
5-6.4.2 Test Goals. Subsections 5-1 through 5-3 should be reviewed prior to the use of para. 5-6.4.

5-6.4.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured dry-bulb temperature of the air at Plane 2 is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the primary cooling + chilling loop.

5-6.4.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured temperature of the air leaving the test boundary that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine the corrected exit temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f9} = multiplicative correction for working-fluid temperature at Plane 9

Fig. 5-6.4.1-1 Inlet Chiller Test Boundary Diagram: Coils, Primary Cooling Loop, and Chiller Loop



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

NOTES:
(1) Pump(s) may or may not be included with the coils.
(2) Pump(s) may or may not be included on heat exchanger intake (Plane 9) and/or discharge (Plane 10).

αX_{f9} = multiplicative correction for working-fluid composition at Plane 9
αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

Therefore, the correction equation becomes

$$T_{db2,\text{corr}} = T_{db2,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha T_{f9} \times \alpha X_{f9} \times \alpha m_{f9} \quad (5\text{-}6\text{-}21)$$

5-6.4.2.3 Measured Temperature Difference, $\Delta T_{2-1,\text{meas.}}$ The measured temperature difference of the GT inlet air across the primary cooling + chilling loop (Plane 2 to Plane 1) is determined following the guidelines provided in this Code. The measured air temperature difference is the bulk average temperature difference across the primary cooling + chilling loop.

5-6.4.2.4 Corrected Temperature Difference, $\Delta T_{2-1,\text{corr.}}$ For the corrected temperature difference of the GT inlet air, the following correction factors apply:

αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f9} = multiplicative correction for working-fluid temperature at Plane 9
αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9
αX_9 = multiplicative correction for working-fluid composition at Plane 9

Therefore, the correction equation becomes

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f9} \times \alpha m_{f9} \times \alpha X_9 \quad (5\text{-}6\text{-}22)$$

5-6.4.2.5 Measured Pressure Drop, $\Delta p_{2-1,\text{meas.}}$ The measured pressure drop of the GT inlet air across the primary cooling and chilling loop (Plane 1 to Plane 2) is determined following the guidelines provided in this Code. The measured GT inlet air pressure drop across the primary cooling and chilling loop is the bulk average GT inlet air pressure difference across the primary cooling and chilling loop.

5-6.4.2.6 Corrected Pressure Drop, $\Delta p_{2-1,corr.}$ For the corrected GT inlet air pressure drop, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

Therefore, the correction equation becomes

$$\Delta p_{2-1,\mathrm{corr}} = \Delta p_{2-1,\mathrm{meas}} \times \alpha m_1 \times \alpha m_{f9} \qquad (5\text{-}6\text{-}23)$$

5-6.4.2.7 Measured Temperature Difference of the Heat-Rejection Fluid, $\Delta T_{10-9,meas.}$ The measured temperature difference of the heat-rejection fluid across the primary cooling + chilling loop (Plane 10 to Plane 9) is determined following the guidelines provided in this Code. The measured heat-rejection fluid temperature difference is the bulk average heat-rejection fluid temperature difference across the primary cooling + chilling loop.

5-6.4.2.8 Corrected Temperature Difference of the Heat-Rejection Fluid, $\Delta T_{10-9,corr.}$ For the corrected temperature difference of the heat-rejection fluid, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_9 = multiplicative correction for working-fluid pressure at Plane 9

αT_{f9} = multiplicative correction for working-fluid temperature at Plane 9

αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

αX_9 = multiplicative correction for working-fluid composition at Plane 9

Therefore, the correction equation becomes

$$\Delta T_{10-9,\mathrm{corr}} = \Delta T_{10-9,\mathrm{meas}} \times \alpha T_1 \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_9 \times \alpha T_{f9} \times \alpha m_{f9} \times \alpha X_9 \qquad (5\text{-}6\text{-}24)$$

5-6.4.2.9 Measured Pressure Drop, of the Heat-Rejection Fluid, $\Delta p_{10-9,meas.}$ The measured pressure drop of the heat-rejection fluid across the primary cooling + chilling loop (Plane 10 to Plane 9) is determined following the guidelines provided in this Code. The measured heat-rejection fluid pressure drop across the primary cooling + chilling loop is the bulk average heat-rejection fluid pressure difference across the primary cooling + chilling loop.

5-6.4.2.10 Corrected Pressure Drop of the Heat-Rejection Fluid, $\Delta p_{10-9,corr.}$ For the corrected pressure drop of the heat-rejection fluid, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αX_9 = multiplicative correction for working-fluid composition at Plane 9

αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

Therefore, the correction equation becomes

$$\Delta p_{10-9,\mathrm{corr}} = \Delta p_{10-9,\mathrm{meas}} \times \alpha m_1 \times \alpha X_9 \times \alpha m_{f9} \qquad (5\text{-}6\text{-}25)$$

5-6.4.2.11 Measured Efficiency, $\eta_{meas,}$ and/or Load, $q_{meas,}$ of the Inlet Primary Cooling + Chilling Loop. The measured chilling loop load (Plane 4 to Plane 3) is determined following the guidelines provided previously in this Code. The measured efficiency and/or load of the primary cooling + chilling loop are taken from the bulk average parameters across the primary cooling + chilling loop. The measured efficiency of the primary cooling + chilling loop is determined as follows:

$$\eta_{\mathrm{meas}} = [AUX_0 + m_{f9} \times C_{p,9-10} \times (T_{f10} - T_{f9})] \,/\, q_{4-3} \qquad (5\text{-}6\text{-}26)$$

5-6.4.2.12 Corrected Efficiency, $\eta_{corr,}$ and/or Load, $q_{corr,}$ of the Inlet Primary Cooling + Chilling Loop. For the corrected chiller efficiency or load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_2 = multiplicative correction for barometric pressure at Plane 2

αT_{f9} = multiplicative correction for working-fluid temperature at Plane 9

αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

αX_9 = multiplicative correction for working-fluid composition at Plane 9

Therefore, the correction equation for efficiency becomes

$$\eta_{corr} = \eta_{meas} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f9} \times \alpha m_{f9} \times \alpha X_9 \quad (5\text{-}6\text{-}27)$$

and the correction equation for load becomes

$$q_{corr} = q_{meas} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f9} \times \alpha m_{f9} \times \alpha X_9 \quad (5\text{-}6\text{-}28)$$

5-6.4.2.13 Measured Auxiliary Load, $AUX_{0,meas.}$ The measured auxiliary load (Plane 0) of the primary cooling + chilling loop is determined following the guidelines provided in this Code. The measured primary cooling + chilling loop auxiliary load is the auxiliary load across the primary cooling + chilling loop.

5-6.4.2.14 Corrected Auxiliary Load, $AUX_{0,corr.}$ For corrected auxiliary load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f9} = multiplicative correction for working-fluid temperature at Plane 9
αm_{f9} = multiplicative correction for working-fluid mass flow rate at Plane 9

Therefore, the correction equation becomes:

$$AUX_{0,corr} = AUX_{0,meas} \times \alpha m_1 \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha m_{f9} \times \alpha T_9 \quad (5\text{-}6\text{-}29)$$

5-6.5 Entire Chilling System

5-6.5.1 Test Boundary for the Entire Chilling System. Figure 5-6.5.1-1 shows an example test boundary for a chiller system. This test boundary includes the equipment associated with the chiller [including secondary heat exchanger(s)], as well as equipment included in the scope of the chiller inlet air coil loop, the primary cooling loop, and the primary cooling and chilling coil loop, as described in paras. 5.6.2, 5.6.3, and 5.6.4, respectively. In this case, Planes 11 and 12 refer to the cooling fluid for the heat-rejection loop (e.g., seawater or cooling-tower cooling air). The heat-rejection fluid, secondary working fluid, and primary working fluid are all entirely contained within (and do not cross) this test boundary. The assumptions are that the cooling fluid is sent through a heat exchanger (such as a cooling tower) for heat transfer with the heat-rejection fluid, and that the GT inlet air is exchanging heat with the chiller inlet air coil (containing the primary working fluid).

5-6.5.2 Test Goals. Subsections 5-1 through 5-3 should be reviewed prior to the use of para. 5-6.5.

5-6.5.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured dry-bulb temperature at the exit of the test boundary (Plane 2) is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the entire chilling system.

5-6.5.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,corr.}$ Measured dry-bulb temperature at the exit of the test boundary (Plane 2) that is corrected to base reference conditions is commonly known as "corrected exit dry-bulb temperature." To determine the corrected exit dry-bulb temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f11} = multiplicative correction for working-fluid temperature at Plane 11
αX_{f11} = multiplicative correction for working-fluid composition at Plane 11
αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11

Therefore, the correction equation becomes

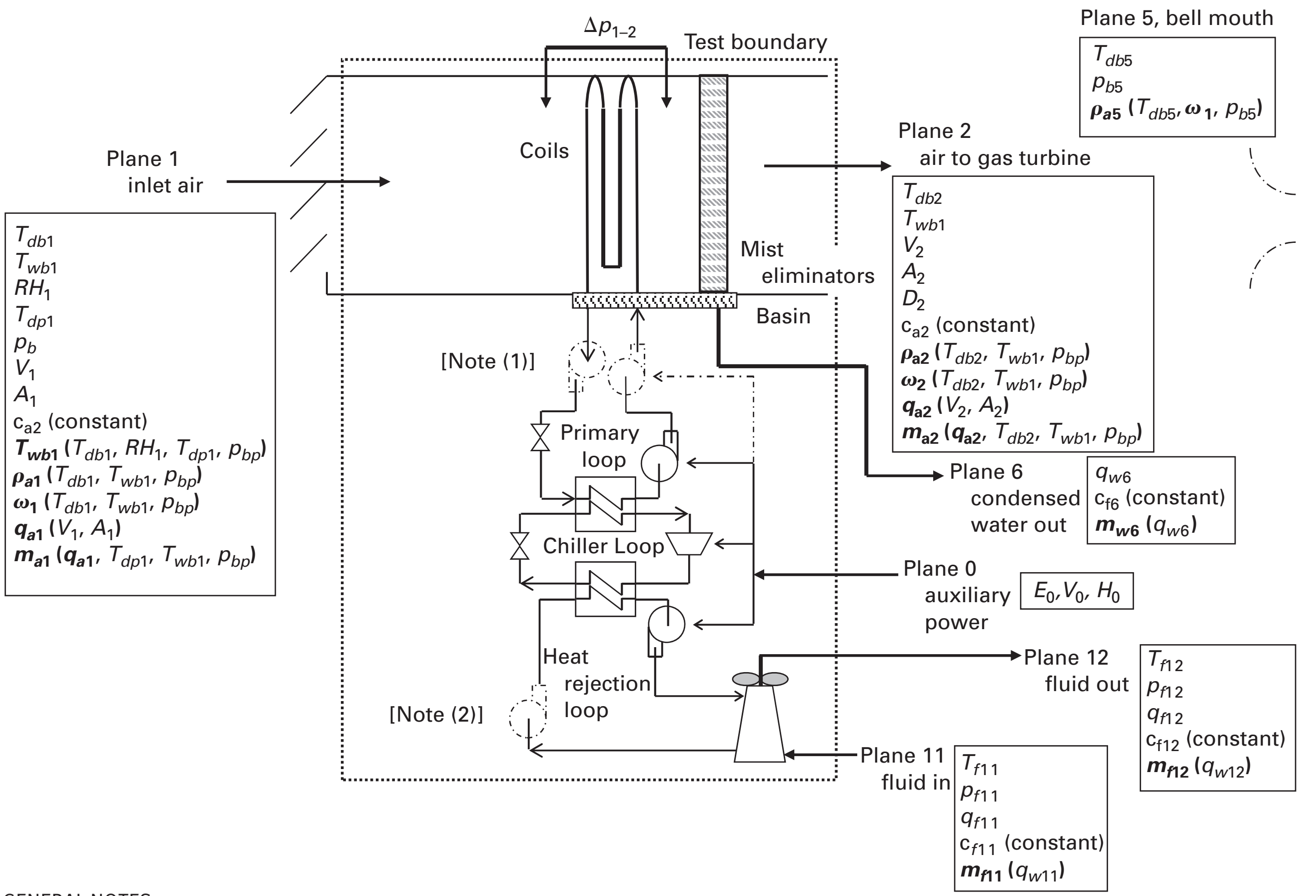
$$T_{db2,corr} = T_{db2,meas} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha T_{f11} \times \alpha X_{f11} \times \alpha m_{f11} \quad (5\text{-}6\text{-}30)$$

5-6.5.2.3 Measured Temperature Difference, $\Delta T_{2-1,meas.}$ The measured temperature difference of the GT inlet air across the entire chilling system (Plane 2 to Plane 1) is determined following the guidelines provided in this Code. The measured air temperature difference is the bulk average temperature difference across the entire chilling system.

5.6.5.2.4 Corrected Temperature Difference ($\Delta T_{2-1,corr}$). Measured temperature difference across the chilling system (Plane 2 − Plane 1) that is corrected to base reference conditions is commonly known as the "corrected system temperature difference." To determine the corrected system temperature difference, the following correction factors may apply:

αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2

Figure 5-6.5.1-1 Inlet Chiller Test Boundary Diagram: Entire Chiller System



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

NOTES:
(1) Pump(s) may or may not be included with the coils.
(2) Pump(s) may or may not be included on heat exchanger intake (Plane 11) and/or discharge (Plane 12), and there may be no cooling tower.

αT_{f11} = multiplicative correction for working-fluid temperature at Plane 11

αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11

αX_{11} = multiplicative correction for working-fluid composition at Plane 11

Therefore, the correction equation becomes

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f11} \times \alpha \text{m}_{f11} \times \alpha X_{11} \quad (5\text{-}6\text{-}31)$$

5-6.5.2.5 Measured Pressure Drop, $\Delta p_{2-1,\text{meas.}}$ The measured pressure drop of the GT inlet air across the entire chilling system (Plane 1 to Plane 2) is determined following the guidelines provided in this Code. The measured air pressure drop of the GT inlet across the entire chilling system is the bulk average GT inlet air pressure difference across the entire chilling system.

5-6.5.2.6 Corrected Pressure Drop, $\Delta p_{2-1,\text{corr.}}$ For the corrected pressure drop of the GT inlet air, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11

Therefore, the correction equation becomes

$$\Delta p_{2-1,\text{corr}} = \Delta p_{2-1,\text{meas}} \times \alpha m_1 \times \alpha m_{f11} \quad (5\text{-}6\text{-}32)$$

5-6.5.2.7 Measured Temperature Difference of the Cooling Fluid, $\Delta T_{12-11,\text{meas.}}$ The measured temperature difference of the cooling fluid across the entire chilling system (Plane 12 to Plane 11) is determined following the guidelines provided in this Code. The measured cooling-fluid temperature difference is the bulk average temperature difference across the entire chilling system.

5-6.5.2.8 Corrected Cooling Fluid Temperature Difference, $\Delta T_{12-11,corr.}$ For the corrected cooling-fluid temperature difference, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_{11} = multiplicative correction for working-fluid pressure at Plane 11
αT_{f11} = multiplicative correction for working-fluid temperature at Plane 11
αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11
αX_{11} = multiplicative correction for working-fluid composition at Plane 11

Therefore, the correction equation becomes

$$\Delta T_{12-11,\text{corr}} = \Delta T_{12-11,\text{meas}} \times \alpha T_1 \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_{11} \times \alpha T_{f11} \times \alpha m_{f11} \times \alpha X_{11} \quad (5\text{-}6\text{-}33)$$

5-6.5.2.9 Measured Pressure Drop of the Cooling Fluid, $\Delta p_{12-11,meas.}$ The measured pressure drop of the cooling fluid across the entire chilling system (Plane 12 to Plane 11) is determined following the guidelines provided in this Code. The measured cooling-fluid pressure drop across the entire chilling system is the bulk average cooling-fluid pressure difference across the entire chilling system.

5-6.5.2.10 Corrected Pressure Drop of the Cooling Fluid, $\Delta p_{12-11,corr.}$ For the corrected cooling-fluid pressure drop, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1
αX_{11} = multiplicative correction for working-fluid composition at Plane 11
αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11

Therefore, the correction equation becomes

$$\Delta p_{12-11,\text{corr}} = \Delta p_{12-11,\text{meas}} \times \alpha m_1 \times \alpha X_{11} \times \alpha m_{f11} \quad (5\text{-}6\text{-}34)$$

5-6.5.2.11 Measured Efficiency, $\eta_{meas,}$ and Load, $q_{meas,}$ of the Entire Inlet Chilling System. The measured load of the entire chilling system (Plane 4 to Plane 3) is determined following the guidelines provided in this Code. The measured efficiency or load of the entire chilling system are taken from the bulk average parameters across the entire chilling system. The measured efficiency of the entire chilling system is determined as follows:

$$\eta_{\text{meas}} = AUX_0 \ / \ q_{4-3} \quad (5\text{-}6\text{-}35)$$

NOTE: Units are often reported in kW/ton, which would require additional unit conversions.

5-6.5.2.12 Corrected Efficiency, $\eta_{corr,}$ and/or Load, $q_{corr,}$ of the Entire Inlet Chilling System. For the corrected chiller efficiency and/or load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f11} = multiplicative correction for working-fluid temperature at Plane 11
αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11
αX_{f11} = multiplicative correction for working-fluid composition at Plane 11

Therefore, the correction equation for efficiency becomes

$$\eta_{\text{corr}} = \eta_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f11} \times \alpha m_{f11} \times \alpha X_{f11} \quad (5\text{-}6\text{-}36)$$

and the correction equation for load becomes

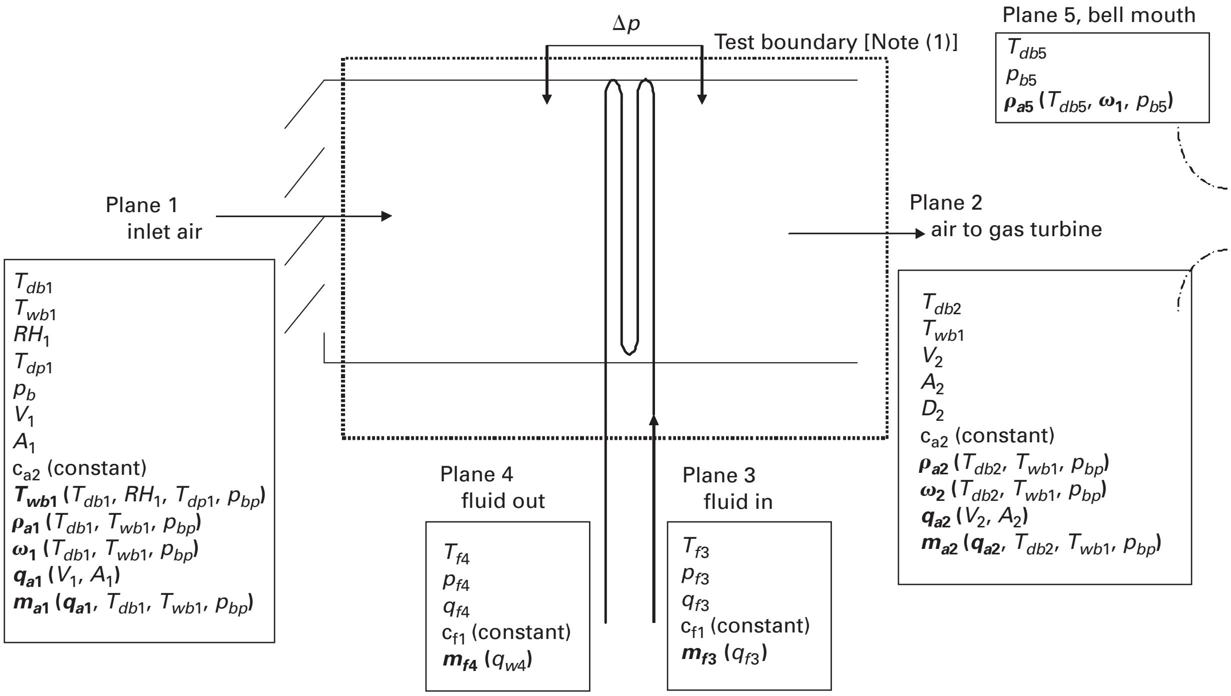
$$q_{\text{corr}} = q_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha T_{wb1} \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f11} \times \alpha m_{f11} \times \alpha X_{f11} \quad (5\text{-}6\text{-}37)$$

5-6.5.2.13 Measured Auxiliary Load, $AUX_{0,meas.}$ The measured system auxiliary load for the entire chilling system (Plane 0) is determined following the guidelines provided in this Code. The measured chilling-system auxiliary load is the auxiliary load for the entire chilling system.

5-6.5.2.14 Corrected Auxiliary Load, $AUX_{0,corr.}$ For the corrected auxiliary load of the entire chilling system, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αT_{wb1} = multiplicative correction for wet-bulb temperature at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f11} = multiplicative correction for working-fluid temperature at Plane 11
αm_{f11} = multiplicative correction for working-fluid mass flow rate at Plane 11

Fig. 5-7.1-1 Inlet Heater Test Boundary Diagram



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).

NOTE:
(1) For direct electrical heaters, this same test boundary applies, with electrical power (Plane 0) replacing fluid in (Plane 3) and fluid out (Plane 4).

Therefore, the correction equation becomes

$$AUX_{0,corr} = AUX_{0,meas} \times \alpha m_1 \times \alpha T_{db1} \times \alpha T_{wb1} \times \alpha m_{f11} \times \alpha T_{11} \quad (5\text{-}6\text{-}38)$$

5-7 INLET HEATING USING CLOSED-LOOP SYSTEMS (COILS)

5-7.1 Test Boundary for a Closed-Loop Inlet Heating System

Subsection 5-7 includes heating systems designed to transfer heat to the GT compressor inlet air stream with no mass transfer via thermal or electrical means. An example would be homogenous heating fluid channeled through a set of coils in the inlet filter house that transfers heat to the GT compressor inlet air, but no mixing of the heating fluid and the GT compressor inlet air occurs. Figure 5-7.1-1 shows a test boundary for the closed-loop inlet heating system.

5-7.2 Test Goals

Subsections 5-1 through 5-3 should be reviewed prior to the use of para 5-7.2. The most common test goals for closed-loop inlet heating are described in paras. 5-7.2.1 through 5-7.2.10.

5-7.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured GT compressor inlet air temperature at the exit of the test boundary (Plane 2) is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the heater.

5-7.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,corr.}$ The measured temperature of the air leaving the test boundary that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine corrected exit temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αAUX_0 = multiplicative correction for heater auxiliary energy consumption (electrical or thermal) at Plane 0
αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation (for thermal heating) becomes

$$T_{db2,\text{corr}} = T_{db2,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha AUX_0 \times \alpha T_{f3} \quad (5\text{-}7\text{-}1)$$

5-7.2.3 Measured Pressure Drop, $\Delta p_{2-1,\text{meas.}}$ The measured pressure drop of the GT compressor inlet air across the heater (Plane 1 − Plane 2) is determined following the guidelines provided in this Code. The measured pressure drop across the heater is the bulk average pressure difference across the heater.

5-7.2.4 Corrected Pressure Drop, $\Delta p_{2-1,\text{corr.}}$ For corrected air pressure drop, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation becomes

$$\Delta p_{2-1,\text{corr}} = \Delta p_{2-1,\text{meas}} \times \alpha m_1 \times \alpha m_{f3} \quad (5\text{-}7\text{-}2)$$

5-7.2.5 Measured Auxiliary Load, $AUX_{0,\text{meas.}}$ The measured heater auxiliary energy consumption (Plane 0) is determined following the guidelines provided in this Code. The auxiliary energy consumption is the work done on the working fluid in order for the heating system to function properly.

5-7.2.6 Corrected Auxiliary Load, $AUX_{0,\text{corr.}}$ For corrected auxiliary energy consumption, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1

αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation becomes

$$AUX_{0,\text{corr}} = AUX_{0,\text{meas}} \times \alpha m_1 \times \alpha T_{db1} \times \alpha m_{f3} \times \alpha T_3 \quad (5\text{-}7\text{-}3)$$

5-7.2.7 Measured Temperature Difference, $\Delta T_{2-1,\text{meas.}}$ The measured temperature difference of the GT compressor inlet air across the heater (Plane 2 − Plane 1) is determined following the guidelines provided in this Code. The measured air temperature difference is the bulk average temperature difference across the heater.

5-7.2.8 Corrected Temperature Difference, $\Delta T_{2-1,\text{corr.}}$ For the corrected temperature difference of the GT compressor inlet air, the following correction factors apply:

αp_1 = multiplicative correction for barometric pressure at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_1 = multiplicative correction for working-fluid pressure at Plane 1

αT_{f3} = multiplicative correction for working-fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working-fluid mass flow rate at Plane 3

Therefore, the correction equation (for thermal heating) becomes

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \quad (5\text{-}7\text{-}4)$$

5-7.2.9 Measured Heater Efficiency, $\eta_{\text{meas,}}$ and/or Load, q_{meas}. The measured heater efficiency and/or load are determined following the guidelines provided in this Code. The measured heater efficiency or load is taken from the bulk average parameters across the heater. The equation for measured heater efficiency is

$$\eta_{\text{meas}} = (T_{2,\text{meas}} - T_{1,\text{meas}}) / (T_{3,\text{meas}} - T_{1,\text{meas}}) \quad (5\text{-}7\text{-}5)$$

5-7.2.10 Corrected Heater Efficiency, $\eta_{\text{corr,}}$ and/or Load, q_{corr}. For corrected heater efficiency and/or load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry bulb temperature at Plane 1

αp_1 = multiplicative correction for barometric pressure at Plane 1

αm_1 = multiplicative correction for air mass flow rate at Plane 1

αp_2 = multiplicative correction for barometric pressure at Plane 2

αT_{f3} = multiplicative correction for working fluid temperature at Plane 3

αm_{f3} = multiplicative correction for working fluid mass flow rate at Plane 3

NOTE: Enthalpy may be used as a correction basis instead of temperature.

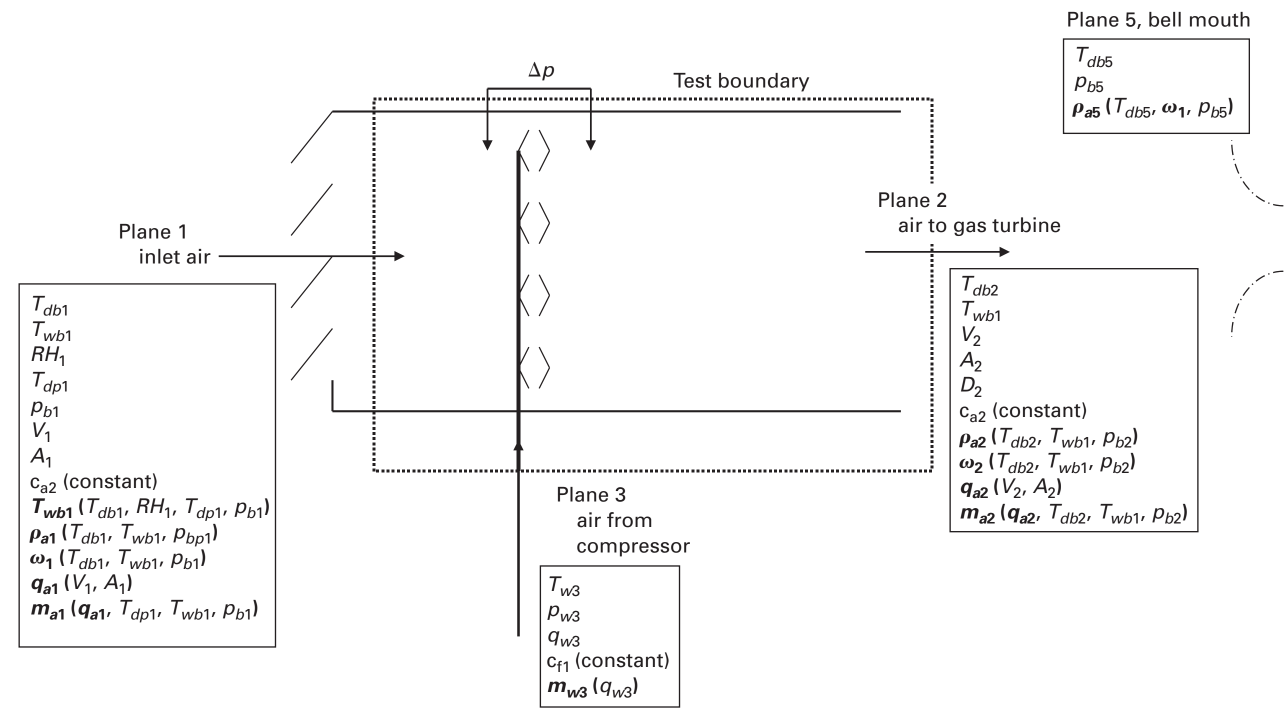
Therefore, the correction equation for efficiency becomes

$$\eta_{\text{corr}} = \eta_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \quad (5\text{-}7\text{-}6)$$

and the correction equation for load becomes

$$q_{\text{corr}} = q_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha AUX_0 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha T_{f4} \quad (5\text{-}7\text{-}7)$$

Fig. 5-8.1-1 Compressor Air Heater Test Boundary Diagram



GENERAL NOTES:
(a) Measured variables are shown in italic.
(b) Calculated variables are shown in bold (these are calculated from measured variables).
(c) This diagram also applies to the closed-tube-type air heaters in which no mixing occurs.

5-8 INLET HEATING USING OPEN-LOOP HEATING SYSTEMS (COMPRESSOR BLEED)

5-8.1 Test Boundary for an Open-Loop Inlet Heating System

Subsection 5-8 includes heating systems designed to transfer heat to the GT compressor inlet air stream with mass transfer via mechanical/thermal means. An example would be compressor-bleed injection heating, where there is mixing of the heated injection air with the cool GT compressor inlet air. The assumption is that both the inlet stream and the mixing fluid are gases. Figure 5-8.1-1 shows a test boundary for the open loop inlet heating system.

5-8.2 Test Goals

Sections 5-1 through 5-3 should be reviewed prior to the use of subsection 5-8. The most common test goals for open-loop inlet heating are described in paras. 5-8.2.1 through 5-8.2.10.

5-8.2.1 Measured Exit Dry-Bulb Temperature, $T_{db2,meas.}$ The measured GT compressor inlet air temperature at exit of test boundary (Plane 2) is determined following the guidelines provided in this Code. The final measured air temperature is the bulk average temperature at the exit plane of the heater.

5-8.2.2 Corrected Exit Dry-Bulb Temperature, $T_{db2,corr.}$ The measured temperature of the air leaving the test boundary that is corrected to base reference conditions is commonly known as the "corrected exit temperature." To determine the corrected exit temperature, the following correction factors may apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f3} = multiplicative correction for injection-fluid temperature at Plane 3
αp_{f3} = multiplicative correction for injection-fluid pressure at Plane 3

Therefore, the correction equation (for thermal heating) becomes

$$T_{db2,\text{corr}} = T_{db2,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha T_{f3} \times \alpha p_{f3} \tag{5-8-1}$$

5-8.2.3 Measured Pressure Drop, $\Delta p_{2-1,meas.}$ The measured pressure drop of the GT compressor inlet air across the heater (Plane 1 − Plane 2) is determined following the guidelines provided in this Code. The measured pressure drop across the heater is the bulk average pressure difference across the heater.

5-8.2.4 Corrected Pressure Drop, $\Delta p_{2-1,corr.}$ For the corrected pressure drop of the GT compressor inlet air, the following correction factors apply:

αm_1 = multiplicative correction for air mass flow rate at Plane 1
αm_{f3} = multiplicative correction for injection-fluid mass flow rate at Plane 3

Therefore, the correction equation becomes

$$\Delta p_{2-1,\text{corr}} = \Delta p_{2-1,\text{meas}} \times \alpha m_1 \times \alpha m_{f3} \tag{5-8-2}$$

5-8.2.5 Measured Consumption of the Heater Injection Fluid, $m_{f3,meas.}$ The measured consumption (Plane 3) of heater injection fluid is determined following the guidelines provided in this Code.

5-8.2.6 Corrected Consumption of the Heater Injection Fluid, $m_{f3,corr.}$ For the corrected injection-fluid consumption, the following correction factors apply:

αT_{db1} = multiplicative correction for dry-bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αT_{f3} = multiplicative correction for injection-fluid temperature at Plane 3
αp_{f3} = multiplicative correction for injection-fluid pressure at Plane 3

Therefore, the correction equation becomes

$$m_{f3,\text{corr}} = m_{f3,\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha T_{f3} \times \alpha p_{f3} \tag{5-8-3}$$

5-8.2.7 Measured Temperature Difference, $\Delta T_{2-1,meas.}$ The measured temperature difference of the GT compressor inlet air across the heater (Plane 2 − Plane 1) is determined following the guidelines provided in this Code. The measured air temperature difference is the bulk average temperature difference across the heater.

5-8.2.8 Corrected Temperature Difference, $\Delta T_{2-1,corr.}$ For the corrected temperature difference of the GT compressor inlet air, the following correction factors apply:

αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for injection-fluid pressure at Plane 2
αT_{f3} = multiplicative correction for injection-fluid temperature at Plane 3
αm_{f3} = multiplicative correction for injection-fluid mass flow rate at Plane 3
αp_{f3} = multiplicative correction for injection-fluid pressure at Plane 3

Therefore, the correction equation becomes

$$\Delta T_{2-1,\text{corr}} = \Delta T_{2-1,\text{meas}} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha p_{f3} \tag{5-8-4}$$

5-8.2.9 Measured Heater Efficiency, $\eta_{meas,}$ and/or Load, q_{meas}. The measured heater efficiency and/or load are determined following the guidelines provided in this Code. The measured heater efficiency is taken from the bulk average parameters across the heater.

5-8.2.10 Corrected Heater Efficiency, $\eta_{corr,}$ and/or Load, q_{corr}. For corrected heater efficiency and/or load, the following correction factors apply:

αT_{db1} = multiplicative correction for dry bulb temperature at Plane 1
αp_1 = multiplicative correction for barometric pressure at Plane 1
αm_1 = multiplicative correction for air mass flow rate at Plane 1
αp_2 = multiplicative correction for barometric pressure at Plane 2
αT_{f3} = multiplicative correction for injection fluid temperature at Plane 3
αm_{f3} = multiplicative correction for injection fluid mass flow rate at Plane 3
αp_{f3} = multiplicative correction for injection fluid pressure at Plane 3

NOTE: Enthalpy may be used as a correction factor instead of temperature.

Therefore, the correction equation for efficiency becomes

$$\eta_{\text{corr}} = \eta_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha p_{f3} \tag{5-8-5}$$

and the correction equation for load becomes

$$q_{\text{corr}} = q_{\text{meas}} \times \alpha T_{db1} \times \alpha p_1 \times \alpha m_1 \times \alpha p_2 \times \alpha T_{f3} \times \alpha m_{f3} \times \alpha p_{f3} \tag{5-8-6}$$

Section 6
Report of Results

6-1 GENERAL REQUIREMENTS

The test report shall incorporate all documentation and information pertaining to the test(s) in a concise and clear manner. The following lists the general requirements in a recommended report format:

(a) executive summary, described in subsection 6-2
(b) introduction, described in subsection 6-3
(c) calculations and results, described in subsection 6-4
(d) instrumentation and measurements, described in subsection 6-5
(e) conclusion, described in subsection 6-6
(f) appendices, described in subsection 6-7

Other formats are acceptable provided they contain all information described in subsections 6-2 through 6-7.

6-2 EXECUTIVE SUMMARY

The executive summary shall present a brief overview of the test. Definitive statements describing the test, which consist of the following information, shall be provided:

(a) test background information, such as the project name, location, date, and time
(b) equipment owner and identification information
(c) plant type, cycles, and operating configuration
(d) parties conducting and responsible for the test
(e) object and scope of the test
(f) summary of the results and conclusions of the test(s), including uncertainty.

6-3 INTRODUCTION

The introduction shall present a detailed account of the background and scope of the test as well as include any additional information about the plant and test not given in the executive summary. The introduction should include, at minimum, the following essential information:

(a) a brief history of the equipment operation and date of commercial operation (if necessary)
(b) a description of the equipment to be tested an all such ancillary equipment that may influence the test
(c) cycle diagrams showing the test boundaries and test readings
(d) a list of all representatives of the Parties to the Test(s)
(e) pretest agreements not included in the executive summary
(f) organization of test personnel
(g) test goals per Sections 3 and 5 of this Code.

6-4 CALCULATIONS AND RESULTS

The calculations and results should include in detail all assumptions, data reduction, calculations, corrections, and analysis used to determine the results and uncertainty of the test. The following information shall be provided:

(a) the title, issue date, and revision number of the test procedure that applied to the test
(b) the tabulation of overall results of the critical objectives of the testing program
(c) a list of any deviations to the test procedure and the rationale for the deviations
(d) a reference to the appendix containing the tabulated data, and a reference to the appendix containing the calculation summary
(e) direct references to standard conversions, scientific constants, and property information
(f) supporting information and calculations to support elimination of data for outlier reasons, or for any other reasons
(g) a demonstration of the repeatability of the test runs.

6-5 INSTRUMENTATION AND MEASUREMENTS

The instrumentation and measurements section of the test report shall detail all the instrumentation utilized in the test. The following instrument information shall be provided:

(a) a list of any deviations to the instrumentation and measurements included in the test procedure
(b) tabulation of instrumentation used for the primary and secondary measurements, including type, make, model number, and accuracy class
(c) a description of each instrument's respective measurement location, connections, and any identifying tag number or address
(d) a reference to the appendix containing the documentation of calibration traceability of each test instrument
(e) identification of instruments that were used as backup
(f) the means of data collection for each data point, such as temporary or permanent data acquisition systems or manual data sheets
(g) description and specifications of the data acquisition system(s) used.

6-6 CONCLUSION

The conclusion should be included if a more detailed discussion of the test results is required or there are any recommendations for changes to future test procedures due to "lessons learned."

6-7 APPENDICES

The appendix to the test report should comprise any information not practical to include in the body of the report, such as, but not limited to, the following:

(a) tabulation of the reduced data necessary to calculate the results and any additional operating conditions not part of such reduced data

(b) a summary of results of each step of the calculation procedure as defined by the test procedure, including detailed calculation of primary flow rates from applicable data, including intermediate results, if required

(c) copies of original data sheets, data acquisition system(s) printouts, or both

(d) copies of correction curves utilized in the calculation of test results if not previously disclosed in the test procedure

(e) copies of operational information during the test, such as operation logs, control system printouts, or other recording of operating activity

(f) copies of signed valve line-up sheets and other documentation indicating required test configuration and disposition of operation

(g) instrumentation calibration results from laboratories and certification from manufacturers

(h) documentation of the pretest and posttest calibration traceability of each test instrument.

Section 7
Test Uncertainty

7-1 INTRODUCTION

Test uncertainty is an estimate of the limit of error of a test result. It is the interval about a test result that contains the true value with a given probability, or level of confidence. It is based on calculations involving probability theory, instrumentation information, calculation procedure, and actual test data. ASME PTC 19.1 is the Performance Test Code Supplement that covers general procedures for calculation of test uncertainty. Uncertainty shall be calculated for a 95% level of confidence. This means that there is a 95% probability that the true value of performance lies within the uncertainty interval. It also means that there is a 2.5% probability that the true value lies below the lower level and a 2.5% probability that it lies above the upper level of the interval.

7-2 INPUTS FOR AN UNCERTAINTY ANALYSIS

To perform an uncertainty analysis on the test result(s), two sets of inputs are required: estimates of the uncertainties of each of the required measurements, and sensitivity coefficients.

7-2.1 Estimates of the Uncertainties of Each of the Required Measurements

Two types of uncertainties make up the total uncertainty:

(a) Random or precision error. Due principally to the nonrepeatability of the measurement system, the random error varies during repeated measurements. It may be reduced by increasing both the number of instruments used to measure a given parameter, and the number of readings taken.

(b) Systematic or fixed error. This is usually an accumulation of individual errors not eliminated through calibration. It is a constant value despite repeated measurements, and is frequently difficult to quantify.

The total uncertainty is calculated from the root sum square of the random and systematic components (see ASME PTC 19.1).

7-2.2 Sensitivity Coefficients

Sensitivities, or influence coefficients, are defined here as sensitivity coefficients. Each of the parameters measured has an influence on corrected performance. These sensitivities are a function of the specific performance parameter and plant design, and can be calculated based on the correction procedure described in Section 5.

7-3 ERROR SOURCES

It is necessary to identify the error sources that affect the test result, and to characterize them as systematic or random.

7-4 CALCULATION OF UNCERTAINTY

The uncertainty of the result is the root sum square value of the uncertainty for each measurement multiplied by the sensitivity coefficient of the parameter. Simplified equations for overall uncertainty are shown below. The Code user should consult subsection 7-1 for specific derivation and assumptions behind each of the equations to determine their applicability.

$$U_R = 2\left[\sum\left(\Theta_i \frac{B_i}{2}\right)^2 + \sum\left(\Theta_i S_i\right)^2\right]^{0.5}$$

$$U_R = 2\,[\Sigma(\Theta^2{}_i\{(\frac{B_i}{2})^2 + S_i{}^2\}]^{0.5}$$

$$U_R = [\Sigma(\Theta_i\{B_i^2 + (2S_i)^2\}]^{0.5}$$

$$U_R = [\Sigma(\Theta^2{}_i U_{Ti}{}^2)]^{0.5}$$

or

$$U_R = [\Sigma\, U_i{}^2]^{0.5}$$

where

B_i = systematic error of parameter i
S_i = standard deviation of the mean of parameter i
U_i = uncertainty due to parameter i
U_R = uncertainty of the result
U_{Ti} = combined random and systematic error of parameter i
Θ_i = sensitivity coefficient of parameter i

In developing the estimate of test uncertainty, care shall be taken to consider correlated uncertainties (see ASME PTC 19.1 and subsection 7-5).

For each parameter, the random uncertainty has been estimated as $2S_{\bar{x}}$, and the systematic error has been estimated at 95% confidence as B_i. This reflects the desire to have a 95% confidence level that the true value lies within $\pm U_{Ti}$ of the mean. $S_{\bar{x}}$ can be calculated from

$$S_{\bar{x}} = \frac{1}{\sqrt{M}}\sqrt{\sum_{k=1}^{k=N}\frac{(X_k - \bar{X})^2}{(N-1)}}$$

where

M = number of independent readings
N = number of measurements
$S_{\bar{x}}$ = the standard deviation of the mean
X_k = individual measurement value
$\bar{X}$ = mean

7-5 CORRELATED AND NONCORRELATED APPROACHES TO UNCERTAINTY MEASUREMENT

When listing all sources of uncertainty from different categories, the sources should be defined where possible so that the uncertainties in the various sources are independent of each other. The parameters and their associated uncertainties are then said to be considered uncorrelated. Where the parameters or the uncertainty in those parameters are not independent of each other, they are said to be correlated. The correlation can be either positive or negative and can be between 0% and 100%.

There are many situations where systematic errors from some of the parameters are not independent. Examples include using the same instrument to measure different parameters, calibrating different instruments against the same standard, or using similar instruments to measure the same parameter. In these cases, some of the systematic errors are said to be correlated and these nonindependent errors must be considered in the determination of the systematic uncertainty. For example, a group of potential transformers purchased from the same factory at the same point in time may exhibit a characteristic bias that is dependent upon the specific equipment, materials, and processes used in their manufacture. Similar effects may be seen with flow-metering devices, temperature-measurement devices, or pressure transmitters.

The handling of correlated uncertainties can be difficult, and for partial correlation can be particularly so, since it uses mathematically complex procedures to establish the covariances. As such, for most practical applications, the simpler techniques as described below should be performed to estimate the effects of correlated systematic uncertainties.

If the mathematical relationship of the correlated parameters cannot be redefined to eliminate the correlations, experience and engineering judgment is required to estimate the degree of correlation. One approach is to use an analysis technique that divides the sources of uncertainty into correlated and uncorrelated and carry out parallel analyses adding contributions linearly for the correlated sources and by root sum square for the uncorrelated as described in ASME PTC 19.1.

An alternate approach is to perform uncertainty analyses based on fully correlated and uncorrelated measurements to establish a range.

7-6 MEASUREMENTS

Prior to the test, the variables and their sensitivity coefficients are tabularized in a format similar to that shown in Nonmandatory Appendix B.

7-7 ESTIMATED UNCERTAINTIES

Uncertainties should be determined based on the physical properties of the instruments and the physical conditions of the measurands that persist at the time of the test, following the guidelines established in ASME PTC 19.1. For uncertainty elements that cannot be readily quantified at the time of the test using a reasonable amount of instrumentation, prior test experience can be considered. When prior test experience must be considered, suitable documentation of the prior experience should be included for all parties to review. Estimates should reflect the 95% confidence level used for ASME PTC Codes. The values used in the tables of Nonmandatory Appendix B are representative of those achievable with appropriate selection of instruments, number of readings, etc. As shown, the total uncertainty of each parameter meets the Code requirement for that measurement.

7-8 POSTTEST UNCERTAINTY ANALYSIS

A posttest uncertainty analysis shall be conducted to verify the assumptions made in the pretest uncertainty analysis. In particular, the data should be examined for sudden shifts and outliers. The assumptions for random errors and sensitivity factors should be checked by determining the degrees of freedom, the standard deviation of each measurement, and the actual test conditions.

7-9 REPEATABILITY

Paragraphs 3-3.6 and 3-3.7 provide guidance on the expected repeatability of test results.

7-10 SPATIAL SYSTEMATIC UNCERTAINTY

Spatial systematic uncertainty errors occur during the measurement of a spatially diverse sample. Spatial error is defined as the difference between the true average value of a parameter and the average produced by an array of instruments used to measure the parameter. Spatial errors for an inlet cooler or heater test will occur during the measurement of any spatially diverse parameter, including inlet wet-bulb and dry-bulb temperatures, humidity, and outlet air temperature.

Consideration of the parameter sensitivity to the test result will provide guidance to the number of measurement stations required to conduct a test that meets Code uncertainty requirements. This determination should be made as part of the pretest uncertainty analysis. The minimum number of measurement points recommended for the calculation of spatial uncertainty

Table 7-10-1 Spatial Systematic Uncertainty Calculation (Step-by-Step)

Step	Description	Symbol	Formula	Value
1	Number of stations	M	$= 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1$	9.0
2	Average of the air temperatures	$\overline{\overline{X}}$	$= (72.89 + 73.06 + 74.03 + 74.33 + 74.82 + 75.81 + 76.05 + 76.52 + 77.42) / 9$	74.99
3	Standard deviation	$S_{Spatial}$	$= \sqrt{[(72.89 - 74.99)^2 + (73.06 - 74.99)^2 + (74.03 - 74.99)^2 + (74.33 - 74.99)^2 + (74.82 - 74.99)^2 + (75.81 - 74.99)^2 + (76.05 - 74.99)^2 + (76.52 - 74.99)^2 + (77.42 - 74.99)^2]}$	1.563
4	Student's *t*	t_{m-1}	Per cumulative distribution function	2.306
5	Spatial systematic uncertainty	B_{SP}	$= 1.563 \times 2.306 / \sqrt{9}$	1.201

Fig. 7-10-1 Outlet Air Temperature Distribution at the Outlet of an Evaporative Condenser

Average temperature	72.89	73.06	74.03
Average temperature	74.33	74.82	75.81
Average temperature	76.05	76.52	77.42

should be determined in accordance with the guidance of para. 4-3.6.3.1. In practice, the potential for interference from nearby heat sources or humidity sources will impact the variability of the parameter across the plane of measurement and dictate the number of instruments required to determine a representative average.

Spatial uncertainties are calculated from the average of local measurements in space and are thus independent of time. In general, spatial distributions are not random. That is, there is a definite pattern in the variation of the test parameter in space. In principle, the uncertainty associated with this variation could be calculated as an integration error because a finite set of measurements cannot determine the stream conditions in between the measurement points; this variation contributes to the systematic uncertainty.

Per the guidelines of ASME PTC 19.1 [eq. (4-3.5)], spatial uncertainties are calculated from the following formula:

$$B_{Sp} = \frac{S_{spatial}\ t_{m-1}}{\sqrt{M}}$$

$$S_{spatial} = \sqrt{\frac{\sum_{k=1}^{M}(\overline{X}_k - \overline{\overline{X}})^2}{M-1}}$$

where

B_{Sp} = systematic uncertainty due to spatial variation
M = the number of measurement locations
$S_{spatial}$ = standard deviation
t_{m-1} = student t value for $m - 1$ degrees of freedom
$\overline{X}k$ = time-averaged value at the measurement location k
$\overline{\overline{X}}$ = average value of the group of measurements

Table 7-10-1 and Fig. 7-10-1 illustrate the calculation of a spatial uncertainty associated with the distribution on the outlet of an evaporative condenser.

If inlet air enters in more than one area (defined by a physical separation), the spatial uncertainty of each area may be calculated separately. When combining the uncertainties, it is necessary to weight the uncertainties by area or velocity, using the same weighting factors used to produce the average.

Section 8
References

8-1 REFERENCES

[1] The American Society of Mechanical Engineers (ASME), 1986, PTC 19.3 – 1974 (R1986), chap. 9, para. 70, ASME, New York, pp. 106–116.

[2] Dahl, A. I., 1941, "Stability of Base-metal Thermocouples in Air from 800 to 2200ºF." National Bureau of Standards, Washington, D.C., in *Temperature*, vol. 1, Reinhold, New York, p. 1238.

[3] American Society of Testing and Materials (ASTM), MNL 12, *Manual on the Use of Thermocouples in Temperature Measurement*, chap. 7, "Reference Junctions,"ASTM, West Conshohocken, PA, p. 17.

[4] ASTM E 1137-97, *Standard Specification for Industrial Platinum Resistance Thermometers*, ASTM, West Conshohocken, PA.

[5] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2005, *2005 ASHRAE Handbook—Fundamentals*, chap. 6, ASHRAE, Atlanta, GA, p. 25.

[6] International Organization for Standardization (ISO), 1974, ISO/TC-30/SC-3, "Draft Proposal for an ISO Standard: Measurement of Fluid Flow in Closed Conduits by the Velocity Area Method Using Pitot-Static Tubes," February 1974, ISO, Geneva, Switzerland.

[7] U.S. Environmental Protection Agency (EPA), 1976, EPA Report PB-257-090, "Particulate Sampling Strategies for Large Power Plants including Non-uniform Flow," June 1976, EPA, Washington, D.C.

[8] Gerhart, P., Nuspl, S., Wood, C., and Lovejoy, S., 1979, "An Evaluation of Velocity Probes for Measuring Non-uniform Gas Flow in Large Ducts," *Journal of Engineering for Power*, October 1979.

[9] Brown, N., 1975, ASHRAE Paper 2325, "A Mathematical Evaluation of Pitot Tube Traverse Methods,"ASHRAE, Atlanta, GA.

[10] Wyler, J. S., 1975, "Probe Blockage Effects in Free Jets and Closed Tunnels," *Journal of Engineering for Power*, October 1975.

[11] Benedict, R. P., 1977, *Fundamentals of Temperature, Pressure, and Flow Measurements*, 2nd Edition, Wiley-Interscience, pp. 356–359.

[12] IEEE, ANSI/IEEE Standard 120, *IEEE Master Test Guide for Electrical Measurements in Power Circuits*, IEEE, Piscataway, NJ.

[13] IEEE, 1993, IEEE Std C57.13-1993, *IEEE Standard Requirements for Instrument Transformers*, IEEE, Piscataway, NJ.

[14 A] National Institute of Standards and Technology (NIST), *Handbook 100*, NIST, Gaithersburg, MD.

[14 B] Cooling Tower Manual, Chapter 5, p. 5.26, Cooling Tower Field Test Handbook.

[15] ASTM B33-10, *Standard Specification for Tin-Coated Soft or Annealed Copper Wire for Electrical Purposes*, ASTM, West Conshohocken, PA.

[16] Insulated Power Cable Engineers Association, Standard No. S-19-81.

[17] National Electrical Manufacturers Association (NEMA), Standard No. WC3-1964.

[18] ASME, PTC 11-1998, *Fans*, ASME, New York.

[19] (Ref EPA Test Method 20 for NOx Emissions)

[20] Keenan, J.H., and J. Kaye, 1948, *Gas Tables*, John Wiley and Sons.

8-2 ADDITIONAL REFERENCED ASME DOCUMENTS

ASME *Steam Tables*
PTC 4.4, *Gas Turbine Heat Recovery Steam Generators*
PTC 12.4, *Moisture Separator Reheaters*
PTC 19.1, *Test Uncertainty*
PTC 19.2, *Pressure Measurement*
PTC 19.3, *Temperature Measurement*
PTC 19.5, *Flow Measurement*
PTC 19.22, *Data Acquisition Systems*
PTC 22, *Gas Turbines*

Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016-5990; Order Department: 22 Law Drive, P.O. Box 2900, Fairfield, NJ 07007-2900

INTENTIONALLY LEFT BLANK

NONMANDATORY APPENDIX A
METHOD OF TESTING ATOMIZING NOZZLES

INTRODUCTION

This protocol is a standalone test protocol to be executed in a laboratory environment. It is intended to be used to standardize the testing and results when concerns are raised about the capabilities of nozzles.

Over the past decade and especially over the past five years, the application of inlet fogging for the power augmentation of gas turbines has become increasingly popular. It is estimated that approximately 700 gas turbines worldwide have fogging systems at this time, including several new F-class gas turbines.

A major problem faced by gas turbine users considering the utilization of inlet fogging is that different fog nozzle manufacturers and suppliers present data in very different formats and under different operating conditions. In this protocol, the key operating parameters that are pivotal in uniform wind tunnel testing are specifically documented and a standard method of test and data presentation is recommended.

Adherence to this protocol should provide consistent internozzle performance rankings for tests carried out in the laboratories of fogger nozzle suppliers, turbine engine manufacturers, and turbine system purchasers.

Measurements should be conducted in accordance with optimal measurement procedures. However, experimental conditions may not allow complete adherence to this standard. Where this is the case, all deviations from the standard shall be documented.

When comparing the performance of two or more nozzles, the tests should be performed by the same laboratory during the same day or time period to eliminate as many test variables as possible. Relying on test data from different laboratories or different time periods increases the uncertainty value that may make the results misleading.

This Appendix establishes a uniform method of laboratory testing for atomizing nozzles intended for use in fogging systems for evaporative air-cooling and humidification for industrial gas turbines for power generation.

A-1 OBJECTIVE AND SCOPE

A-1.1 Scope

The scope of this Appendix covers a method of testing for droplet size, droplet distribution, spray angle, and water flow rate of high-pressure nozzles.

A-1.2 Tests Included

Covered tests also include the methods for measuring droplet size and distribution, water pressure and temperature, and air velocity and relative humidity. In the case of air-assisted nozzles, air pressure and flow shall also be tested.

A-1.3 Use of Ratings

The ratings resulting from application of this protocol are intended for use by manufacturers, specifiers, installers, and users of high-pressure nozzles used for evaporative cooling and humidification.

A-2 DEFINITIONS AND DESCRIPTION OF TERMS

A-2.1 Symbols

The symbols in Table A-2.1-1 are used unless otherwise defined in text.

A-2.2 Subscripts

The following subscripts are used unless otherwise defined in text:

Subscript	Description
0	Plane 0
1	Plane 1
2	Plane 2
3	Plane 3
4	Plane 4
n	Nominal
std	Standard
x	Plane 0, 1, 2, ... as appropriate

A-2.3 Definitions

See Section 2 for definitions of the following terms used in this Nonmandatory Appendix:

– *air-assisted nozzle*
– *atomizing nozzle*
– *cocurrent flow*
– D_{10} [arithmetic mean diameter (*AMD*)]
– D_{20} [surface area mean diameter (*SAMD*)]
– D_{21} [surface area-length (absorption) diameter]
– D_{30} [volume mean diameter (*VMD*)]

Table A-2.1-1 Symbols

Symbol	Description	SI Unit
A	Area of cross section of tunnel at nozzle	m^2
A_d	Surface area of the droplet	m^2
AD or D_{21}	Absorption diameter	μm
AMD or D_{10}	Arithmetic mean diameter	μm
CV	Concentration volume	ppm
Dd	Droplet diameter	μm
ED or D_{31}	Evaporative diameter	μm
MMD or Dv_{50}	Mass median diameter	μm
n	Number of readings	Dimensionless
p_b	Ambient barometer pressure	Pa
Q_0	Airflow rate	m^3/s
Q_w	Water flow rate	l/s
$SAMD$	Surface area mean diameter	μm
SMD or D_{32}	Sauter mean diameter	μm
Span	Range of values	Dimensionless
SSA	Specific surface area	m^2/cc
T_{dx}	Dry-bulb temperature at Plane X	°C
T_{wx}	Wet-bulb temperature at Plane X	°C
V	Air velocity at nozzle	m/s
V_{rel}	Droplet relative velocity	m/s
Vd	Droplet volume	m^3
VMD or D_{30}	Volume mean diameter	μm
ρ	Density of the air	kg/m^3
Σ	Sum	...

– D_{31} [volume length (evaporative) diameter (*ED*)]
– D_{32} [sauter mean diameter (*SMD*)]

NOTE: Additional information on the diameter definitions can be found in the standards listed at the end of Nonmandatory Appendix A under "Additional Useful Documents."

– *dimensionless groups*
– Dv_{01} (also known as Dv_{10})
– Dv_{05} [also known as Dv_{50}, or mass median diameter (*MMD*)]
– Dv_{09} (also known as Dv_{90})
– *flux technique*
– *impingement nozzle*
– *ligament*
– *light-scattering (diffraction) instrument*
– *Nukiyama-Tanasawa*
– *obscuration (optical concentration)*
– *records*
– *relative span factor (RSF)*
– *Rosin-Rammler [Rosin Rammler Sperling Bennett (RRSB)]*
– *spatial technique*
– *swirl nozzle*
– *temporal technique*
– *test*
– *transmission*
– *vignetting (optical cutoff)*

A-2.4 Units of Measure

The units of measure used in this Appendix are as follows:

(a) Flow rate. The unit of flow rate for air is the cubic meter per second, m^3/s. The unit of flow rate for water is the liter per second, l/s.

(b) Velocity. The unit of velocity is the meter per second, m/s.

(c) Gas properties. The unit of density is the kilogram per cubic meter, kg/m^3.

(d) Pressure. The unit of pressure is the bar. The mm mercury column shall be based on a 1-mm column of mercury at 0°C, under standard gravity in vacuum.

A-3 GUIDING PRINCIPLES

A-3.1 Test Points

The number of test points required to establish the performance of a nozzle depends upon the size of the plume. The plume shall be traversed in equal intervals to obtain a representative sampling of the droplet distribution. Surveys across the plume shall be taken and droplet distributions obtained at the centerline, the edge of the plume, and three intermediate radial locations. If the nozzle has asymmetries such as an impact pin, then sufficient surveys shall be taken to assess the effect of the asymmetry. At least three determinations shall be made at each test point.

Nozzle plumb traverses may be made when practical; also the data shall be processed with correct mass balance closure.

A-3.2 Droplet Measurement

The technology for droplet measurement is still developing; currently the different techniques have different strengths. Care should be taken to use the appropriate testing method for the intended results.

A-3.2.1 Laser Light Diffraction Instrumentation. Measurements shall be made with a forward light-scattering (also called diffraction) instrument. Spray measurements shall be collected across a plane perpendicular to the nozzle axis. Droplets shall be measured and characterized using a laser-type instrument having a demonstrated accuracy in the range of droplet size produced by the nozzle being tested.

A-3.2.1.1 Verification. Instrument calibration verification shall be checked before and after each series of tests. The manufacturer shall specify the method and technique for calibration. The instrument shall have a calibration verification performed with a known source of droplets or, in the case of laser diffraction instruments, with a photo mask reticle in accordance with ref. [1]. An alternative method would be to measure reference particles in a liquid suspension, as supplied by the instrument manufacturer.

Laser-light diffraction is a measurement system where size distributions are determined by measuring the intensity of light scattering from a spray as a function of angle. This light-scattering or diffraction pattern is then mathematically interpreted using an appropriate optical model based on known light-scattering principles, which predicts how particle scattering relates to particle size.

A-3.2.1.2 Pros and Cons of Laser Light Diffraction

(a) *Pros*

(1) simplicity of setup

(2) rapid sampling

(3) broad size range of droplets

(4) speed of measurement

(5) concentration range (especially with multiple scattering extensions)

(6) working size range of droplets

(7) ability to measure semispherical particles

(8) good sampling (ensemble technique)

(b) *Cons*

(1) uses a spatial technique, and is therefore subject to velocity bias if extraction is not set

(2) samples from chord, not a single point

(3) provides no velocity information

A-3.2.2 Phase Doppler Particle Analyzer (PDPA). Measurements shall be made with a phase Doppler interferometer instrument, also called a PDPA. Data shall be acquired along three profiles through the spray, 120 deg apart.

The size of the beam crossing or measurement region (waist) shall be made to be roughly equal to or larger than the size of the largest droplet present. Selection of beam expander and transmitting lens determines the waist size.

A-3.2.2.1 Verification. The instrument is optically calibrated during production, and this is a lifetime calibration. Electronic phase calibration is normally done for each set of instrument settings, particularly PMT voltage, sampling rate (pass band), and laser power level. This is done using a built-in calibration diode that generates a Doppler burstlike signal. Calibration values may also be obtained for various PMT voltages, for example, and recorded for later input during testing.

The accuracy depends on instrument settings, mainly through the SNR. Experienced users can expect typical values to be within ±1% of the reading +2° phase.

The resolution in phase is 1/4,096, or 0.0878906°.

The repeatability also depends on instrument settings, and with experience an operator may be expected to achieve typical values of ±2° phases.

PDPA is one form of flux technique.

A-3.2.2.2 Pros and Cons of PDPA

(a) *Pros*

(1) measures both velocity and size

(2) uses flux technique; therefore, there is no velocity bias

(3) provides high spatial resolution (single point)

(4) uses a high-resolution (counting) technique

(5) is sensitive enough to work with at very low concentrations

(b) *Cons*

(1) It is relatively difficult to set up (laser-crossing angle, etc).

(2) Sampling is poor (single-point, single-particle counter).

(3) Nonsphericity prevents accurate size analysis (the solution falls apart).

(4) Need to avoid particle coincidence within the measurement zone.

(5) Particles must be homogeneous (no bubbles).

(6) Relatively narrow size range of droplets.

A-3.3 Data to Be Recorded

A-3.3.1 Test Unit Information [2]. The description of the nozzle and setup shall be recorded, including the manufacturer's part number, materials of construction, design pressure if provided by the manufacturer, and nozzle type (i.e., impingement, swirl, or air assisted). A close-up photograph of the nozzle and manifold shall be included.

A-3.3.2 Test Setup [2]. A description of the test setup, including specific dimensions, shall be recorded. Reference may be made to the figures in this standard. Alternatively, a drawing or annotated photograph of the setup may be attached to the data.

A-3.3.3 Instruments [2]. The instruments and apparatus used in the test shall be listed. Names, model numbers, serial numbers, scale ranges, software version number, and calibration verification shall be recorded.

A-3.3.4 Test Data [2]. Test data for each determination shall be recorded. For all tests, the following shall be recorded when the readings are steady:

– droplet count
– air dry-bulb temperature, $T_{db,0}$
– air wet-bulb temperature, $T_{wb,0}$
– ambient air barometric pressure, p_b
– air velocity
– duct static pressure
– water flow
– water temperature, T_w
– water conductivity
– water pressure to the nozzle
– droplet measurement distance from the orifice
– number of volume samples
– number of timed/counted samples
– droplet count
– spray angle (calculated from diameter at measurement plane)
– spray plume diameter at measurement plane
– atomizing air temperature
– atomizing air dry-bulb temperature
– atomizing air wet-bulb temperature
– atomizing air pressure
– droplet size distribution

A-3.3.5 Personnel. The names of test personnel shall be listed with the data for which they are responsible.

A-4 INSTRUMENTS AND METHODS OF MEASUREMENTS

A-4.1 Precision and Uncertainty

Refer to refs. [3] and [4] for use of the terms "random error" and "systematic error."

A-4.2 Droplet Measurement Technologies

A-4.2.1 Number Density Weighted Sampling (Laser) Spray. Measurements shall not be made where ligaments, sheets, or other nonspherical structures are known to exist, as the resulting data may be misleading. Examples of such locations are very close to the nozzle before the drops have formed, and at a point where drips form, such as on an impingement pin.

Diodes should not be suppressed/turned off (killing channels) for measurements, or if diode suppression is unavoidable, no more than one shall be suppressed. All other methods of removing the vibration, lens contamination, or other reasons for spurious measurements shall be exhausted prior to suppressing a diode. If required, a slightly smaller lens should be tried (since vibration effects are reduced as lens diameter decreases, due to the change in focal distance) even if that results in the loss of measurement of the largest droplets — as long as truncation is still below 1% to 2% by volume, this is preferable to suppressing/turning off diodes (killing channels).

Additional considerations of the Number Density Weighted Sampling technique are as follows:

(a) Spray measurements shall be made to capture as much of the droplet-size distribution as possible. As a result, the instrument's collecting-lens focal length should be chosen to yield volume fractions in the largest and smallest size bins of less than 1%. If this truncation must be higher (2% max.), it is to be stated in the report. The report shall also specify the lens focal length in millimeters.

(b) If applicable, purge air should be applied to prevent water deposition on the system optics. Alternatively, a larger lens may be chosen to provide a larger working distance. This will allow the spray plume to be repositioned further away from the lens, thus avoiding water deposition on the lens.

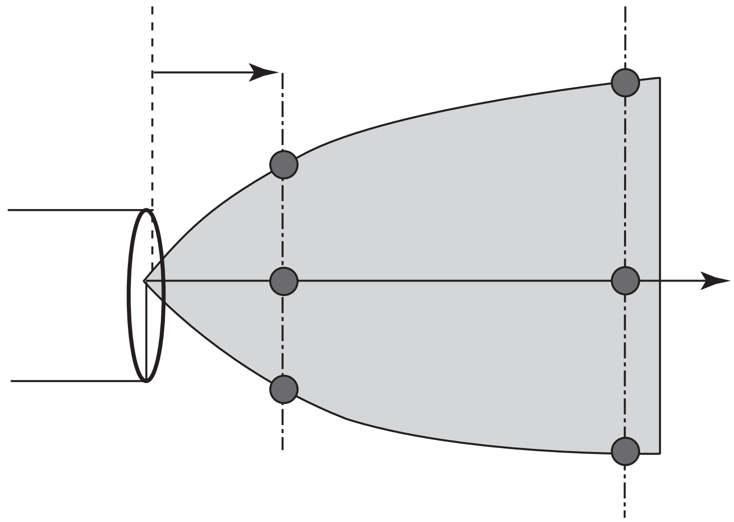
(c) The report shall contain the distance in millimeters from the farthest edge of the spray to the outside surface of the collecting lens. This distance should be within the vendor-recommended working distance to prevent the lens from missing smaller droplets.

(d) If applicable, spray measurements should be made at a distance of 75 mm from the nozzle exit face. The report shall contain the distance in millimeters from the nozzle to the plane where measurements are made. Refer to Fig. A-4.2.1-1.

(e) Spray measurements shall be made to minimize or eliminate statistical scatter. Each measurement shall be repeated at least three times to provide a measure of experimental reproducibility. Data shall be deemed acceptable when the standard deviations about the means for the measurements D_{32} and D_{v09} are each less than 10% of their respective means.

(f) The report shall contain the instrument-reported transmission (or obscuration), given as a percentage, for measurements across the spray diameter.

Fig. A-4.2.1-1 Spatial Location for Experimental Testing



(g) Data should be reported for lower transmission (higher obscuration) values if the instrument has a manufacturer-supplied algorithm for multiple-scattering effects. When presenting such data, the report shall include the measured transmission (or obscuration), detail of the algorithm used to compensate or correct for multiple scattering, and the manufacturer-stated limits of applicability for that algorithm. If the transmission is below the vendor recommendation for the instrument or if vignetting is inevitable, then consideration may be given to using an air curtain or purge tube to selectively block 50% of the spray from the laser beam. In principle, this will provide measurements on half of the spray droplets, but care should be taken to ensure it is a representative half.

(h) Spray measurements shall be made to collect from as much of the spray mass as is practicable. To accomplish this, line-of-sight measurements shall be made across two spray diameters that are oriented at 90 deg to one another. This will ensure that the maximum spray obscuration is 40% or less (transmission is 60% or better).

(i) Next, droplet-size data shall be acquired across the entire spray. This is accomplished by

(1) arranging to translate the entire spray across the (fixed) instrument laser beam

(2) initiating data acquisition when the laser beam enters the spray and transmission drops below 98% (obscuration rises above 2%)

(3) continuing data acquisition until the laser beam exits the spray and transmission rises above 98% again (obscuration falls below 2% again)

A-4.2.2 Flux-Type Droplet-Measuring Device (PDPA). The Phase Doppler particle analyzer (PDPA) shall acquire data along three profiles through the mechanical axis of the nozzle, 120 deg apart. If the injector has an inherent asymmetry (e.g., pin, internal swirl channels, etc.), then one of the profiles shall be aligned with the asymmetry and noted as such in the test records. Data shall be acquired in at least three locations along each profile: one at the maximum total volume flux (MTVF) location, then another at each 50% MTVF location. See Fig. A-4.2.2-1. If the spray plume has two flux peaks, then data shall be acquired at both MTVF locations, and corresponding 50% MTVF points, as shown in Fig. A-4.2.2-2.

Additional considerations of the Phase Doppler Particle Analyzer technique are as follows:

(a) The receiver should be positioned at 30 deg off axis from the forward direction. The receiver shall be in a plane perpendicular to the plane of the green beams, from which phase is obtained.

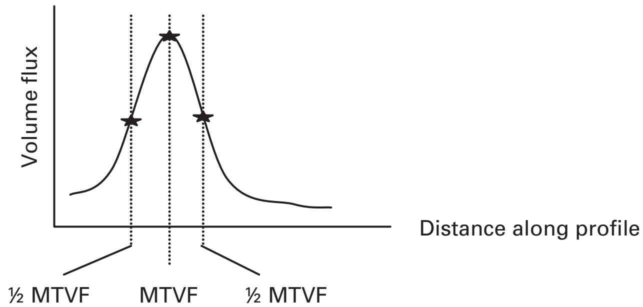
(b) The size of the beam crossing or measurement region (waist) shall be made to be roughly equal to or larger than the size of the largest droplet present. There may thus be a dependence of waist size on injection pressure, nozzle type, etc. Selection of beam expander and transmitting lens determines the waist size. Refer to the PDPA instruction manual for optics considerations.

(c) The same waist size shall be used for testing nozzles of the same type at the same operating conditions and the same downstream (axial) location.

(d) The shifted and unshifted transmitted beam power shall be within 10% of each other, as measured before and after testing by a power meter with a calibration traceable to the National Institute of Standards and Technology (NIST).

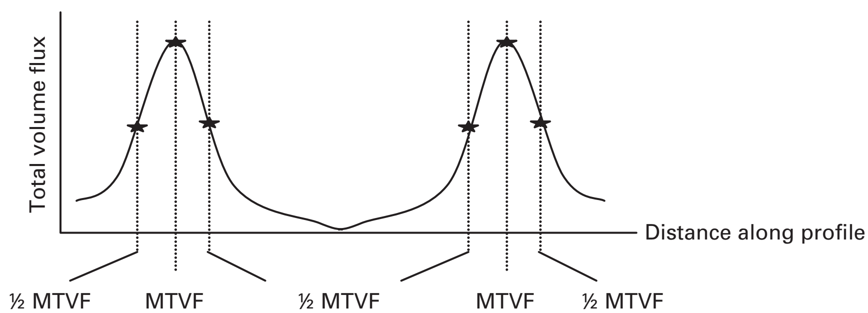
(e) The beam overlap at the measurement region shall be checked before and after testing to ensure that an overlap of >90% is maintained. Refer to the PDPA instruction manual for further details.

Fig. A-4.2.2-1 PDPA Measurement Locations for a Single Simple Spray Plume (Reprinted by Permission of Joseph Shakal)



GENERAL NOTE: For a single-spray plume, data are saved at three locations: the location of maximum total volume flux (MTVF), then at both 50% down points.

Fig. A-4.2.2-2 PDPA Measurement Locations for a Hollow-Cone Spray Plume (Reprinted by Permission of Joseph Shakal)



GENERAL NOTE: For a hollow-cone spray plume, data are saved at six locations: the location of maximum total volume flux (MTVF), then at both 50% down points, then repeated for the other side.

(f) The diameter vs. diameter difference plot shall be monitored during data acquisition to ensure that the data is centered at a diameter difference of 0.

(g) Intensity validation shall be used, with the following settings:

(1) The upper intensity limit reaches saturation (1 000 MV) at about $\frac{1}{3}$ D_{max}.

(2) The ratio of upper limit slope to lower limit slope = 10.

(3) The upper limit intercept is set to about 150 MV, and the lower limit intercept is set to 0.

(4) PMT voltage and laser power are set to raise the data to the upper intensity limit.

(h) The processor sampling rate or pass-band shall not be set higher than necessary, in terms of the velocity and transit times present.

(i) The same sampling rate or pass-band shall be used for testing nozzles of the same type at the same operating conditions and the same downstream (axial) location.

(j) The number of attempts shall be set to at least 25,000, and the validation rates shall be >95% for velocity and >75% for diameter.

(k) The laser shall be operated in light-regulated mode, not current-regulated mode.

A-4.3 Air-Side Parameters

A-4.3.1 Duct Airflow. Duct volumetric airflow shall be calculated from measurements according to ref. [5].

A-4.3.2 Nozzle Air flow Rate. Volumetric airflow rate at the location of the nozzle shall be the same as the duct volumetric airflow rate.

A-4.3.3 Air Density. Air density shall be calculated from measurements of wet-bulb temperature, dry-bulb temperature, barometric pressure, and tunnel static pressure. Other parameters may be measured and used if the maximum error in the calculated density does not exceed 5%.

A-4.3.4 Air Temperature. Both wet- and dry-bulb temperatures shall be measured in accordance with ref. [6]. Measurement accuracy of ±0.25°C or better shall be obtained. Temperature measurement devices shall be readable to 0.25°C or better. Upstream of the nozzle, air dry-bulb temperature, T_{db0}, shall be between 7°C and 27°C and the relative humidity between 70% and 100% during the testing period for the test results to be considered valid. Temperature measurement devices shall be calibrated over the range of temperatures to be encountered during test against a temperature-measurement device with a calibration that is traceable to NIST or other national physical measure recognized as equivalent by NIST [2].

A-4.3.5 Air Wet-Bulb. The wet-bulb temperature sensor shall have an air velocity over the water-moistened wick-covered bulb of 3.5 m/s to 10 m/s. The dry-bulb temperature sensor shall be mounted upstream of the wet-bulb temperature sensor so its reading will not be depressed [2, 6].

A-4.3.6 Contamination. The chamber shall be tested at ambient conditions with no water flow to the nozzle to confirm there is no contamination from upstream or from instrument access locations.

A-4.3.7 Air Velocity. Air velocity measured in the axial direction in the duct shall be 2.5 m/s and 13 m/s. Nozzles shall be tested at these two air velocities. The test velocity shall be included in the test report. It shall be demonstrated that the airflow is even across the testing plane.

A-4.4 Water-Side Parameters

A-4.4.1 Water Flow. Water flow shall be measured using a flow-measurement device having an accuracy of ±2.0% of observed reading or better. Water flow instruments shall be calibrated over the range of flow to be encountered during test against a standard that is traceable to NIST or other national physical measure recognized as equivalent by NIST.

A-4.4.2 Water Temperature. Water temperatures shall be measured in accordance with ref. [6]. Measurement accuracy of ±0.5°C (±1.0°F) or better shall be obtained. Water temperature shall not be lower than the upstream dew point temperature, and not more than 27°C. The relative difference between the water and air temperature shall not be more or less than 3°C at the location of the measured spray nozzle. Temperature sensors shall be calibrated over the range of temperatures to be encountered during test against a temperature-measurement device with a calibration that is traceable to NIST or other national physical measure recognized as equivalent by NIST [2].

A-4.4.3 Water Conductivity. Water conductivity shall be measured using a conductivity meter having an accuracy ±10% of observed reading. The meter shall have a means for temperature compensation.

A-4.4.4 Droplet Resolution. Droplet-size resolution shall be 1 μm to 200 μm.

A-4.4.5 Water Pressure. Water pressure shall be measured using a pressure-measurement device having an accuracy of ±2.0% of observed reading. Oil-filled gages shall not be allowed because they will dampen the actual pressure fluctuations. The test water pressure shall be maintained at the design pressure set by the manufacturer. Pressure shall be dampened to maintain test pressure ±2%. Pressure-measurement instruments shall be calibrated for the pressure range to be encountered during test against a standard that is traceable to NIST or other national physical measure recognized as equivalent by NIST.

A-4.4.6 Acceptable Water Quality. The water shall be treated by reverse osmosis or demineralization. Conductivity of the water supplied to the nozzle shall ≤ 25 μS (micro Siemens). Water shall be filtered with a filter rated at ≤ 5 μm absolute.

A-4.5 Other Parameters

A-4.5.1 Chronometer. A quality watch with a sweep second hand, or a digital watch with a display in seconds that keeps time within 2 min per day is considered a primary instrument.

A-4.5.2 Barometer. The barometric pressure shall be measured with a mercury column barometer or other instrument with a demonstrated accuracy of ±200 Pa and readable to 50 Pa or finer [2]. Barometers shall be calibrated against a mercury column barometer with a calibration that is traceable to NIST or other national physical measures recognized as equivalent by NIST. A convenient method of doing this is to use an aneroid barometer as a transfer instrument and carry it back and forth to the National Weather Service for comparison [2]. A permanently mounted mercury column barometer should hold its calibration well enough so that comparisons every 3 mo should be sufficient. Transducer-type barometers shall be calibrated for each test. Barometers shall be maintained in good condition [2].

A-4.5.3 Corrections. Barometric readings shall be corrected for any difference in mercury density from standard or any change in length of the graduated scale due to temperature. Refer to manufacturer's instructions.

A-4.5.4 Equilibrium. Equilibrium conditions shall be established before each determination. Inlet water pressure shall fluctuate no more than ±5%.

A-4.6 Setup

A suggested nozzle-testing setup is diagrammed in Fig. A-4.6-1. Refer to Fig. A-4.6-2 for more detail of the laser diffraction instrument configuration.

A-4.6.1 High-Pressure Nozzle Orientation. The nozzle shall be oriented cocurrent to the airflow. The nozzle adaptor and manifold shall be constructed according to the nozzle manufacturer's recommendation. Setup shall minimize turbulence and vortices of the air stream. Nozzles with multiple heads shall be installed according to the manufacturer's recommendation.

A-4.6.2 Leakage. The ducts, chambers, manifolds, and other equipment utilized shall be designed to withstand the pressure and other forces to be encountered.

A-4.6.3 Resonance. It shall be demonstrated that the amplitude of dynamic pulsation shall not exceed ±2%. Such documentation shall be made available at the test site.

A-4.6.4 Chambers. A chamber shall be incorporated in a laboratory setup to provide a droplet-measuring station. It may be round, rectangular, or prismatic in shape to allow both the transmitter and receiver (as applicable) to be perpendicular to their window. The duct shall accommodate the plume of the nozzle that is tested to allow full formation of the nozzle pattern at its normal full-spray angle.

Strategically placed holes in the chamber are recommended for laser measurements to eliminate optical interference. Minimal purge air may be used to eliminate any spray contamination on the instrument optics outside of the chamber.

If measurements are through a glass window, the window shall be as thin as practical and made of laser-quality low-iron glass, with antireflective coatings on both sides, and with a Refractive Index (sodium D line) of 1.523 or better. Minimal external forced-air heating and/or heated purge air may be used to prevent fogging.

Windows shall be perpendicular to the transmitter and receiver (as applicable), or, if that is not practical, the receiver shall be perpendicular to its window.

Upstream and downstream duct lengths shall be sufficient to minimize turbulence and vortices.

A-4.6.5 Airflow-Settling Means. Airflow-settling means shall be installed upstream of the nozzle-measuring chamber where indicated on the test setup shown in Fig. A-4.6-1.

Any combination of screens or perforated plates that will meet these requirements may be used, but in general, a reasonable chamber length for the settling means is necessary to meet both requirements. Screens of square mesh, round wire with open areas of 50% to 60% should be used, and several will usually be needed to meet the above performance specifications. A performance check shall be performed to verify that the airflow settling means are providing proper airflow patterns [2]. The tunnel airflow should be characterized for both mean and turbulent airflow velocities. The spray should be located in regions of constant air velocities away from tunnel boundary layers. Top-hat velocity profiles with very small boundary-layer thickness are preferred.

A-5 COMPUTATION OF RESULTS

There is no computation of results. The measured data shall be reported as measured and the test conditions documented. Any conversions between measured values and the reported values shall be clearly stated and fully documented, i.e., measuring *MMD* and reporting in *VMD*, or vice versa.

A-6 REPORT OF RESULTS

The report shall include object, results, test data, and descriptions of the test setup and test instruments as outlined in Section A-3. All equipment measurement uncertainties/validation intensities, calibration verification technique(s), instrument software version(s), etc., shall be included. The laboratory shall be identified by name and location. Performance data for a nozzle shall be summarized in a manner similar to that shown in Form A-6-1. Droplet-size histograms for number and volume distribution shall be included. Cumulative number and volume distribution curves shall be included. A sample histogram is shown in Fig. A-6-1.

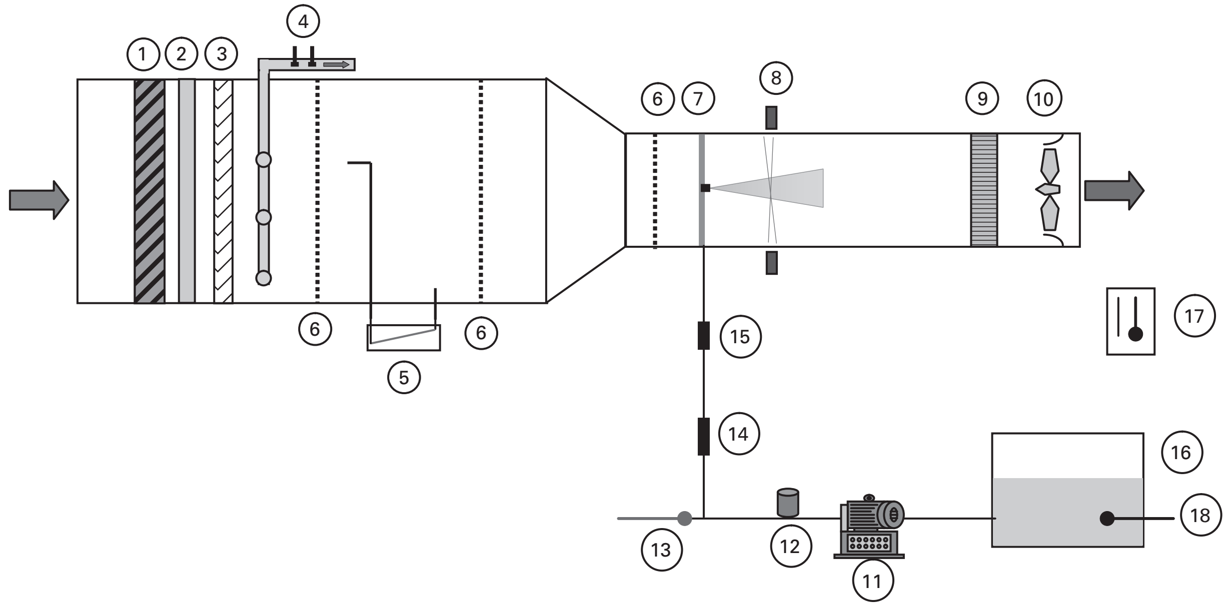
A-6.1 Diffraction Analyzer

Spray data shall be analyzed using a model-independent data-reduction routine. Spray data should not be analyzed using two or three parameter routines. Data shall be reported as weight fractions (given as percent by weight) in each of a minimum of 30 size bins, along with upper and lower diameters (in micrometers) for all bins.

Data-reduction routines such as Fraunhofer and Mie should be used to analyze the data. These methods are described in ref. [7], which provides guidance regarding the range of applicability of each model. Selection of the correct optical model becomes critical when a significant volume of material exists below 50 μm in size. The optical model used to calculate the results should be identified in any reports as either Mie or Fraunhofer.

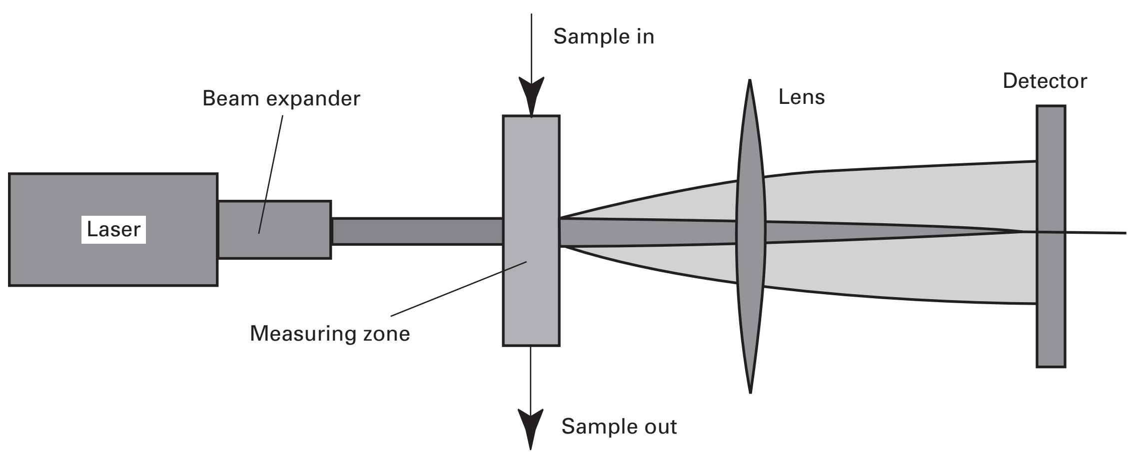
The report shall include D_{32} and D_{v09} (in micrometers) for each spray. The report should also include all additional representative sizes provided by the instrument, including D_{10}, D_{20}, D_{21}, D_{30}, D_{43}, D_{v01}, D_{v05}, and relative span, as applicable.

Fig. A-4.6-1 Suggested Wind Tunnel Setup for Testing a Nozzle



LEGEND:
1 = Humidifier
2 = Mist eliminator
3 = Filter
4 = Temperature sampling tree
5 = Static pressure / velocity pressure measurement
6 = Setting means (to eliminate the vena contracta sensor and create a developed flow profile)
7 = Nozzle manifold
8 = Droplet measurement device and test plane
9 = Flow straightener
10 = Fan
11 = Pump
12 = Filter
13 = Pressure refill and temperature sensor
14 = Flow meter
15 = Pressure
16 = Water reservoir
17 = Barometric station
18 = Conductivity sensor

Fig. A-4.6-2 Block Diagram of a Typical Laser Diffraction Instrument Configuration (Reprinted by Permission of Sympatec, Inc.)



A-6.2 Phase Doppler Particle Analyzer (PDPA)

Probe volume corrected (PVC-enabled) values shall be reported for the phase Doppler instrument, rather than raw values.

The following PDPA instrument parameters shall be recorded:

– waist diameter
– fringe spacing
– receiver slit width
– receiver-lens focal length
– transmitter-lens focal length
– beam expansion (0.5, 1, 2, etc.)
– processor model
– software revision number
– PMT voltage
– sampling rate or pass-band
– laser power or current setting

The following PDPA measured variables shall be recorded:

– *SMD*, temporal PVC mean
– *SMD*, spatial PVC mean
– D_{10}, temporal PVC mean
– D_{10}, spatial PVC mean
– D_{31}, temporal PVC mean
– D_{31}, spatial PVC mean
– D_{50}, temporal PVC mean
– D_{50}, spatial PVC mean
– D_{90}, temporal PVC mean
– D_{90}, spatial PVC mean
– total volume flux
– profile ID (12:00, 2:00, or 4:00)
– radial position along the profile
– "U" velocity mean
– "U" velocity RMS
– "V" velocity mean (if available)
– "V" velocity RMS (if available)
– "W" velocity mean (if available)
– "W" velocity RMS (if available)
– number of valid diameter samples

A-6.3 Identification

Performance sheets shall list the test nozzle and test setup. Sufficient details shall be listed to identify clearly the nozzle and setup.

A-6.4 Diffraction Analyzer Bin Data

The droplet data shall be presented in bin-size increments as specified in Section 6. The bin data shall include diameter and cumulative percent by volume, and may include count, velocity, and cumulative percent by number. The mathematical conversion between number and volume shall be reported.

A-6.5 Performance Curves

The results of a nozzle test shall be presented in both graphical and tabular form.

A-6.6 Test Points

The results for each determination shall be shown on the graphical distribution as a series of circled points or other appropriate legend, one for each variable plotted as ordinate.

A-6.7 Curve Fitting

Curves for each variable shall be obtained by drawing a curve or curves using the test points for reference. The curves shall not depart from the test points by more than 0.5% of any test value, and the sum of the deviations shall approximate zero.

A-6.8 Discontinuities

When discontinuities exist, they shall be identified with a broken line. If equilibrium cannot be established for any determination, the curves joining the points for that determination with adjacent points shall be drawn as broken lines.

A-6.9 Coordinates for Size Distribution Data of Packaged Nozzles

Size distribution curves shall be drawn with droplet-size data as abscissa. Cumulative volume and volume percentage shall be plotted as ordinates. A typical packaged-nozzle performance curve format is shown in Fig. A-6-1.

A-7 REFERENCES

[1] American Society of Testing and Materials (ASTM), ASTM E1458-92(2001) (withdrawn by ASTM).

[2] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 1985, ANSI/ASHRAE 51-1985, ANSI/AMCA Standard 210-85, *Laboratory Methods of Testing Fans for Rating*, ASHRAE, Atlanta, GA.

[3] ASTM, ASTM Standard E177-10, *Practice for Use of the Terms Precision and Bias in ASTM Test Methods*, ASTM, West Conshohocken, PA.

[4] The American Society of Mechanical Engineers (ASME), PTC 19.1, *Test Uncertainty*, ASME, New York.

[5] ASHRAE, 1992, ANSI/ASHRAE 41.2-1987(RA 92), *Standard Methods for Laboratory Airflow Measurement*, ASHRAE, Atlanta, GA.

[6] ASHRAE, 1991, ANSI/ASHRAE 41.1-1986(RA 91), *Standard Method for Temperature Measurement*, ASHRAE, Atlanta, GA.

[7] International Organization for Standardization (ISO), ISO 13320, *Particle Size Analysis — Laser Diffraction Methods — Part 1 General Principles*, ISO, Geneva, Switzerland.

Form A-6-1 Typical Performance Format for a Nozzle

TYPE OF ATOMIZATION MECHANISM: Swirl _______ Impact pin _______ Atomizing air _______

DIAMETER	VOLUME	NUMBER

TEST CONDITIONS

Air dry-bulb temperature, $T_{db,0}$: ____________________

Air wet-bulb temperature, $T_{wb,0}$: ____________________

Ambient air barometric pressure, p_b : ____________________

Air velocity at nozzle, $V_{a,N}$: ____________________

Duct static pressure: ____________________

Water flow: ____________________

Water conductivity: ____________________

Water temperature, T_w : ____________________

Water pressure to the nozzle: ____________________

Droplet measurement distance from orifice: ____________________

Number of timed/counted samples: ____________________

Number of volume samples: ____________________

Droplet count: ____________________

Spray angle [Note (1)]: ____________________

Spray plume diameter [Note (1)]: ____________________

Atomizing air dry-bulb temperature [Note (2)]: ____________________

Atomizing air wet-bulb temperature [Note (2)]: ____________________

Atomizing air pressure [Note (2)]: ____________________

NOTES:

(1) Calculated from diameter at measurement plane.

(2) If applicable

Date of test: ____________________ Test no.: ____________________ Project no.: ____________________

Manufacturer: ____________________ Model no.: ____________________

Appurtenances: ____________________

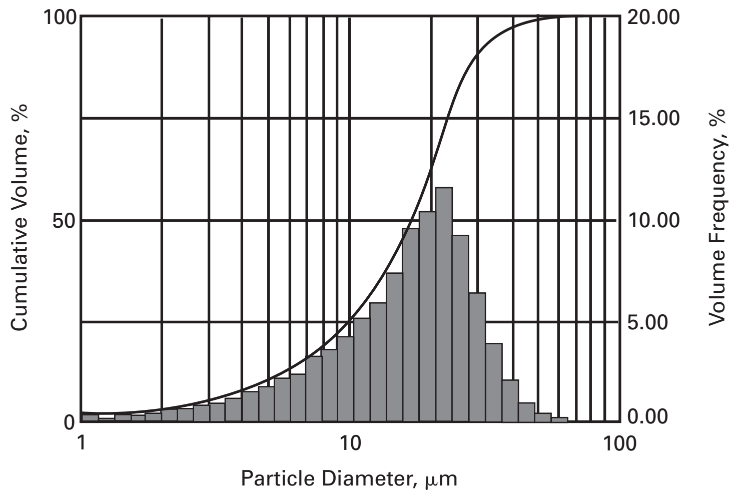
____

Name of testing laboratory: ____________________ Curve by: ____________________

Address of testing laboratory: ____________________ Signature: ____________________

____________________ Date: ____________________

Fig. A-6-1 Sample Droplet Size Histogram for Volume and Number Distribution



GENERAL NOTES:
(a) Standard Values:
Transmission = 18.99%
Cv = 544.4 ppm
SSA = 0.735 m^2/cc
D_{v10} = 4.93 μm
D_{v50} = 17.01 μm
D_{v90} = 30.14 μm
Span = 1.48
D[3][2] = 8.16 μm
D[4][3] = 17.15 μm
(b) Sixty-one records averaged.

A-8 ADDITIONAL READINGS ON THE TOPIC OF SPRAY NOZZLES

The following references are cited in ASME Paper No. 2002-GT-30563 from the *Proceedings of the ASME Turbo Expo 2002*.

Arnold, A. C., 1987, "The Drop Size of the Spray From Agricultural Fan Spray Atomizers as Determined by a Malvern and the Particle Measuring System (PMS) Instrument," *Atomization and Spray Technology*, 3:155–167.

Arnold, A. C., 1990, "A Comparative Study of Drop Sizing Equipment for Agricultural Fan-Spray Atomizers," *Aeronautical Science and Technology*, 12:431–445.

Chaker, M., Meher-Homji, C. B., and Mee, T. R. III, 2002, "Inlet Fogging of Gas Turbine Engines — Part A: Fog Droplet Thermodynamics, Heat Transfer and Practical Considerations," ASME Paper No: 2002-GT-30562, *Proceedings of ASME Turbo Expo 2002*, Amsterdam, The Netherlands, June 3–6, 2002.

Chaker, M., Meher-Homji, C. B., and Mee, T. R. III, 2002, "Inlet Fogging of Gas Turbine Engines — Part B: Fog Droplet Size Analysis, Nozzle Types, Measurement and Testing," ASME Paper No: 2002-GT-30563, *Proceedings of ASME Turbo Expo 2002*, Amsterdam, The Netherlands, June 3–6.

Chaker, M., Meher-Homji, C. B., and Mee, T. R. III, 2002, "Inlet Fogging of Gas Turbine Engines — Part C: Fog Behavior in Inlet Ducts, CFD Analysis and Wind Tunnel Experiments," ASME Paper No: 2002-GT-30564, *Proceedings of ASME Turbo Expo 2002*, Amsterdam, The Netherlands, June 3–6, 2002.

Doble, S. J., Matthews, G. A., Rutherford, I., and Southcombe, E. S. E., 1985, "1A System for Classifying Hydraulic Nozzles and Other Atomizers into Categories of Spray Quality," *Proceedings of the 1985 British Crop Protection Conference: Weeds*, vol. 9A-5, 1125–1133.

Dodge, L. G., 1987, "Comparison of Performance of Drop-Sizing Instruments," *Applied Optics*, 27:1328–1341.

Dupouy, D., Flores, B., Lisiecki, D., and Dumouchel C., 1994, "Behavior of Swirl Atomizers of Small Dimensions," ICLASS 94, Rouen, France, July 1994, 374–381.

Le Coz, J. F., 1998, "Comparison of Different Drop Sizing Techniques on Direct Injection Gasoline Sprays," Ninth International Symposium on Application of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 13–16, 1998.

Obokata, T., and Long, W. Q., 1994, "LDA/PDA Characterization of Conical Spray for Diesel Engine," ICLASS 94, Rouen, France, July 1994, 278–285.

Pilch, M., and Erdman, C. A., 1987, "The Use of Breakup Time Data and Velocity History Data to Predict the Maximum Size of Stable Fragments for Acceleration-Induced Breakup of Liquid Drop," *International Journal of Multiphase Flow*, 13:741–757.

Teske, M. E., Thistle, H. W., Hewitt, A. J.,, and Kirk, I. W., 2000, "Conversion of Droplet Size Distributions From PMS Optical Array Probe to Malvern Laser Diffraction," Eighth International Conference on Liquid Atomization and Spray Systems, Pasadena, CA, July 2000.

Young, B. W., and Bachalo, W. B, 1987, "The Direct Comparison of Three 'In-Flight' Droplet Sizing Techniques for Pesticide Spray Research," International Symposium on Optical Particle Sizing: Theory and Practice, Rouen, France, 1987.

A-9 ADDITIONAL USEFUL DOCUMENTS

Page, C.H., and Vigoureux, P., 1972, The International System of Units (SI), NBS Special Publication 330, National Bureau of Standards, Gaithersburg, MD.

ASHRAE, 1996, *HVAC Systems and Equipment Handbook*, chap. 19, ASHRAE, Atlanta, GA.

ASHRAE, 1975, ASHRAE Standard 41.5-75, *Standard Measurement Guide, Engineering Analysis of Experimental Data*, ASHRAE, Atlanta, GA.

ASHRAE, 1993, *Fundamentals Handbook*, chap. 6, ASHRAE, Atlanta, GA.

ASTM E799, *Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis*.

ASTM E1620, *Standard Terminology Relating to Liquid Particles and Atomization*

ASTM Z8711Z (working draft), *Standard Test Method for Determining Cross-Section Averaged Liquid Drop Size Characterizations in a Spray Using Laser Diffraction Instruments*

Publisher: American Society of Testing and Materials, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959 (www.astm.org)

ISO 9276-1, *Representation of Results of Particle Size Analysis — Graphical Representation*

ISO 9276-2, *Representation of Results of Particle Size Analysis — Calculation of Average Particle Sizes / Diameters and Moments from Particle Size Distributions*

Publisher: International Organization for Standardization (ISO) Central Secretariat, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211 Genève 20, Switzerland/Suisse (www.iso.org)

A-10 BIBLIOGRAPHY

ASHRAE, 1989, ANSI/ASHRAE 41.3-1989, *Standard Method for Pressure Measurement*, ASHRAE, Atlanta, GA.

ASHRAE, 1994, ANSI/ASHRAE 41.6-1994, *Standard Methods for Measurement of Moist Air Properties*, 1982, ASHRAE, Atlanta, GA.

ISO, 1991, ISO 5167-1:1991E, *Measurement of Fluid Flow by Means of Pressure Differential Devices — Part 1: Orifice Plates, Nozzles and Venturi Tubes in Circular Cross-section Conduits Running Full*, ISO, Geneva, Switzerland.

NONMANDATORY APPENDIX B
SAMPLE UNCERTAINTY ANALYSES

B-1 EVAPORATIVE COOLER EFFECTIVENESS

This system consists of an evaporative cooler where water is mixed with inlet air in a direct-contact heat exchanger. Water is supplied to the system by an electrical pump run at constant speed, and a blowdown stream is used to maintain water quality. The unit operation is such that the system is in service and not actively controlled. It is assumed in this example there is no water carryover to affect the downstream temperature measurement.

The performance test goal is to determine the corrected effectiveness of the system.

B-1.1 Test Boundary Description

The test boundary is shown on Fig. B-1.1-1. The streams crossing the test boundary that are to be determined are

(a) air entering the evaporative cooler
(b) air leaving the evaporative cooler

B-1.2 Base Reference Conditions and Required Correction Factors

Table B-1.2-1 tabulates the applicable base reference conditions. For the test, multiplicative corrections are made to the measured effectiveness using the α correction factors.

B-1.3 Required Corrections Factors

For the test, multiplicative corrections are made to the measured effectiveness using the α correction factors as follows:

$\alpha_{\rho 0}$ = correction to effectiveness to account for inlet air density
α_{V0} = correction to effectiveness to account for inlet air velocity

Correction to effectiveness to account for inlet air velocity different than design is calculated as follows:

$$\alpha_{V0} = 0.89325 + 0.035V \qquad \text{(B-1-1)}$$

where

V = inlet air velocity, m/s (fpm × 0.054681)

Correction to effectiveness to account for inlet air density different than design is calculated as follows:

$$\alpha\rho_0 = 0.988865 + 0.01\rho \qquad \text{(B-1-2)}$$

where

ρ = inlet air density, kg/m^3 (16.02 × lbm/ft^3)

B-1.4 Performance Equations

$$\varepsilon_{corr} = \varepsilon_{meas}\alpha_{V0}\alpha_{\rho 0} \qquad \text{(B-1-3)}$$

where

$$\varepsilon_{meas} = \left(\frac{T_{db1} - T_{db0}}{T_{db1} - T_{wb0}}\right) \qquad \text{(B-1-4)}$$

ε = effectiveness

B-1.5 Measured Values

The measured temperature values necessary for the determination of the corrected effectiveness of the evaporative cooler are shown in Table B-1.5-1.

B-1.6 Results and Calculations

Based on the test data (see Table B-1.5-1), the measured effectiveness is calculated.

$$\varepsilon_{\text{meas}} = (30.11 - 20.86) \,/\, (30.11 - 19.98) = 0.91282$$

The inlet air velocity at test conditions is as measured.

$$V_{\text{meas}} = 3.15129 \text{ m/s}$$

This results in a correction for air velocity different than design of

$$\alpha_{V0} = 0.89325 + 0.035V = 0.89325 + 0.035(3.15129) = 1.00355$$

The inlet air density at test conditions is calculated at the measured inlet dry- and wet-bulb temperatures and the barometric pressure.

$$\rho_{\text{meas}} = f\,(T_{db0}, T_{wb0}, P_0) = f\,(30.11, 20.86, 100.77) = 1.13856 \text{ kg/m}^3$$

This results in a correction for inlet air density different than design of

$$\alpha_{\rho 0} = 0.988865 + 0.01\rho = 0.988865 + 0.01(1.13856) = 1.00025$$

Thus, the corrected effectiveness is

$$\varepsilon_{\text{corr}} = \varepsilon_{\text{meas}} \times \alpha_{V0} \times \alpha_{\rho 0} = 0.91282 \times 1.00355 \times 1.00025 = 0.91629$$

B-1.7 Sensitivity Coefficient Determination

To determine the test uncertainty, it is necessary to calculate the impact that each measurement has on the

Fig. B-1.1-1 Evaporative Cooler Test Boundary Diagram

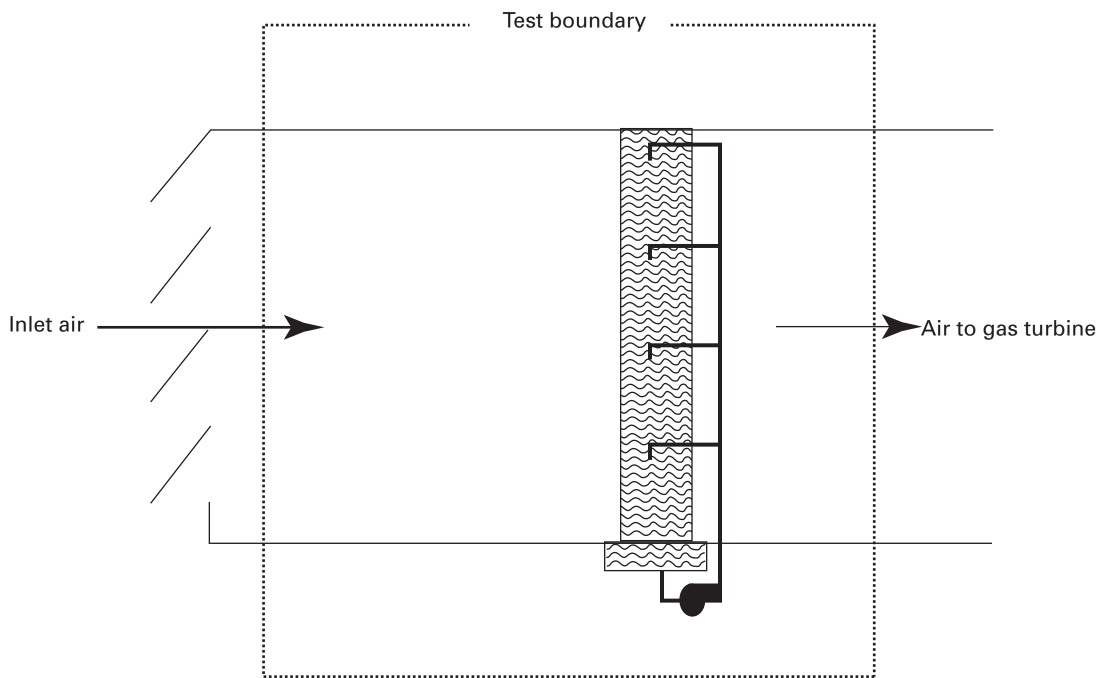


Table B-1.2-1 Base Reference Conditions

Description	Value
Inlet air velocity	3.05 m/s (32.808 fpm)
Inlet air density	1.1135 kg/m^3 (0.0695 lbm/ft^3)
Inlet air pressure	101.3 kPa (14.692 psia)
Inlet air dry-bulb temperature	35.0°C (95.0°F)
Inlet air wet-bulb temperature	25.0°C (77.0°F)
Exit air dry-bulb temperature	26°C (78.8°F)

relevant performance factor. ASME PTC 19.1 contains a rigorous discussion of the methods that can be used. For this analysis, perturbation analysis is used. This is done by calculating the change in test result that results from changing one parameter when all others are held constant.

For inlet dry-bulb temperature, a two-way perturbation follows.

$$\varepsilon_{corr} = [(T_{db0} - T_{db1})/(T_{db0} - T_{wb0})]\ \varepsilon_{meas} \times \alpha_{V0} \times \alpha_{\rho 0}$$
$$= 0.91282$$

$$\varepsilon_{corr+} = \{[(T_{db0} + 0.1) - T_{db1}]/[(T_{db0} + 0.1) - T_{wb0}]\}\varepsilon_{meas} \times \alpha_{V0} \times \alpha_{\rho 0}'$$
$$= 0.91714$$

where

$\alpha_{\rho 0}'$ = the correction for inlet air density different than design due to changes in inlet air dry-bulb temperature

$$\varepsilon_{corr-} = \{[(T_{db0} - 0.1) - T_{db1}]/[(T_{db0} - 0.1) - T_{wb0}]\}\varepsilon_{meas} \times \alpha_{V0} \times \alpha_{\rho 0}''$$
$$= -0.91542$$

So, the sensitivity coefficient is

$$\Delta\varepsilon_{corr/Tdb0} = (\varepsilon_{corr+} - \varepsilon_{corr-}) / [(T_{db0} + 0.1) - (T_{db0} - 0.1)]$$
$$= (0.91714 - 0.91542) / (0.2)$$
$$= 0.008605 / ºC$$

This value is then converted to percent per degrees Celsius, %/°C, for later use in the total test uncertainty calculations.

$$\delta\,\varepsilon_{corr\ /Tdb0}\ (\%/°C) = \delta\,\varepsilon_{corr\ /Tdb0} \times (100 / \varepsilon_{corr})$$
$$= 0.008605 \times 100 / 0.91629$$
$$= 0.93909\%/°C$$

For this calculation, a perturbation step size of 0.1°C was used. Care must be taken to choose step sizes small enough so that the calculated sensitivity coefficients approximate the partial derivative of the test result with respect to the parameter of interest. This is most important in calculations that involve highly nonlinear equations.

As a comparison point, the above sensitivity coefficient determination is repeated here using differential equations, which yields an exact value as follows.

$$\delta\,\varepsilon_{corr\,/Tdb0} = (T_{db1} - T_{wb0})/(T_{db0} - T_{wbo})^{\wedge}2$$
$$= 0.008575\ /\ °C$$

For this variable, the perturbation and the differentiation methods produce an equivalent result.

Repeating the process, as based on the perturbation method, for the other measured parameters, with perturbation step sizes of 0.1°C for temperature and 0.1% for pressure and flow, yields the values for sensitivity coefficients shown in Table B-1.7-1.

B-1.8 Parameter of Interest Uncertainty Determination

The uncertainty of each measurement is determined by combining the systematic and random uncertainties of all measurements in the system.

B-1.8.1 Systematic Uncertainty Calculation. The systematic uncertainty of the dry-bulb temperature at the inlet to the test boundary is calculated per the methods described in ASME PTC 19.1.

As can be seen from Table B-1.8-1, it is necessary to identify the contributors to the systematic uncertainty, as well as assess the magnitude of each contributor. The "Notes" column of this table provides information on how the magnitude of each contributor was established. Of particular interest is the row titled "Spatial Gradient," which is a reflection of how well the bulk-fluid temperature is known.

The spatial gradient is a statistically determined value that is a function of the standard deviation of the measurements in a grid at each time point, and the inverse of the number of measurements. Thus, the spatial gradient uncertainty contribution tends to increase as the difference in grid readings increases, or as the number of measurement points is reduced. The calculation is shown in Table B-1.8.1-2.

Similarly, the systematic uncertainties for the other parameters are developed as shown in Table B-1.8.1-3.

B-1.8.2 Random Uncertainty Calculation. The random uncertainty is calculated per ASME PTC 19.1 using the test measurements. Random uncertainty is a function of the standard deviation of measurements taken at different time points in the test period, and is inversely related to the number of readings.

For parameter T_{db0}, the standard deviation of the readings, S_x, is calculated as the average standard deviation of readings taken from each of the nine instruments (see first rows of Table B-1.5-1). In this example, this value is 0.095°C (average of the nine values in the stdev column of Table B-1.5-1). The random uncertainty, P_r, of this variable is then calculated as follows:

P_r = [Student's T value (95% confidence interval, 31 measurements)] $\times S_x$ / √ number of measurements
$= 2.042 \times 0.095\ /\ \sqrt{31}$
$= 0.035°C$

This value, when multiplied by the sensitivity factor, yields the random uncertainty contribution of T_{db0}.

$P_r = 0.939\ \%/°C \times 0.035°C$
$= 0.033\ \%$

In Table B-1.8.2-1, the total test uncertainty is calculated based on the sensitivity coefficients and systematic uncertainties, as calculated above, and the random uncertainties as calculated in columns 8 through 14.

The corrected effectiveness test uncertainty is 8.04%. Another way of saying this is that the corrected effectiveness is 0.91629 ± 0.074.

B-2 MEASURED EXIT DRY-BULB TEMPERATURE OF THE INLET FOGGER

This system consists of an inlet fogger where pressurized water is sprayed into inlet air in a direct-contact heat exchanger. Water is supplied to the system by variable-speed electrical pumps, and a drain in the floor of the inlet is used to remove water that is not evaporated. The water-spray flow is controlled with the aim of maintaining a downstream air temperature that is always 1°C greater than the air wet-bulb temperature. It is assumed in this example there is no water carryover to affect the downstream temperature measurement.

The performance test goal is to determine the measured exit dry-bulb temperature of the fogger.

B-2.1 Test Boundary Description

The test boundary is shown on Fig. B-2.1-1. The streams crossing the test boundary that are to be determined are

(a) the air entering the inlet fogger
(b) the air leaving the inlet fogger

B-2.2 Base Reference Conditions and Required Correction Factors; Performance Equations

For the test, no corrections are required because the test goal is a measured parameter (see Table B-2.2-1). Base reference conditions are provided for information only. For the exit-air dry-bulb temperature, the base reference value is 22.0ºC (71.6ºF). The performance equation is as follows:

$$T_{db2,meas} = T_{db2,meas} \qquad \text{(B-2-1)}$$

B-2.3 Results Calculations

Based on the test data, the exit-air dry-bulb temperature is

$$T_{db2,meas} = 24.03°C$$

B-2.4 Sensitivity Coefficient Determination

To determine the test uncertainty, it is necessary to calculate the impact that each measurement has on the relevant performance factor. ASME PTC 19.1 contains a rigorous discussion of the methods that can be used. For this analysis, an examination of the fundamental equation reveals that the test goal is one measured parameter without any corrections, hence it will have a sensitivity coefficient of unity.

Table B-1.5-1 begins on next page

Table B-1.5-1 Measured Data

Description	Measured Values, °C													
Elapsed Test Time, min	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Description														
Inlet Air Dry Bulb Temp., #1	30.0	30.1	30.2	30.2	30.0	30.1	30.1	29.9	30.0	30.1	30.2	30.2	30.0	30.1
Inlet Air Dry Bulb Temp., #2	29.0	29.1	29.2	29.2	29.0	29.1	29.1	28.9	29.0	29.1	29.2	29.2	29.0	29.1
Inlet Air Dry Bulb Temp., #3	30.5	30.6	30.7	30.7	30.5	30.6	30.6	30.4	30.5	30.6	30.7	30.7	30.5	30.6
Inlet Air Dry Bulb Temp., #4	30.3	30.4	30.5	30.5	30.3	30.4	30.4	30.2	30.3	30.4	30.5	30.5	30.3	30.4
Inlet Air Dry Bulb Temp., #5	29.8	29.9	30.0	30.0	29.8	29.9	29.9	29.7	29.8	29.9	30.0	30.0	29.8	29.9
Inlet Air Dry Bulb Temp., #6	31.0	31.1	31.2	31.2	31.0	31.1	31.1	30.9	31.0	31.1	31.2	31.2	31.0	31.1
Inlet Air Dry Bulb Temp., #7	30.8	30.9	31.0	31.0	30.8	30.9	30.9	30.7	30.8	30.9	31.0	31.0	30.8	30.9
Inlet Air Dry Bulb Temp., #8	29.6	29.7	29.8	29.8	29.6	29.7	29.7	29.5	29.6	29.7	29.8	29.8	29.6	29.7
Inlet Air Dry Bulb Temp., #9	29.3	29.4	29.5	29.5	29.3	29.4	29.4	29.2	29.3	29.4	29.5	29.5	29.3	29.4
Average	30.03	30.13	30.23	30.23	30.03	30.13	30.13	29.93	30.03	30.13	30.23	30.23	30.03	30.13
Standard deviation	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Inlet Air Wet Bulb Temp., #1	20.0	19.9	19.8	19.9	19.8	19.9	20.2	20.1	20.0	20.0	19.9	19.8	19.9	19.8
Inlet Air Wet Bulb Temp., #2	19.0	18.9	18.8	18.9	18.8	18.9	19.2	19.1	19.0	19.0	18.9	18.8	18.9	18.8
Inlet Air Wet Bulb Temp., #3	20.5	20.4	20.3	20.4	20.3	20.4	20.7	20.6	20.5	20.5	20.4	20.3	20.4	20.3
Inlet Air Wet Bulb Temp., #4	20.3	20.2	20.1	20.2	20.1	20.2	20.5	20.4	20.3	20.3	20.2	20.1	20.2	20.1
Inlet Air Wet Bulb Temp., #5	19.8	19.7	19.6	19.7	19.6	19.7	20.0	19.9	19.8	19.8	19.7	19.6	19.7	19.6
Inlet Air Wet Bulb Temp., #6	21.0	20.9	20.8	20.9	20.8	20.9	21.2	21.1	21.0	21.0	20.9	20.8	20.9	20.8
Inlet Air Wet Bulb Temp., #7	20.8	20.7	20.6	20.7	20.6	20.7	21.0	20.9	20.8	20.8	20.7	20.6	20.7	20.6
Inlet Air Wet Bulb Temp., #8	19.6	19.5	19.4	19.5	19.4	19.5	19.8	19.7	19.6	19.6	19.5	19.4	19.5	19.4
Inlet Air Wet Bulb Temp., #9	19.3	19.2	19.1	19.2	19.1	19.2	19.5	19.4	19.3	19.3	19.2	19.1	19.2	19.1
Average	20.03	19.93	19.83	19.93	19.83	19.93	20.23	20.13	20.03	20.03	19.93	19.83	19.93	19.83
Standard deviation	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Exit Air Dry Bulb Temp., #1	20.8	20.8	20.7	20.8	20.9	21.0	20.9	20.7	20.8	20.8	20.8	20.7	20.8	20.9
Exit Air Dry Bulb Temp., #2	19.8	19.8	19.7	19.8	19.9	20.0	19.9	19.7	19.8	19.8	19.8	19.7	19.8	19.9
Exit Air Dry Bulb Temp., #3	21.3	21.3	21.2	21.3	21.4	21.5	21.4	21.2	21.3	21.3	21.3	21.2	21.3	21.4
Exit Air Dry Bulb Temp., #4	21.1	21.1	21.0	21.1	21.2	21.3	21.2	21.0	21.1	21.1	21.1	21.0	21.1	21.2
Exit Air Dry Bulb Temp., #5	20.6	20.6	20.5	20.6	20.7	20.8	20.7	20.5	20.6	20.6	20.6	20.5	20.6	20.7
Exit Air Dry Bulb Temp., #6	21.8	21.8	21.7	21.8	21.9	22.0	21.9	21.7	21.8	21.8	21.8	21.7	21.8	21.9
Exit Air Dry Bulb Temp., #7	21.6	21.6	21.5	21.6	21.7	21.8	21.7	21.5	21.6	21.6	21.6	21.5	21.6	21.7
Exit Air Dry Bulb Temp., #8	20.4	20.4	20.3	20.4	20.5	20.6	20.5	20.3	20.4	20.4	20.4	20.3	20.4	20.5
Exit Air Dry Bulb Temp., #9	20.1	20.1	20.0	20.1	20.2	20.3	20.2	20.0	20.1	20.1	20.1	20.0	20.1	20.2
Average	20.83	20.83	20.73	20.83	20.93	21.03	20.93	20.73	20.83	20.83	20.83	20.73	20.83	20.93
Standard deviation	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Inlet air velocity, m/s	3.15	3.16	3.16	3.16	3.15	3.14	3.14	3.15	3.15	3.16	3.16	3.16	3.15	3.14
Blowdown flow, kg/s	1.0	1.1	1.1	1.0	0.9	1.0	1.0	1.1	1.1	1.0	0.9	1.0	1.0	1.1
Inlet air static pressure, ckPa	1.01	1.02	1.02	1.00	1.01	0.99	1.00	1.01	1.02	1.00	1.01	1.02	1.02	1.00

Table B-1.5-1 Measured Data (Cont'd)

Measured Values, °C																		
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Avg.	Stdev
30.1	29.9	30.0	30.1	30.2	30.2	30.0	30.1	30.1	29.9	30.0	30.1	30.2	30.2	30.0	30.1	30.1	30.08	0.09
29.1	28.9	29.0	29.1	29.2	29.2	29.0	29.1	29.1	28.9	29.0	29.1	29.2	29.2	29.0	29.1	29.1	29.08	0.09
30.6	30.4	30.5	30.6	30.7	30.7	30.5	30.6	30.6	30.4	30.5	30.6	30.7	30.7	30.5	30.6	30.6	30.58	0.09
30.4	30.2	30.3	30.4	30.5	30.5	30.3	30.4	30.4	30.2	30.3	30.4	30.5	30.5	30.3	30.4	30.4	30.38	0.09
29.9	29.7	29.8	29.9	30.0	30.0	29.8	29.9	29.9	29.7	29.8	29.9	30.0	30.0	29.8	29.9	29.9	29.88	0.09
31.1	30.9	31.0	31.1	31.2	31.2	31.0	31.1	31.1	30.9	31.0	31.1	31.2	31.2	31.0	31.1	31.1	31.08	0.09
30.9	30.7	30.8	30.9	31.0	31.0	30.8	30.9	30.9	30.7	30.8	30.9	31.0	31.0	30.8	30.9	30.9	30.88	0.09
29.7	29.5	29.6	29.7	29.8	29.8	29.6	29.7	29.7	29.5	29.6	29.7	29.8	29.8	29.6	29.7	29.7	29.68	0.09
29.4	29.2	29.3	29.4	29.5	29.5	29.3	29.4	29.4	29.2	29.3	29.4	29.5	29.5	29.3	29.4	29.4	29.38	0.09
30.13	29.93	30.03	30.13	30.23	30.23	30.03	30.13	30.13	29.93	30.03	30.13	30.23	30.23	30.03	30.13	30.13	**30.11**	...
0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	...	...
19.9	20.2	20.1	20.0	20.0	19.9	19.8	19.9	19.8	20.0	19.9	19.8	19.9	19.8	19.9	20.2	20.1	19.94	0.13
18.9	19.2	19.1	19.0	19.0	18.9	18.8	18.9	18.8	19.0	18.9	18.8	18.9	18.8	18.9	19.2	19.1	18.94	0.13
20.4	20.7	20.6	20.5	20.5	20.4	20.3	20.4	20.3	20.5	20.4	20.3	20.4	20.3	20.4	20.7	20.6	20.44	0.13
20.2	20.5	20.4	20.3	20.3	20.2	20.1	20.2	20.1	20.3	20.2	20.1	20.2	20.1	20.2	20.5	20.4	20.24	0.13
19.7	20.0	19.9	19.8	19.8	19.7	19.6	19.7	19.6	19.8	19.7	19.6	19.7	19.6	19.7	20.0	19.9	19.74	0.13
20.9	21.2	21.1	21.0	21.0	20.9	20.8	20.9	20.8	21.0	20.9	20.8	20.9	20.8	20.9	21.2	21.1	20.94	0.13
20.7	21.0	20.9	20.8	20.8	20.7	20.6	20.7	20.6	20.8	20.7	20.6	20.7	20.6	20.7	21.0	20.9	20.74	0.13
19.5	19.8	19.7	19.6	19.6	19.5	19.4	19.5	19.4	19.6	19.5	19.4	19.5	19.4	19.5	19.8	19.7	19.54	0.13
19.2	19.5	19.4	19.3	19.3	19.2	19.1	19.2	19.1	19.3	19.2	19.1	19.2	19.1	19.2	19.5	19.4	19.24	0.13
19.93	20.23	20.13	20.03	20.03	19.93	19.83	19.93	19.83	20.03	19.93	19.83	19.93	19.83	19.93	20.23	20.13	**19.98**	...
0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	...	...
21.0	20.9	20.7	20.8	20.8	20.7	20.8	20.9	21.0	20.8	20.8	20.7	20.8	20.9	21.0	20.9	20.7	20.83	0.10
20.0	19.9	19.7	19.8	19.8	19.7	19.8	19.9	20.0	19.8	19.8	19.7	19.8	19.9	20.0	19.9	19.7	19.83	0.10
21.5	21.4	21.2	21.3	21.3	21.2	21.3	21.4	21.5	21.3	21.3	21.2	21.3	21.4	21.5	21.4	21.2	21.33	0.10
21.3	21.2	21.0	21.1	21.1	21.0	21.1	21.2	21.3	21.1	21.1	21.0	21.1	21.2	21.3	21.2	21.0	21.13	0.10
20.8	20.7	20.5	20.6	20.6	20.5	20.6	20.7	20.8	20.6	20.6	20.5	20.6	20.7	20.8	20.7	20.5	20.63	0.10
22.0	21.9	21.7	21.8	21.8	21.7	21.8	21.9	22.0	21.8	21.8	21.7	21.8	21.9	22.0	21.9	21.7	21.83	0.10
21.8	21.7	21.5	21.6	21.6	21.5	21.6	21.7	21.8	21.6	21.6	21.5	21.6	21.7	21.8	21.7	21.5	21.63	0.10
20.6	20.5	20.3	20.4	20.4	20.3	20.4	20.5	20.6	20.4	20.4	20.3	20.4	20.5	20.6	20.5	20.3	20.43	0.10
20.3	20.2	20.0	20.1	20.1	20.0	20.1	20.2	20.3	20.1	20.1	20.0	20.1	20.2	20.3	20.2	20.0	20.13	0.10
21.03	20.93	20.73	20.83	20.83	20.73	20.83	20.93	21.03	20.83	20.83	20.73	20.83	20.93	21.03	20.93	20.73	**20.86**	...
0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	...	...
3.14	3.15	3.15	3.16	3.16	3.16	3.15	3.14	3.14	3.15	3.16	3.16	3.16	3.15	3.14	3.14	3.15	**3.151**	0.01
1.1	1.0	0.9	1.0	1.0	1.1	1.1	1.0	0.9	1.0	1.0	1.1	1.1	1.0	0.9	1.0	1.0	**1.016**	0.07
1.01	0.99	1.00	1.01	1.02	1.01	1.02	1.02	1.00	1.01	0.99	1.00	1.01	1.02	1.00	1.00	1.00	**1.008**	0.01

Table B-1.7-1 Calculation of Sensitivity Coefficients

Parameter	Design	Test	Tdb0 Perturbation		Twb0 Perturbation		Tdb1 Perturbation		P0 Perturbation		V0 Perturbation	
Tdb0	35	30.11	30.21	30.01	30.11	30.11	30.11	30.11	30.11	30.11	30.11	30.11
Twb0	25	19.98	19.98	19.98	20.08	19.88	19.98	19.98	19.98	19.98	19.98	19.98
Tdb1	26	20.86	20.86	20.86	20.86	20.86	20.96	20.76	20.86	20.86	20.86	20.86
P0	101.3	100.77	100.77	100.77	100.77	100.77	100.77	100.77	100.87	100.67	100.77	100.77
E_{meas}	0.90000	0.91282	0.91367	0.91195	0.92192	0.90391	0.90296	0.92269	0.91282	0.91282	0.91282	0.91282
V0	3.05000	3.15129	3.15129	3.15129	3.15129	3.15129	3.15129	3.15129	3.15129	3.15129	3.15444	3.14814
$\rho 0$	1.11350	1.13856	1.13827	1.13886	1.13832	1.13880	1.13856	1.13856	1.13972	1.13741	1.13856	1.13856
$\alpha V0$	1.00000	1.00355	1.00355	1.00355	1.00355	1.00355	1.00355	1.00355	1.00355	1.00355	1.00366	1.000343
$\alpha \rho 0$	1.00000	1.00025	1.00025	1.00025	1.00025	1.00025	1.00025	1.00025	1.00026	1.00024	1.00025	1.00025
E_{corr}	0.90000	0.91629	0.91714	0.91542	0.92541	0.90734	0.90639	0.92619	0.91630	0.91628	0.91639	0.91619
Sensitivity: % / units			0.93909		9.86079		−10.80516		0.000105		0.0320	
Sensitivity: %/%									0.0115		0.1099	

NOTE: Units of Tdb0 are deg C, of Twb0 are deg C, of Tdb1 are deg C, of V0 are m/s and of $\rho 0$ are kg/m^3. The other parameters are non-dimensional.

Table B-1.8.1-1 Inlet Dry-Bulb Temperature Systematic Uncertainty Calculation

Tdb1 Instrument Uncertainty

Description	Sensitivity Factor, A	Units	Systematic Uncertainty, B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Calibration standard	1.000	°C/°C	0.100	°C	0.100	°C	From laboratory information
Calibration curve fit	1.000	°C/°C	0.020	°C	0.020	°C	Review of lab data points and cal curve
Cold junction temperature	1.000	°C/°C	0.000	°C	0.000	°C	4-wire RTD
Drift	1.000	°C/°C	0.010	°C	0.010	°C	OEM data = 0.1%/5 yr, in service $^1/_2$ year
Data acquisition system	1.000	°C/°C	0.005	°C	0.005	°C	DAS channels checked in lab
Spatial gradient	1.000	°C/°C	0.520	°C	0.520	°C	. . .
			Total		**0.530**	°C	

Table B-1.8.1-2 Inlet Dry-Bulb Temperature Measurement Spatial Gradient Calculation

Tdb0 Spatial Gradient Uncertainty Calculation

Description	Number of Measurements	Degrees of Freedom	Student's T-Value for 95% Confidence Interval	Average Standard Deviation of Readings at Each Time Stamp	Uncertainty
Symbol	n	$v = n-1$	2θ	std_{av}	=2q x $std_{av} / \sqrt{v}$
Spatial gradient	9	8	2.306	0.676	0.551

Table B-1.8.1-3 Measurement Systematic Uncertainty Calculations

Twb0 Instrument Uncertainty

Description	Sensitivity Factor	Units	Systematic Uncertainty , B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Calibration standard	1.000	°C/°C	0.100	°C	0.100	°C	From laboratory information
Calibration curve fit	1.000	°C/°C	0.020	°C	0.020	°C	Review of lab data points and cal curve
Aspiration water temperature	1.000	°C/°C	0.200	°C	0.200	°C	Engineering estimate
Cold junction temperature	1.000	°C/°C	0.000	°C	0.000	°C	4-wire RTD
Drift	1.000	°C/°C	0.010	°C	0.010	°C	OEM data = 0.1%/ 5 yr, in service 1/2 year
Data acquisition system	1.000	°C/°C	0.005	°C	0.005	°C	DAS channels checked in lab
Spatial gradient	1.000	°C/°C	0.520	°C	0.520	°C	. . .
				Total	**0.566**	°C	. . .

Tdb1 Instrument Uncertainty

Description	Sensitivity Factor	Units	Systematic Uncertainty, B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Calibration standard	1.000	°C/°C	0.100	°C	0.100	°C	From laboratory information
Calibration curve fit	1.000	°C/°C	0.020	°C	0.020	°C	Review of lab data points and cal curve
Cold junction temperature	1.000	°C/°C	0.000	°C	0.000	°C	4-wire RTD
Drift	1.000	°C/°C	0.010	°C	0.010	°C	OEM data = 0.1%/5 yr, in service 1/2 year
Data acquisition system	1.000	°C/°C	0.005	°C	0.005	°C	DAS channels checked in lab
Spatial gradient	1.000	°C/°C	0.520	°C	0.520	°C	. . .
				Total	**0.530**	°C	. . .

P0 Instrument Uncertainty

Description	Sensitivity Factor	Units	Systematic Uncertainty, B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Calibration standard	1.000	%/%	0.050	%	0.050	%	From laboratory information
Calibration curve fit	1.000	%/%	0.020	%	0.020	%	Review of lab data points and cal curve
Hysteresis	1.000	%/%	0.010	%	0.010	%	Review of lab data points and cal curve
Ambient temperature	1.000	%/%	0.025	%	0.025	%	OEM data = 0.05%/50°F (27.8°C) deviation, 25°F (13.9°C) deviation
Installation effect	1.000	%/%	0.100	%	0.100	%	Engineering estimate
Drift	1.000	%/%	0.040	%	0.040	%	OEM data = 0.2%/5 yr, in service 1 yr
Data acquisition system	1.000	%/%	0.005	%	0.005	%	DAS channels checked in lab
				Total	**0.072**	%	. . .

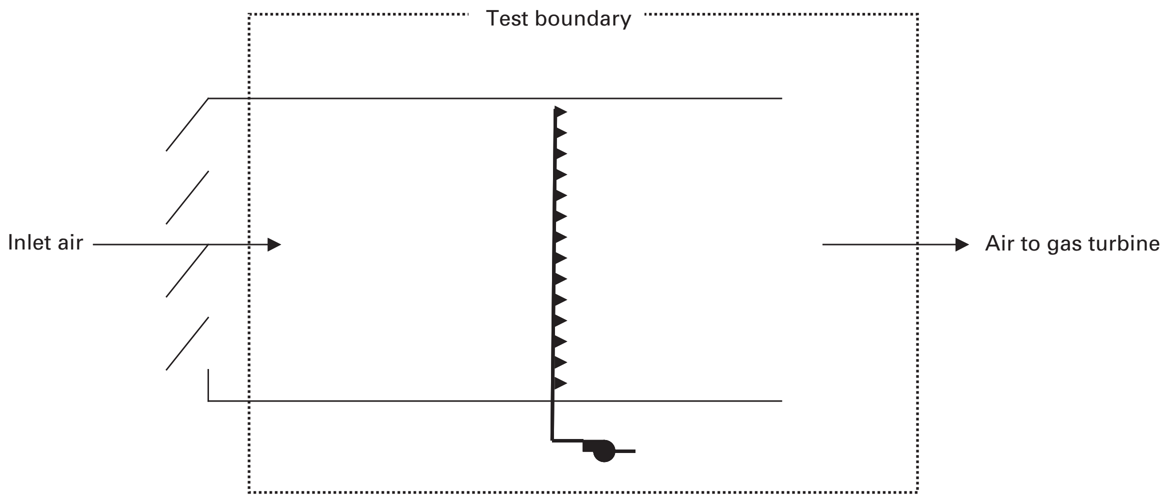
V0 Instrument Uncertainty

Description	Sensitivity Factor	Units	Systematic Uncertainty, B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Instrument	1.000	%/%	2.000	%	2.000	%	Simplification for this example
				Total	**2.000**	%	. . .

Table B-1.8.2-1 Evaporative Cooler Test-Result Uncertainty Calculation

Description	Symbol	Sensitivity Factor	Units	Systematic Uncertainty	Units	Systematic Uncertainty Contribution	Number of Meas.	Student's T-Value for 95% C.I.	STD	Units	Random Uncertainty	Units	Random Uncertainty Contribution
Formula		A		B		$C = A \times B$	D	$E = f(D)$	F		$G = E \times F / \sqrt{D}$		$H = A \times G$
Inlet air dry bulb temp.	Tdb0	0.939	%/°C	0.522	°C	0.491	31	2.042	0.095	°C	0.035	°C	0.033
Inlet air wet bulb temp.	Twb0	9.861	%/°C	0.566	°C	5.585	31	2.042	0.126	°C	0.046	°C	0.455
Exit air dry bulb temp.	Tdb1	−10.805	%/°C	0.530	°C	−5.726	31	2.042	0.096	°C	0.035	°C	−0.382
Inlet air barometric pressure	P0	0.012	%/°C	0.072	%	0.001	31	2.042	0.010	%	0.004	%	0.000
Inlet air velocity	V0	0.110	%/%	2.000	%	0.220	31	2.042	0.008	%	0.003	%	0.000
				Total Systematic		**8.017**						**Total Random**	**0.596**
												Total Uncertainty	**8.039**

Fig. B-2.1-1 Inlet Fogger Test Boundary Diagram



B-3 PARAMETER OF INTEREST UNCERTAINTY DETERMINATION

The uncertainty of each measurement is determined by combining the systematic and random uncertainties of all measurements in the system.

B-3.1 Systematic Uncertainty Calculation

The systematic uncertainty of the dry-bulb temperature at the inlet to the test boundary is calculated per the methods described in ASME PTC 19.1.

As can be seen in Table B-3.1-1, it is necessary to identify the contributors to the systematic uncertainty, as well as assess the magnitude of each contributor. The "Notes" column of this table provides information on how the magnitude of each contributor was established.

B-3.2 Random Uncertainty Calculation

The random uncertainty is calculated per ASME PTC 19.1 using the test measurements. Random uncertainty is a function of the standard deviation of measurements taken at different time points in the test period, and is inversely related to the number of readings.

For parameter $T_{db2\text{meas}}$, the standard deviation of the readings (see values in Table B-2.2-1), S_x, is calculated as the average standard deviaton of readings taken from each of the nine instruments. In this example, this value is 0.162 K. The random uncertainty, P_r, of this variable is then calculated as follows:

P_r = [Student's t value (95% confidence interval, 31 measurements)] × S_x / √ number of measurements

$$P_r = 2.042 \times 0.162 / \sqrt{31} = 0.0595 \text{ K}$$

This value, when multiplied by the sensitivity factor, yields the random uncertainty contribution of $T_{db2\text{ meas}}$:

$$P_r = 1 \text{ K/K} \times 0.0605°\text{C} = 0.0595 \text{ K}$$

In Table B-3.2-1, the total test uncertainty is calculated based on the sensitivity coefficients and systematic uncertainties, as calculated above, and the random uncertainties as calculated in columns 8 through 14.

B-3.3 Total Test Uncertainty

The measured exit-air dry-bulb temperature test uncertainty is 0.533 K. Another way of saying this is that the measured exit-air dry-bulb temperature is 24.03°C ± 0.533 K.

Table B-2.2-1 Measured Data

Description	Measured Values, °C														
Elapsed Test Time, min Description	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Exit Air Dry Bulb Temp., #1	24.0	24.0	24.1	24.0	23.9	23.9	24.0	23.8	24.0	24.1	24.3	23.9	24.0	23.9	23.8
Exit Air Dry Bulb Temp., #2	23.0	23.0	23.1	23.0	22.9	22.9	23.0	22.8	23.0	23.1	23.3	22.9	23.0	22.9	22.8
Exit Air Dry Bulb Temp., #3	24.5	24.5	24.6	24.5	24.4	24.4	24.5	24.3	24.5	24.6	24.8	24.4	24.5	24.4	24.3
Exit Air Dry Bulb Temp., #4	24.3	24.3	24.4	24.3	24.2	24.2	24.3	24.1	24.3	24.4	24.6	24.2	24.3	24.2	24.1
Exit Air Dry Bulb Temp., #5	23.8	23.8	23.9	23.8	23.7	23.7	23.8	23.6	23.8	23.9	24.1	23.7	23.8	23.7	23.6
Exit Air Dry Bulb Temp., #6	25.0	25.0	25.1	25.0	24.9	24.9	25.0	24.8	25.0	25.1	25.3	24.9	25.0	24.9	24.8
Exit Air Dry Bulb Temp., #7	24.8	24.8	24.9	24.8	24.7	24.7	24.8	24.6	24.8	24.9	25.1	24.7	24.8	24.7	24.6
Exit Air Dry Bulb Temp., #8	23.6	23.6	23.7	23.6	23.5	23.5	23.6	23.4	23.6	23.7	23.9	23.5	23.6	23.5	23.4
Exit Air Dry Bulb Temp., #9	23.3	23.3	23.4	23.3	23.2	23.2	23.3	23.1	23.3	23.4	23.6	23.2	23.3	23.2	23.1
Average	24.03	24.03	24.13	24.03	23.93	23.93	24.03	23. 83	24.03	24.13	24.33	23.93	24.03	23.93	23.83
Standard deviation	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68

Table B-3.1-1 Exit Dry-Bulb Temperature Systematic Uncertainty Calculation

Tdb2 Instrument Uncertainty							
Description	Sensitivity Factor	Units	Systematic Uncertainty, B	Units	Systematic Uncertainty Contribution, A×B	Units	Notes
Calibration standard	1.000	°C/°C	0.100	°C	0.100	°C	From laboratory information
Calibration curve fit	1.000	°C/°C	0.020	°C	0.020	°C	Review of lab data points and cal curve
Cold junction temperature	1.000	°C/°C	0.000	°C	0.000	°C	4-wire RTD
Drift	1.000	°C/°C	0.010	°C	0.010	°C	OEM data =0.1%/5 yr, in service $^1/_2$ yr
Data acquisition system	1.000	°C/°C	0.005	°C	0.005	°C	DAS channels checked in lab
Spatial gradient	1.000	°C/°C	0.520	°C	0.520	°C	. . .
				Total	**0.530**	°F	. . .

Table B-2.2-1 Measured Data (Cont'd)

Measured Values, °C																	
15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Avg.	Stdev
24.0	24.2	24.0	24.1	24.3	24.0	24.0	23.8	23.9	23.8	23.7	23.8	24.0	24.0	24.2	24.4	24.00	0.16
23.0	23.2	23.0	23.1	23.3	23.0	23.0	22.8	22.9	22.8	22.7	22.8	23.0	23.0	23.2	23.4	23.00	0.16
24.5	24.7	24.5	24.6	24.8	24.5	24.5	24.3	24.4	24.3	24.2	24.3	24.5	24.5	24.7	24.9	24.50	0.16
24.3	24.5	24.3	24.4	24.6	24.3	24.3	24.1	24.2	24.1	24.0	24.1	24.3	24.3	24.5	24.7	24.30	0.16
23.8	24.0	23.8	23.9	24.1	23.8	23.8	23.6	23.7	23.6	23.5	23.6	23.8	23.8	24.0	24.2	23.80	0.16
25.0	25.2	25.0	25.1	25.3	25.0	25.0	24.8	24.9	24.8	24.7	24.8	25.0	25.0	25.2	25.4	25.00	0.16
24.8	25.0	24.8	24.9	25.1	24.8	24.8	24.6	24.7	24.6	24.5	24.6	24.8	24.8	25.0	25.2	24.80	0.16
23.6	23.8	23.6	23.7	23.9	23.6	23.6	23.4	23.5	23.4	23.3	23.4	23.6	23.6	23.8	24.0	23.60	0.16
23.3	23.5	23.3	23.4	23.6	23.3	23.3	23.1	23.2	23.1	23.0	23.1	23.3	23.3	23.5	23.7	23.30	0.16
24.03	24.23	24.03	24.13	24.33	24.03	24.03	23.83	23.93	23.83	23.73	23.83	24.03	24.03	24.23	24.43	24.03	...
0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	...	...

Table B-3.2-1 Measured Exit Air Dry Bulb Temperature, Post-Test Uncertainty Analysis

Description	Symbol	Sensitivity Factor	Units	Systematic Uncertainty	Units	Systematic Uncertainty Contribution	Number of Meas.	Student's T-Value for 95% C.I.	STD	Units	Random Uncertainty	Units	Random Uncertainty Contribution
Formula		***A***		***B***		$C = A \times B$	D	$E = f(D)$	F		$G = E \times F / \sqrt{D}$		$H = A \times G$
Exit air dry bulb temp.	Tdb2	1.000	K/K	0.530	K	0.530	31	2.042	0.162	K	0.0595	°C	0.0595
			Total Systematic			**0.530**					**Total Random**		**0.060**
											Total Uncertainty		**0.533**

PERFORMANCE TEST CODES (PTC)

General Instructions	PTC 1-2004 (R2009)
Definitions and Values	PTC 2-2001 (R2009)
Fired Steam Generators	PTC 4-1998
Coal Pulverizers	PTC 4.2-1969 (R2009)
Air Heaters	PTC 4.3-1974 (R1991)
Gas Turbine Heat Recovery Steam Generators	PTC 4.4-2008
Steam Turbines	PTC 6-2004
Steam Turbines in Combined Cycles	PTC 6.2-2011
Appendix A to PTC 6, The Test Code for Steam Turbines	PTC 6A-2000 (R2009)
PTC 6 on Steam Turbines — Interpretations 1977–1983	PTC 6
Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines	PTC 6 Report-1985 (R2003)
Procedures for Routine Performance Tests of Steam Turbines	PTC 6S-1988 (R2009)
Centrifugal Pumps	PTC 8.2-1990
Compressors and Exhausters	PTC 10-1997 (R2009)
Fans	PTC 11-2008
Closed Feedwater Heaters	PTC 12.1-2000 (R2005)
Steam Surface Condensers	PTC 12.2-2010
Deaerators	PTC 12.3-1997 (R2009)
Moisture Separator Reheaters	PTC 12.4-1992 (R2009)
Single Phase Heat Exchangers	PTC 12.5-2000 (R2005)
Reciprocating Internal-Combustion Engines	PTC 17-1973 (R2003)
Hydraulic Turbines and Pump-Turbines	PTC 18-2011
Test Uncertainty	PTC 19.1-2005
Pressure Measurement	PTC 19.2-2010
Temperature Measurement	PTC 19.3-1974 (R2004)
Flow Measurement	PTC 19.5-2004
Measurement of Shaft Power	PTC 19.7-1980 (R1988)
Flue and Exhaust Gas Analyses	PTC 19.10-1981
Steam and Water Sampling, Conditioning, and Analysis in the Power Cycle	PTC 19.11-2008
Data Acquisition Systems	PTC 19.22-2007
Guidance Manual for Model Testing	PTC 19.23-1980 (R1985)
Particulate Matter Collection Equipment	PTC 21-1991
Gas Turbines	PTC 22-2005
Atmospheric Water Cooling Equipment	PTC 23-2003
Ejectors	PTC 24-1976 (R1982)
Pressure Relief Devices	PTC 25-2008
Speed-Governing Systems for Hydraulic Turbine-Generator Units	PTC 29-2005 (R2010)
Air Cooled Heat Exchangers	PTC 30-1991 (R2011)
Air-Cooled Steam Condensers	PTC 30.1-2007
Ion Exchange Equipment	PTC 31-1973 (R1991)
Waste Combustors With Energy Recovery	PTC 34-2007
Measurement of Industrial Sound	PTC 36-2004
Determining the Concentration of Particulate Matter in a Gas Stream	PTC 38-1980 (R1985)
Steam Traps	PTC 39-2005 (R2010)
Flue Gas Desulfurization Units	PTC 40-1991
Wind Turbines	PTC 42-1988 (R2004)
Overall Plant Performance	PTC 46-1996
Integrated Gasification Combined Cycle Power Generation Plants	PTC 47-2006 (R2011)
Fuel Cell Power Systems Performance	PTC 50-2002 (R2009)
Gas Turbine Inlet Air-Conditioning Equipment	PTC 51-2011
Ramp Rates	PTC 70-2009
Performance Monitoring Guidelines for Steam Power Plants	PTC PM-2010

The ASME Publications Catalog shows a complete list of all the Standards published by the Society. For a complimentary catalog, or the latest information about our publications, call 1-800-THE-ASME (1-800-843-2763).

ASME Services

ASME is committed to developing and delivering technical information. At ASME's Information Central, we make every effort to answer your questions and expedite your orders. Our representatives are ready to assist you in the following areas:

ASME Press
Codes & Standards
Credit Card Orders
IMechE Publications
Meetings & Conferences
Member Dues Status

Member Services & Benefits
Other ASME Programs
Payment Inquiries
Professional Development
Short Courses
Publications

Public Information
Self-Study Courses
Shipping Information
Subscriptions/Journals/Magazines
Symposia Volumes
Technical Papers

How can you reach us? It's easier than ever!

There are four options for making inquiries* or placing orders. Simply mail, phone, fax, or E-mail us and an Information Central representative will handle your request.

Mail
ASME
22 Law Drive, Box 2900
Fairfield, New Jersey
07007-2900

Call Toll Free
US & Canada: 800-THE-ASME
(800-843-2763)
Mexico: 95-800-THE-ASME
(95-800-843-2763)
Universal: 973-882-1167

Fax—24 hours
973-882-1717
973-882-5155

E-Mail—24 hours
Infocentral@asme.org

* Information Central staff are not permitted to answer inquiries about the technical content of this code or standard. Information as to whether or not technical inquiries are issued to this code or standard is shown on the copyright page. All technical inquiries must be submitted in writing to the staff secretary. Additional procedures for inquiries may be listed within.

INTENTIONALLY LEFT BLANK

INTENTIONALLY LEFT BLANK

ASME PTC 51-2011

ISBN 978-0-7918-3352-0

9 780791 833520

C07511