ASME PTC 12.1-2015
[Revision of ASME PTC 12.1-2000 (R2005)]

Closed Feedwater Heaters

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of
Mechanical Engineers

ASME PTC 12.1-2015

[Revision of ASME PTC 12.1-2000 (R2005)]

Closed Feedwater Heaters

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of
Mechanical Engineers

Two Park Avenue • New York, NY • 10016 USA

Date of Issuance: June 30, 2016

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 Code. Interpretations are published on the Committee Web page and under go.asme.org/InterpsDatabase. Periodically certain actions of the ASME PTC Committee may be published as Code Cases. Code Cases are published on the ASME Web site under the PTC Committee Page at go.asme.org/PTCcommittee 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 PTC Committee Page can be found at go.asme.org/PTCcommittee. 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.

ASME is the registered trademark of The American Society of Mechanical Engineers.

This code or standard was developed under procedures accredited as meeting the criteria for American National Standards. The Standards Committee that approved the code or standard was balanced to assure that individuals from competent and concerned interests have had an opportunity to participate. The proposed code or standard was made available for public review and comment that provides an opportunity for additional public input from industry, academia, regulatory agencies, and the public-at-large.

ASME does not “approve,” “rate,” or “endorse” any item, construction, proprietary device, or activity.

ASME does not take any position with respect to the validity of any patent rights asserted in connection with any items mentioned in this document, and does not undertake to insure anyone utilizing a standard against liability for infringement of any applicable letters patent, nor assumes any such liability. Users of a code or standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Participation by federal agency representative(s) or person(s) affiliated with industry is not to be interpreted as government or industry endorsement of this code or standard.

ASME accepts responsibility for only those interpretations of this document issued in accordance with the established ASME procedures and policies, which precludes the issuance of interpretations by individuals.

No part of this document may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.

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

Copyright © 2016 by
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
All rights reserved
Printed in U.S.A.

CONTENTS

Notice		v
Foreword		vi
Committee Roster		vii
Correspondence With the PTC Committee		viii
Section 1	**Object and Scope**	1
1-1	General	1
1-2	Object	1
1-3	Scope	1
1-4	Uncertainty	2
Section 2	**Definitions and Descriptions of Terms**	3
2-1	Symbols	3
2-2	Nomenclature	3
2-3	Subscripts	3
Section 3	**Guiding Principles**	7
3-1	Items for Agreement	7
3-2	Parameters Affecting Feedwater Heater Performance	7
3-3	Methods of Operating During the Test	7
3-4	Preparation for the Test	8
3-5	Duration of Runs and Frequency of Readings	10
3-6	Steady-State Limits	10
3-7	Measurement Uncertainty	10
3-8	Location of Test Points	11
Section 4	**Instruments and Methods of Measurement**	22
4-1	General	22
4-2	Pressure Measurement	22
4-3	Temperature Measurement	22
4-4	Water Flow Measurement	23
4-5	Split Stream Feedwater Heater Testing	24
4-6	Multiple Inlet Steam Nozzles	25
4-7	Instrument Uncertainties	25
Section 5	**Computation of Results**	26
5-1	Introduction	26
5-2	Performance Calculation Procedures	26
5-3	Uncertainty Calculation Procedures	38
Section 6	**Report of Results**	40
Section 7	**References**	42
Figures		
3-3.2-1	Typical DCA and TTD Versus Heater Internal Liquid Level	9
3-8-1	Three-Zone Heater Test Points: Desuperheating, Condensing, and Drain Cooling Zones	12
3-8-2	Thermal Profile: Desuperheating, Condesing, and Drain Cooling Zones	13
3-8-3	Two-Zone Heater Test Points: Desuperheating and Condensing Zones	14
3-8-4	Thermal Profile: Desuperheating and Condensing Zones	15
3-8-5	Two-Zone Heater Test Points: Condensing and Drain Cooling Zones	16
3-8-6	Thermal Profile: Condensing and Drain Cooling Zones	17
3-8-7	Single-Zone Heater Test Points: Condensing Zone Only	18

3-8-8 Thermal Profile: Condensing Zone 19
3-8-9 Single-Zone Heater Test Points: External Drain Cooler 20
3-8-10 Thermal Profile: External Drain Cooler 21
4-4-1 Typical Transducer Installation 24

Form
6-1 Performance Testing of Closed Feedwater Heaters 41

Tables
2-1-1 Symbols 4
2-2-1 Nomenclature 6
3-6-1 Deviation Limits of Parameters 10
4-7-1 Maximum Uncertainty Values 25
5-2.1-1 Manufacturer Design Data 27

Nonmandatory Appendices

A **Basic Heat Transfer Equations** 43

B **Heater Performance Calculation Examples** 46

C **Uncertainty Considerations** 56

D **Principal Quantities and Commonly Used Conversion Factors in Heat Transfer (SI Units)** 61

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

The Performance Test Code Committee 12.1 was assembled to review, edit, and update the 1978 Code edition. The Code was extensively revised to comply with the requirements in ASME PTC 1-1991, General Instructions, including the required uncertainty analysis. The 2000 edition of this Code incorporated a revised calculation procedure including examples. The calculation method requires iterations and may be performed manually but is best done by computer. The Code incorporated an alternative for using ultrasonic flow measurement techniques to test individual or split-string feedwater heaters when flow nozzles are not available.

The PTC 12.1 Committee was once again assembled to review, edit, and update the 2000 edition. This Code has been extensively revised to make it more intuitive including more descriptive subscripts, variable names, modified figures, test forms, and notes, an expanded Nonmandatory Appendix A, and a general emphasis on educating the engineer on heater testing and performance. The uncertainty calculations have been updated to reflect the latest ASME PTC 19.1 terminology.

The 2015 edition of the Code provides a relatively simple but accurate method of calculating the performance of a feedwater heater utilizing the Code procedure with a minimum knowledge of the design characteristics of the feedwater heater.

The PTC 12.1 Committee would like to acknowledge the contributions from Mr. George Osolsobe to this Performance Test Code. This revision was approved by the Board on Performance Test Codes on June 25, 2015 and as an American National Standard on October 26, 2015.

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

P. G. Albert, *Chair*
J. Milton, *Vice Chair*
F. Constantino, *Secretary*

STANDARDS COMMITTEE PERSONNEL

P. G. Albert, Consultant
J. Burns, Burns Engineering
A. E. Butler, GE Power & Water
W. C. Campbell, True North Consulting, LLC
F. Constantino, The American Society of Mechanical Engineers
J. W. Cuchens, Southern Company Services
M. J. Dooley, Alstom Power
G. J. Gerber, Consultant
P. M. Gerhart, University of Evansville
J. Gonzalez, Iberdrola Ingeniería y Construcción, SAU
R. E. Henry, Sargent & Lundy
D. Keyser, Survice Engineering Co.
T. K. Kirkpatrick, McHale & Associates, Inc.
S. J. Korellis, Electric Power Research Institute
M. McHale, McHale & Associates, Inc.
J. Milton, Chevron, USA
S. P. Nuspl, Consultant
R. Pearce, Kansas City Power & Light
R. R. Priestley, Consultant
S. Scavuzzo, The Babcock & Wilcox Co.
T. C. Heil, *Alternate,* The Babcock & Wilcox Co.
J. A. Silvaggio Jr., Turbomachinery, Inc.
T. L. Toburen, T2E3
G. E. Weber, OSIsoft, LLC
W. C. Wood, Duke Energy
R. Jorgensen, *Honorary Member,* Consultant
P. M. McHale, *Honorary Member,* McHale & Associates, Inc.
R. E. Sommerlad, *Honorary Member,* Consultant

PTC 12.1 COMMITTEE — FEEDWATER HEATERS

G. E. Weber, *Chair,* OSIsoft, LLC
N. Thompson, *Vice Chair,* Performance Consultants
A. L. Guzman, *Secretary,* The American Society of Mechanical Engineers
G. S. Anderson, Fuel Tech, Inc.
M. C. Catapano, Powerfect, Inc.
K. Hwang, *Contributing Member,* KEPCO Research Institute
S. J. Korellis, *Contributing Member,* Electric Power Research Institute
R. Pearce, Kansas City Power & Light
A. Siman, Thermal Engineering International
J. L. Tsou, *Contributing Member,* Consultant

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 or a Case, and attending Committee meetings. Correspondence should be addressed to:

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

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 and 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 at go.asme.org/Inquiry.

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 may be rewritten in the appropriate 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 regularly hold meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the PTC Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at go.asme.org/PTCcommittee.

CLOSED FEEDWATER HEATERS

Section 1
Object and Scope

1-1 GENERAL

(a) For the purpose of this Code, a closed feedwater heater is a power plant heat exchanger designed to heat a given quantity of feedwater through a specified temperature range. The heating medium is steam or condensate at a specified temperature and pressure. In feedwater heaters, the feedwater and heating medium typically are routed through the tubes and shell, respectively. Feedwater heaters are typically designed to be configured in one of the following ways:

(1) horizontal

(2) vertical channel down

(3) vertical channel up

(4) duplex (two separate tube bundles in a single divided shell)

(b) In some cases, more than one feedwater heater is required for a given feedwater flow and extraction steam source. In such instances, the feedwater heater is divided into two or three parallel heaters, which constitute a multiple string arrangement.

The shell side of the heater may be constructed with one, two, or three independent zones and arranged in various combinations:

(1) desuperheating zone

(2) condensing zone

(3) drain cooling zone

Each zone is considered to be an independent heat transfer entity contained within the same shell.

Extraction steam from the turbine is the heating medium in the desuperheating zone. Depending on the heater design, extraction steam from the turbine together with other possible energy sources such as incoming drains are the heating medium in the condensing zone. Condensate is the heating medium in the drain cooling zone.

(c) This Code is written in accordance with the ASME PTC 1, General Instructions. ASME PTC 2, Definitions and Values, defines certain technical terms and numerical constants which are used in this Code with the significance and value therein established. The PTC 19 Series, Supplements on Instruments and Apparatus, which covers the instruments prescribed in this Code, should be used for reference.

1-2 OBJECT

The object of this Code is to provide the procedures, direction, and guidance for determining the thermo-hydraulic performance of a closed feedwater heater. It can be utilized to verify contractual performance for a new heater or to calculate performance of an existing heater in comparison to the design point. The overall performance parameters utilized to accomplish this are the following:

(a) terminal temperature difference (TTD), which is the difference between the saturation temperature corresponding to the steam inlet pressure and the feedwater outlet temperature

(b) drain cooler approach (DCA), which is the difference between drain outlet temperature and feedwater inlet temperature

(c) tube-side (feedwater) pressure loss through the heater

(d) shell-side pressure loss through the desuperheating zone

(e) shell-side pressure loss through the drain cooling zone

The Code methodology adjusts the manufacturer's guaranteed performance parameters to the actual test conditions, for a comparison to as-tested performance.

1-3 SCOPE

This Code applies to all horizontal and vertical heaters except those with partial pass full-length drain cooling zones. The heater design is based on a specific operating condition that includes flow, temperature, and pressure. This specific condition constitutes the design point that is found on the manufacturer's feedwater heater specification sheet.

Generally, it is not possible to conduct the test at the exact design point. Therefore, it is necessary to predict the heater performance by adjusting the design parameters for the actual test conditions. Methods of calculating the predicted heater performance are presented in this Code. These predicted values shall then be compared to corresponding measured test values.

Horizontal heaters with partial pass submerged drain cooling zones and vertical channel-up heaters with partial pass drain cooling zones are not applicable to this Code. In those designs, only a portion of the feedwater passes through the drain cooling zones, therefore there are two flow streams with different temperature profiles.

Duplex heaters are applicable as long as the feedwater temperatures, including the temperature between stages, are measurable, and the shell sides are isolated from each other and verified to be at different stage pressures.

This Code is applicable for multitube pass heaters of single zone design. Multizone partial pass heaters cannot be tested under this Code, unless the entire first pass is contained in a single zone. This Code also does not apply to header type heaters.

1-4 UNCERTAINTY

This Code provides recommendations on instrumentation, procedures, and accuracies required for data collection. An example of an uncertainty analysis is provided in Nonmandatory Appendix C, which is based on the recommended instrumentation accuracies described in Section 4 of this Code and the method of calculation described in Section 5.

The uncertainties in Nonmandatory Appendix C are provided as typical values using the instrumentation accuracies, locations, and techniques recommended by this Code. The uncertainties may be reduced through careful placement of alternative or redundant instrumentation. The total uncertainties were calculated using the procedure described in subsection 5-3. The systematic uncertainties were determined by the judgment of this committee for a test adhering to the procedures of this Code.

A post-test uncertainty analysis is recommended. However, a post-test uncertainty analysis is optional if parties to the test agree that the test adhered to all instrumentation requirements and procedures in this Code.

Section 2
Definitions and Descriptions of Terms

2-1 SYMBOLS

Symbols and definitions are listed in Table 2-1-1.

2-2 NOMENCLATURE

Nomenclature is listed in Table 2-2-1.

2-3 SUBSCRIPTS

Subscripts used in this Code denote the following:

c	condensing zone
ci	condensing zone inlet
co	condensing zone outlet
dc	drain cooling zone
dci	drain cooling zone inlet
dco	drain cooling zone outlet
di	drain inlet
ds	desuperheating zone
dsi	desuperheating zone inlet
dso	desuperheating zone outlet
FW	feedwater
FWi	feedwater inlet
FWo	feedwater outlet
fsc	shell-side fouling in condensing zone
fsdc	hell-side fouling in drain cooling zone
fsds	shell-side fouling in desuperheating zone
ftc	tube-side fouling in condensing zone
ftdc	tube-side fouling in drain cooling zone
ftds	tube-side fouling in desuperheating zone
mc	metal resistance in condensing zone
mdc	metal resistance in drain cooling zone
mds	metal resistance in desuperheating zone
sat	saturation
sc	shell-side condensing zone
sdc	shell-side drain cooling zone
sds	shell-side desuperheating zone
si	shell-side inlet
so	shell-side outlet

The following subscripts are generally extensions of the above subscripts and are utilized to differentiate values given by the manufacturer from calculated or assumed.

_*G*	given: represents either design data or design values computed solely using data from the heater manufacturer
_*X*	represents computed values associated with the predicted performance
(no subscript)	represents test data or data computed from test results or obtained from ASME Steam Tables
_*a*	assumed value to begin calculating iterations

Table 2-1-1 Symbols

Symbol	Definition	Given by Manufacturer	Computed	Measured
A_c	Condensing zone area based on outside diameter of tubes (effective surface only)	A_{c_G}	. . .	. . .
A_{dc}	Drain cooling zone area based on outside diameter of tubes (effective surface only)	A_{dc_G}	. . .	. . .
A_{ds}	Desuperheating zone area based on outside diameter of tubes (effective surface only)	A_{ds_G}	. . .	. . .
c_{pFWc}	Specific heat of feedwater in condensing zone	c_{pFWc_G}	. . .	c_{pFWc}
c_{pFWdc}	Specific heat of feedwater in drain cooling zone	c_{pFWdc_G}	. . .	c_{pFWdc}
c_{pds}	Specific heat of steam in desuperheating zone	c_{pds_G}	. . .	c_{pds}
C_{dc}	Shell-side hourly heat capacity flow rate in drain cooling zone	. . .	. . .	C_{dc}
C_{ds}	Shell-side hourly heat capacity flow rate in desuperheating zone	. . .	. . .	C_{ds}
C_{FWdc}	Feedwater hourly heat capacity flow rate in drain cooling zone	. . .	. . .	C_{FWdc}
C_{FWds}	Feedwater hourly heat capacity flow rate in desuperheating zone	. . .	. . .	C_{FWds}
DCA	Drain cooler approach temperature, $T_{dco} - T_{FWdci}$	$DCA_{\_G}$	$DCA_{\_X}$	DCA
h_{di}	Heater drain inlet enthalpy computed from ASME Steam Tables	h_{di_G}	. . .	h_{di}
h_{si}	Heater shell-side steam inlet enthalpy computed from ASME Steam Tables	h_{si_G}	. . .	h_{si}
h_{so}	Heater drain or shell-side outlet enthalpy computed from ASME Steam Tables	h_{so_G}	h_{so_X}	h_{so}
h_{FWi}	Heater feedwater inlet enthalpy computed from ASME Steam Tables	h_{FWi_G}	. . .	h_{FWi}
h_{FWo}	Heater feedwater outlet enthalpy computed from ASME Steam Tables	h_{FWo_G}	h_{FWo_X}	h_{FWo}
ID	Inside tube diameter	$ID_{\_G}$	. . .	. . .
k_m	Tube metal thermal conductivity	. . .	. . .	k_m
k_{FWc}	Feedwater thermal conductivity in condensing zone	k_{FWc_G}	. . .	k_{FWc}
k_{FWdc}	Feedwater thermal conductivity in drain cooling zone	k_{FWdc_G}	. . .	k_{FWdc}
k_{FWds}	Feedwater thermal conductivity in desuperheating zone	k_{FWds_G}	. . .	k_{FWds}
$(NTU)_c$	Number of transfer units in condensing zone	. . .	$(NTU)_{c\_X}$	. . .
$(NTU)_{dc}$	Number of transfer units in drain cooling zone	. . .	$(NTU)_{dc\_X}$	. . .
$(NTU)_{ds}$	Number of transfer units in desuperheating zone	. . .	$(NTU)_{ds\_X}$	. . .
OD	Outside tube diameter	$OD_{\_G}$	. . .	. . .
ΔP_{dc}	Condensate pressure drop in drain cooler or drain cooling zone	ΔP_{dc_G}	ΔP_{dc_X}	ΔP_{dc}
ΔP_{ds}	Steam pressure drop in desuperheating zone	ΔP_{ds_G}	ΔP_{ds_X}	ΔP_{ds}
ΔP_{FW}	Feedwater pressure drop through heater	ΔP_{FW_G}	ΔP_{FW_X}	ΔP_{FW}
P_c	Steam pressure in condensing zone	P_{c_G}	P_{c_X}	P_c
P_{ci}	Steam inlet pressure to condensing zone	P_{ci_G}	P_{ci_X}	P_{ci}
P_{co}	Condensate outlet pressure from condensing zone	P_{co_G}	P_{co_X}	P_{co}
P_{dci}	Condensate inlet pressure to drain cooling zone	P_{dci_G}	. . .	. . .
P_{dsi}	Steam inlet pressure to desuperheating zone	P_{dsi_G}	. . .	P_{dsi}
P_{dco}	Condensate outlet pressure from drain cooling zone	P_{dco_G}	. . .	P_{dco}

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

Symbol	Definition	Given by Manufacturer	Computed	Measured
P_{dso}	Steam outlet pressure from the desuperheating zone	. . .	P_{dso_X}	. . .
P_{di}	Drain inlet pressure to heater	P_{di_G}	. . .	P_{di}
P_{FWi}	Feedwater inlet pressure to heater	P_{FWi_G}	. . .	P_{FWi}
P_{FWo}	Feedwater outlet pressure from heater	P_{FWo_G}	. . .	P_{FWo}
P_{si}	Steam or condensate inlet pressure to heater	P_{si_G}	. . .	P_{si}
P_{so}	Steam or condensate outlet pressure from heater	P_{so_G}	. . .	P_{so}
Q	Total heat transferred	$Q_{\_G}$	$Q_{\_X}$	. . .
Q_{dc}	Heat transferred in drain cooling zone	Q_{dc_G}	Q_{dc_X}	. . .
Q_{di}	Drain inlet heat transfer to shell side	. . .	Q_{di_X}	Q_{di}
Q_c	Heat transferred in condensing zone	Q_{c_G}	Q_{c_X}	. . .
Q_{ds}	Heat transferred in desuperheating zone	Q_{ds_G}	Q_{ds_X}	. . .
R_{dc}	Heat capacity ratio in drain cooling zone or drain cooler	. . .	R_{dc_X}	. . .
R_{ds}	Heat capacity ratio in desuperheating zone	. . .	R_{ds_X}	. . .
r_{fsc}	Shell-side fouling resistance in condensing zone	r_{fsc_G}	. . .	. . .
r_{fsdc}	Shell-side fouling resistance in drain cooling zone	r_{fsdc_G}	. . .	. . .
r_{fsds}	Shell-side fouling resistance in desuperheating zone	r_{fsds_G}	. . .	. . .
r_{ftdc}	Tube-side fouling resistance in drain cooling zone	r_{ftdc_G}	. . .	. . .
r_{ftc}	Tube-side fouling resistance in condensing zone	r_{ftc_G}	. . .	. . .
r_{ftds}	Tube-side fouling resistance in desuperheating zone	r_{ftds_G}	. . .	. . .
r_{mc}	Tube-side metal resistance in condensing zone	r_{mc_G}	. . .	. . .
r_{mdc}	Tube-side metal resistance in drain cooling zone	r_{mdc_G}	. . .	. . .
r_{mds}	Tube-side metal resistance in desuperheating zone	r_{mds_G}	. . .	. . .
r_{sdc}	Shell-side film resistance in drain cooling zone (corrected for reheat)	r_{sdc_G}	r_{sdc_X}	. . .
r_{sc}	Shell-side film resistance in condensing zone	r_{sc_G}	r_{sc_X}	. . .
r_{sds}	Shell-side film resistance in desuperheating zone	r_{sds_G}	r_{sds_X}	. . .
r_{tdc}	Tube-side film resistance in drain cooling zone	r_{tdc_G}	r_{tdc_X}	. . .
r_{tc}	Tube-side film resistance in condensing zone	r_{tc_G}	r_{tc_X}	. . .
r_{tds}	Tube-side film resistance in desuperheating zone	r_{tds_G}	r_{tds_X}	. . .
t	Tube wall thickness	$t_{\_G}$	. . .	. . .
T_c	Steam or condensate temperature in condensing zone	T_{c_G}	T_{c_X}	. . .
T_{ci}	Steam or condensate inlet temperature to condensing zone	T_{ci_G}	T_{ci_X}	. . .
T_{co}	Condensate outlet temperature from condensing zone	T_{co_G}	T_{co_X}	. . .
T_{dci}	Condensate inlet temperature to drain cooling zone	T_{dci_G}	T_{dci_X}	. . .
T_{dco}	Condensate outlet temperature from drain cooling zone	. . .	T_{dco_X}	T_{dco}
T_{di}	Drain inlet temperature to heater	T_{di_G}	. . .	T_{di}
T_{do}	Condensate outlet temperature from heater	. . .	T_{do_X}	T_{do}
T_{dsi}	Steam inlet temperature to desuperheating zone	T_{dsi_G}	. . .	T_{dsi}
T_{dso}	Steam outlet temperature from desuperheating zone	T_{dso_G}	T_{dso_X}	. . .
T_{FWci}	Feedwater inlet temperature to condensing zone	T_{FWci_G}	. . .	. . .
T_{FWco}	Feedwater outlet temperature from condensing zone	T_{FWco_G}	T_{FWco_X}	. . .
T_{FWdci}	Feedwater inlet temperature to drain cooling zone	. . .	T_{FWdci_X}	T_{FWdci}
T_{FWdco}	Feedwater outlet temperature from drain cooling zone	T_{FWdco_G}	T_{FWdco_X}	. . .
T_{FWdsi}	Feedwater inlet temperature to desuperheating zone	T_{FWdsi_G}	T_{FWdsi_X}	. . .

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

Symbol	Definition	Given by Manufacturer	Computed	Measured
T_{FWdso}	Feedwater outlet temperature from desuperheating zone	T_{FWdso_G}	T_{FWdso_X}	. . .
T_{FWi}	Feedwater inlet temperature to heater	T_{FWi_G}	. . .	T_{FWi}
T_{FWo}	Feedwater outlet temperature from heater	T_{FWo_G}	T_{FWo_X}	T_{FWo}
T_{FWo_a}	Feedwater outlet temperature from heater — assumed to begin iterations	. . .	. . .	. . .
T_{sat}	Saturated steam temperature corresponding to steam inlet pressure from ASME Steam Tables	T_{sat_G}	. . .	T_{sat}
T_{si}	Steam or condensate inlet temperature to heater	T_{si_G}	. . .	T_{si}
T_{so}	Steam or condensate outlet temperature from heater	T_{so_G}	T_{so_X}	T_{so}
T_{so_a}	Steam or condensate outlet temperature from heater — assumed to begin iterations	. . .	. . .	. . .
TTD	Terminal temperature difference	$\mathrm{TTD}_{\_G}$	$\mathrm{TTD}_{\_X}$	TTD
U_c	Overall heat transfer coefficient in condensing zone	U_{c_G}	U_{c_X}	. . .
U_{dc}	Overall heat transfer coefficient in drain cooler or drain cooling zone	U_{dc_G}	U_{dc_X}	. . .
U_{ds}	Overall heat transfer coefficient in desuperheating zone	U_{ds_G}	U_{ds_X}	. . .
v_{FW}	Average feedwater velocity (at average temperature)	v_{FW_G}	v_{FW_x}	v_{FW}
W_{di}	Drains inlet flow to heater	W_{di_G}	W_{di_X}	W_{di}
W_{dsi}	Steam inlet flow rate entering desuperheating zone	W_{dsi_G}	W_{dsi_X}	. . .
W_{FW}	Feedwater flow to heater	W_{FW_G}	. . .	W_{FW}
W_{si}	Steam or condensate inlet flow rate to heater	W_{si_G}	W_{si_X}	. . .
W_{so}	Condensate or shell outlet side flow rate exiting heater	W_{so_G}	W_{so_X}	. . .
ϵ_{dc}	Effectiveness in drain cooler or drain cooling zone	. . .	ϵ_{dc_X}	. . .
ϵ_c	Effectiveness in condensing zone	. . .	ϵ_{c_X}	. . .
ϵ_{ds}	Effectiveness in desuperheating zone	. . .	ϵ_{ds_X}	. . .

Table 2-2-1 Nomenclature

Symbol	Term	Unit of Measure	
		U.S. Customary	SI
A	Heat transfer surface area	ft^2	m^2
C	Hourly heat capacity flow rate	Btu/hr-°F	W/K
c_p	Specific heat	Btu/lbm-°F	kJ/kg-K
DCA	Drain cooler approach	°F	°C
h	Enthalpy	Btu/lbm	kJ/kg
k	Thermal conductivity	Btu/hr-ft-°F	W/m-K
ID	Tube inside diameter	in.	mm
NTU	Number of transfer units	. . .	. . .
OD	Tube outside diameter	in.	mm
P	Pressure	psi(a)	Pa
Q	Heat transferred	Btu/hr	W
R	Heat capacity ratio	. . .	. . .
r	Heat transfer resistance	hr-ft^2-°F/Btu	m^2-K/W
t	Tube wall thickness	in.	mm
T	Temperature	°F	°C or K
TTD	Terminal temperature difference	°F	°C
U	Overall heat transfer coefficient	Btu/hr-ft^2-°F	W/m^2-K
v	Feedwater velocity	ft/sec	m/s
W	Flow rate	lbm/hr	kg/s
ρ	Density	lbm/ft^3	kg/m^3
μ	Dynamic viscosity	lbm/hr-ft	Pa-s
Δ	Difference in parameter	. . .	. . .
ϵ	Effectiveness	. . .	. . .

Section 3
Guiding Principles

3-1 ITEMS FOR AGREEMENT

The parties to the test shall reach definitive agreement regarding the specific test objectives in Section 1. This agreement may be included in the form of a test procedure, protocol, or other written document. At a minimum, the following items shall be agreed upon prior to the test:

(a) unit operating conditions during the test; specifically on the means to secure consistent inlet steam conditions and feedwater flow and the method of determining drain flow

(b) data to be recorded, method and frequency of recording/archiving data, duration and number of test runs

(c) full review of the allied system schematics to establish the total test boundaries, and the location of all measurement parameters

(d) instrumentation to be utilized (temporary and/or installed) and any permitted alternatives

(e) instrumentation accuracy and methods and frequency of calibration

(f) determination of parameters not directly measured

(g) fouling resistance to be used in computing design-adjusted TTD and DCA

(h) method of testing and determining performance of multiple-string feedwater heaters

(i) identification of any known damage or deficiency, e.g., plugged tubes

(j) status of continuous vent operation during test

(k) method of determining extraction steam enthalpy for cases where steam quality is less than 100% (see subsection 5-2)

(l) shell liquid-level set point

3-2 PARAMETERS AFFECTING FEEDWATER HEATER PERFORMANCE

(a) In a feedwater heater, the TTD and the DCA are indicators of the ability of the heater to transfer heat under a given set of conditions, i.e., the design point. This ability is represented by the overall heat transfer coefficient for each zone, the log mean temperature difference (LMTD), and the available heat transfer surface area. The total amount of heat transferred to the feedwater is equal to the amount given up by the steam/condensate. This is expressed in terms of overall heater duty. The principal items affecting the heater's ability to transfer heat are

(1) feedwater inlet temperature, pressure, and flow

(2) steam inlet pressure and temperature

(3) drains inlet enthalpy and flow

(b) Operation at conditions other than the design point will result in changes in performance. This means that heater performance cannot be determined simply by comparison of measured TTD and DCA with their guaranteed values. Therefore, it is necessary to predict the heater performance by adjusting the design parameters for the test conditions. These predicted values shall then be compared to the corresponding measured test values.

The following may affect thermal performance:

(1) tube cleanliness

(2) noncondensable gases in the steam or water spaces of the heater

(3) shell liquid level

(4) unbalanced feedwater flow with multiple string arrangements

(5) available heat-transfer area

(6) undesirable leakage across external boundary isolation points (i.e., bypass valves, etc.)

3-3 METHODS OF OPERATION DURING THE TEST

3-3.1 General

The feedwater heater and other components in the turbine cycle shall be operated in steady state as close to design parameters as possible during the test unless specified otherwise by this Code. The heater shall be properly operated to ensure optimum performance. The test runs should be conducted as close to the design conditions as possible. The limits of deviation for test conditions from design points for each test parameter have been established and are given in Table 3-6-1. If a test run average exceeds these limits, the run shall be rejected. If unacceptable deviations are discovered during computation of results from a completed test run, that run shall be rejected.

3-3.2 Heater Operation

It is recommended that any external sources of noncondensable gases such as vents from another apparatus be diverted from the tested heaters during the run. All heater bypass valves or emergency drain valves immediately upstream or downstream of the tested heaters should be checked to ensure that no leakage exists. This applies to separate emergency drain connections from the heater shell or an emergency drain branch downstream of the single drain outlet nozzle. The intent is to ensure that the full drain flow exiting the heater is routed through the normal path for the duration of the test. Temporary modifications such as the installation of various required instruments are subject to agreement between parties, provided their installation has no effect on the operation or performance of the heater.

(a) Venting. Noncondensable gas accumulation in both the condensing and drain cooling zones of the heater may degrade the performance of the heater by blanketing some heat transfer surface area. It may also lead to corrosion of heater internals. If a heater is not performing properly, the venting system design and operation should be checked. Depending on water chemistry control on the generating unit to be tested, the vent operation strategy should be determined by agreement by the parties of the test.

Troubleshooting the entire venting system design is beyond the scope of this Code; however, a simple test to determine whether the vent orifice is properly sized and free of obstruction may be performed as follows. With the heater venting normally, and the cycle at steady-state conditions, conduct a preliminary test run. When this is complete, open the heater vent flow orifice bypass valve to ensure increased vent flow. This mode should be maintained for approximately $\frac{1}{2}$ hr to sufficiently purge the heater of noncondensables. Once this purging is complete, repeat the run. Comparison of the feedwater outlet temperatures of these two runs should yield close agreement. If there is a significant difference, an improperly sized or obstructed orifice should be suspected and corrective actions taken. If the heater is being continuously vented at no more than 0.5% of design steam flow, this will have negligible effect on the thermal performance.

(b) Water Level. It is important that the normal water level at the drain cooling zone inlet is maintained as close as possible to the optimum set point. Keep in mind that the location of liquid level taps shall reflect the level at the zone inlet since the heater liquid level, front to back, is not flat. If the water level is higher than optimum, some additional heat transfer surface area in the condensing zone may be flooded; this may reduce the heat transfer capability, and may, in turn, cause the TTD to be adversely affected. The DCA will decrease slightly when water level in the heater is higher than optimum. If the water level in the heater is such that it allows steam to enter the drain cooling zone, the DCA will significantly increase, and may cause drain cooling zone damage. The TTD will decrease slightly when water level in the heater is lower than optimum.

The following method may be used to establish the optimum normal liquid level set point for horizontal heaters. The intent of this process is to establish the threshold of two-phase flashing flow from which the optimum liquid level set point may be determined. Starting with the normal water level maintained close to the manufacturer's recommended set point and assuming that DCA is operating close to the design, this manual level control test will yield values for DCA for each incremental height of the water level.

The liquid-level controller set point shall be lowered in step increments of approximately 1 in. until the drain outlet temperature increases noticeably. Each step increment shall be held for 5 min or until the drain temperature is stabilized prior to recording the heater drain outlet temperature. The DCA is then calculated and plotted as a function of the internal liquid level. This procedure is repeated until the DCA shows a sharp upward break with a rapid increase in drain outlet temperature.

Conversely, if the DCA is noticeably high prior to starting the test, the opposite approach is taken. The water level is increased in 1-in. increments, drain outlet temperature is allowed to stabilize, and the "DCA vs. internal heater liquid level" curve is once again plotted.

The overall plot of "DCA vs. heater internal liquid level" should resemble the shape of the curve depicted in Fig. 3-3.2-1 (Linley, 1983). The optimum liquid level is determined by finding the "knee break" of the curve and adding an appropriate safety factor. For horizontal heaters, this is typically a minimum of 2.0 in. of liquid level to establish a safe normal operating level set point to prevent steam entering the drain cooling zone. If the optimum level plus the safety factor (2.0 in.) is lower than the manufacturer's level mark, further evaluation of the level to be set during the test should be made, including discussing the discrepancy with the manufacturer's representative. This margin above the minimum level controller set point provides an internal liquid level that may withstand some fluctuations while not exposing the entrance to the drain cooling zone. This final liquid level controller set point shall be constant throughout the duration of the test.

The methodology in the above paragraph may also be used for vertical channel down heaters. In this configuration, the optimum set point is more closely related to the height of the drain cooling zone. Since vertical heaters typically have a smaller amount of liquid capacitance for level control, they are more sensitive to level swings. Consequently a larger safety factor, typically a minimum of 5.0 in. is added above the height of the drain cooling zone as the optimim level set point.

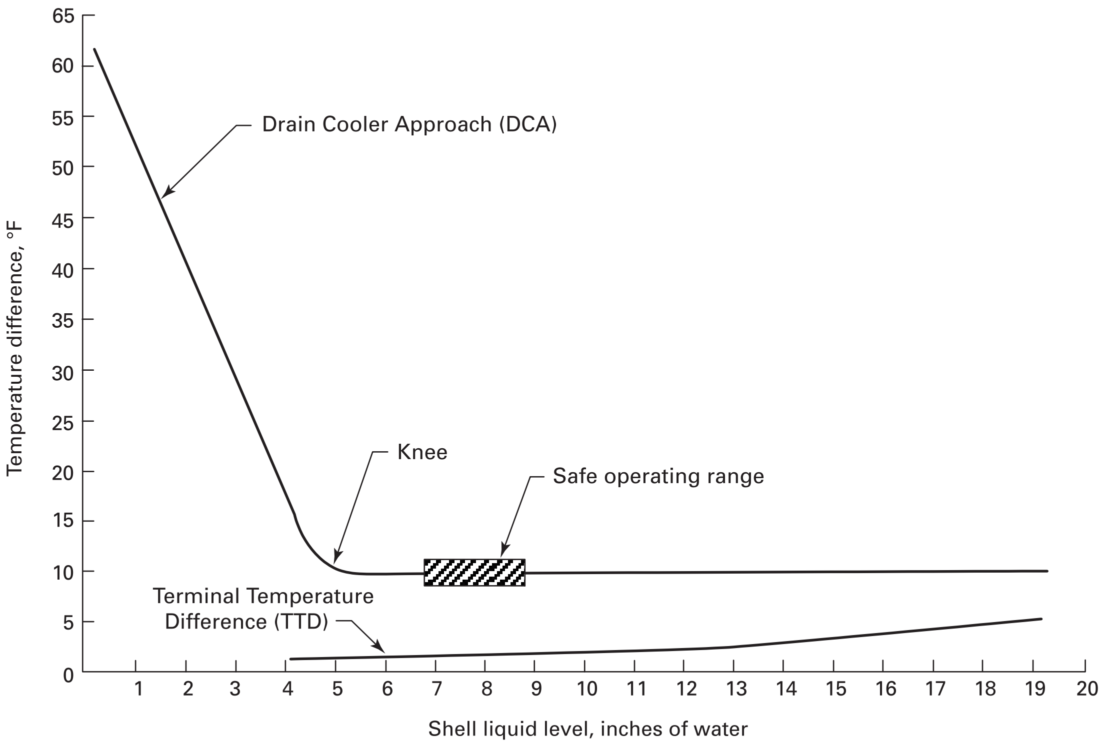
In any case, for either horizontal or vertical installation, the final level set point shall be agreed upon by the parties to the test.

3-4 PREPARATION FOR THE TEST

3-4.1 General

The test preparation shall include examination and familiarization with the apparatus by all involved

Fig. 3-3.2-1 Typical DCA and TTD Versus Heater Internal Liquid Level



parties. If the physical state of the equipment and operating conditions depart from prior agreement, a new agreement shall be reached.

3-4.2 Preliminary Runs

A preliminary run should be conducted for the purposes of

(a) checking all instruments
(b) training personnel
(c) checking heater for adequate venting and proper liquid level
(d) making necessary instrument and equipment adjustments
(e) verifying the computational procedure
(f) ensuring proper valve position and isolation

3-5 DURATION OF RUNS AND FREQUENCY OF READINGS

The test shall consist of a minimum of three runs. During each run, all data shall be recorded at least once per minute over a minimum time period of 30 min at steady-state conditions.

Data shall be taken by automatic data collecting equipment or by a sufficient number of competent observers. Automatic data logging and advanced instrument systems shall be calibrated to the required accuracy. No observer shall be required to take so many readings that lack of time may result in insufficient care and precision.

3-6 STEADY-STATE LIMITS

The feedwater heater shall be brought to the steady-state condition prior to initiating a run, and shall be maintained throughout the run. The steady-state limits are defined in Table 3-6-1. If any measurement during the test run exceeds these limits when compared to the test run average, the run shall be rejected.

Any condition whose variation may affect the test results shall be made as stable as possible before the test run begins and throughout the run. It is desirable to observe and record all readings for a brief period after the unit has attained steady state conditions but before the formal readings are taken.

If inconsistencies are observed for a test run, the run shall be rejected in whole or in part (by agreement among parties to the test), and shall be repeated if necessary to meet the objective of the test.

Table 3-6-1 Deviation Limits of Parameters

Parameter	Limit of Deviation for the Test Conditions from Design Points	Steady State Limit
Feedwater flow	±10.0%	±3%
Feedwater inlet temperature [Note (1)]	±10°F	±2°F
Feedwater inlet pressure	±10.0% of absolute pressure	. . .
Extraction pressure	±10.0% of absolute pressure	±1%
Extraction temperature	±20°F	±4°F
Drains flow in	±10.0%	. . .

NOTE:
(1) Large temperature variations may occur at the inlet to the lowest pressure heater due to condenser backpressure changes caused by seasonal differences in cooling water temperature. Inlet temperature changes from 20°F to 30°F are common on some units for winter versus summer performance. Testing under these conditions is by mutual agreement.

3-7 MEASUREMENT UNCERTAINTY

3-7.1 Introduction

Measurements collected during a test are only representations of a physical process that allow judgments regarding the given process. The value of the resulting judgment is dependent on how well the measurements represent reality. Measurements that have a large uncertainty (see ASME PTC 19.1-2013, Ref. 5 for details) may lead to faulty decisions that may result in a large effort to resolve problems that may not in fact exist or, conversely, the data may mask problems that should be taken into consideration.

Errors associated with measured data may generally be described by the following two primary components:

(a) Random Error. The ability to repeat a measurement given similar test conditions.

(b) Systematic Error. An error that remains constant throughout a test process, resulting primarily from the test setup and calibration of instrumentation.

3-7.2 Random Error

Random error may be reduced by taking many repeated measurements over a period of time or by using redundant instrumentation. For example, the temperature of a static fluid is more accurately determined by using four thermocouples instead of one. If only one thermocouple is available, the average of four separate readings taken at different times would be more representative of the true temperature than a single reading. In fact, in some processes where steady state is represented by a cyclic oscillation of a measured parameter, it is essential to take many readings at various times to get a true representation of the process. In general, random error is inversely proportional to the square root of the number of measurements or readings taken.

3-7.3 Systematic Error

Systematic error is more difficult to control. This type of error will show up consistently regardless of the number of readings. It may result, for example, from the placement of a thermocouple into a fluid stream in which temperature is highly stratified. The thermocouple will read only the local temperature, which may or may not be representative of the average fluid temperature. This is true for pressure, flow, and any other type of measurement. Placement of instrumentation makes the systematic error unique for each installation.

Systematic error is reduced primarily by good judgment and experience regarding the test equipment and the scope of the test. Since most instruments make local measurements, systematic error may sometimes be reduced by making many measurements over the geometry of the test equipment. For example, a traverse over a cross section or an array of instruments provides more information from which good judgment may be made. Careful calibration of instrumentation is another example of reducing systematic error.

In general, accurate test results are obtained through careful placement of reliable instrumentation and by taking many repeated measurements from a steady state condition. A more thorough discussion of measurement uncertainty is provided in ASME PTC 19.1-2013.

3-7.4 Combination of Random and Systematic Uncertainties (Total Uncertainty)

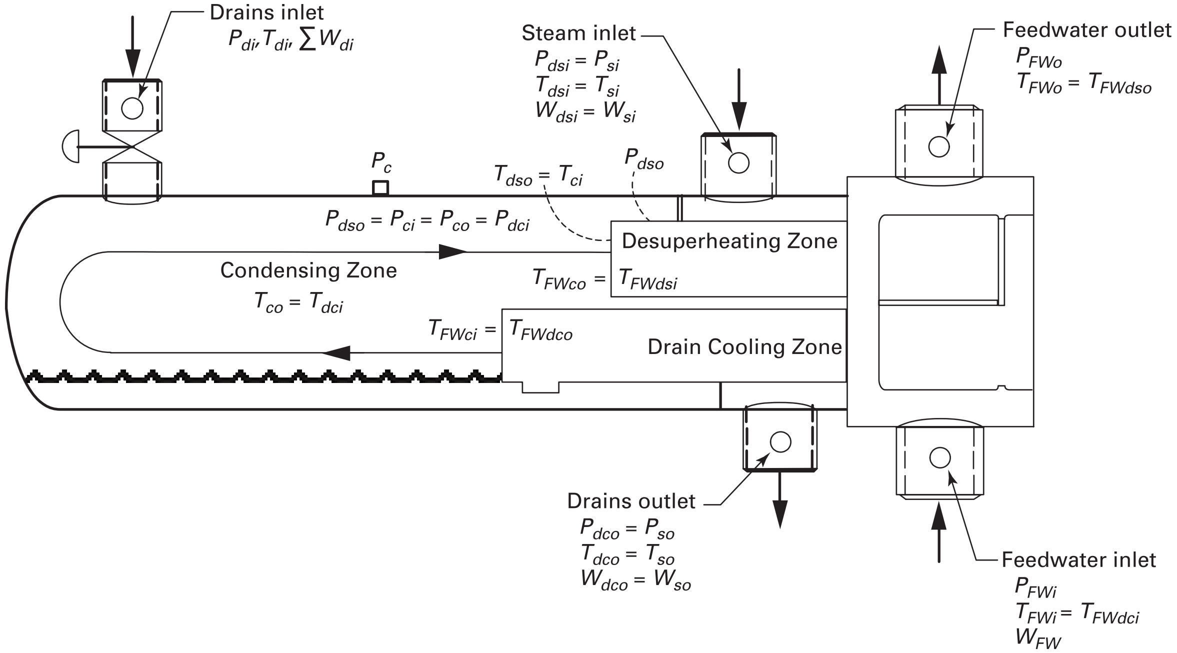
Subsection 5-3 of this Code describes the methodology for combining random and systematic uncertainties based on ASME PTC 19.1.

3-8 LOCATION OF TEST POINTS

Figures 3-8-1 through 3-8-10 list the applicable calculated and measured parameters for the various heater configurations while showing their interrelationships for clarity. The measured test points (specifically noted in each figure) consist of temperature, pressure, and flow measurements. The temperature and pressure test locations are necessary for testing, and the flow points are used when heater flow streams are directly measured instead of calculated by heat balance techniques. Use of these test points is mandatory to obtain the required data to calculate heater performance.

The manufacturer of the heater normally provides taps for the temperature and pressure measurement points in the nozzle connections. Therefore, the potential test point locations are limited to these areas except for the drains inlet pressure measurement, which is measured before the control valve for the purposes of drains inlet enthalpy determination. All other test points indicated in Figs. 3-8-1 through 3-8-10 are generally considered to be adequate for measurement of thermal performance parameters. However, it is the responsibility of the parties to the test to adequately locate proper performance test measurement points.

Fig. 3-8-1 Three-Zone Heater Test Points: Desuperheating, Condensing, and Drain Cooling Zones



GENERAL NOTES:

(a) Measured parameters are: W_{FW}, T_{FWi}, P_{FWi}, T_{FWo}, P_{FWo}, T_{Si}, P_{Si}, T_{So}, P_{So}, W_{di}, T_{di}, and P_{di}.

(b) Tube Side

(1) The feedwater inlet parameters (subscript "*FWi*") are equal to the drain cooling zone inlet parameters (subscript "*FWdci*").

(2) The drain cooling zone outlet parameters (subscript "*FWdco*") are equal to the condensing zone inlet parameters (subscript "*FWci*").

(3) The condensing zone outlet parameters (subscript "*FWco*") are equal to the desuperheating zone inlet parameters (subscript "*FWdsi*").

(4) The desuperheating zone outlet parameters (subscript "*FWdso*") are equal to the feedwater outlet parameters (subscript "*FWo*").

(c) Shell Side

(1) The extraction steam shell inlet parameters (subscript "*si*") are equal to the desuperheating zone inlet parameters (subscript "*dsi*").

(2) The desuperheating zone outlet parameters (subscript "*dso*") are equal to the condensing zone inlet parameters (subscript "*ci*").

(3) The condensing zone outlet parameters (subscript "*co*") are equal to the drain cooling zone inlet parameters (subscript "*dci*").

(4) The drain cooling zone outlet parameters (subscript "*dco*") are equal to the drain (shell) outlet parameters (subscript "*so*").

(5) Multiple drains inputs — This figure depicts a single drain inlet. However, based on unit specific configurations there may be one or more drain inlets from one or more energy sources. These multiple streams shall be thermodynamically weighted and converted into resultant inputs in both the applicable vapor and liquid states based on their respective input parameters.

(6) Terminal temperature difference (TTD) may either be positive or negative for a three-zone heater with a desuperheating zone.

(7) The saturation temperature, T_{sat}, and the temperature at which the steam condenses, T_c, will differ due to the pressure drop across the desuperheating zone.

(8) The DCA will be significantly affected by the liquid level. Refer to para. 3-3.2(b).

Fig. 3-8-2 Thermal Profile: Desuperheating, Condensing, and Drain Cooling Zones

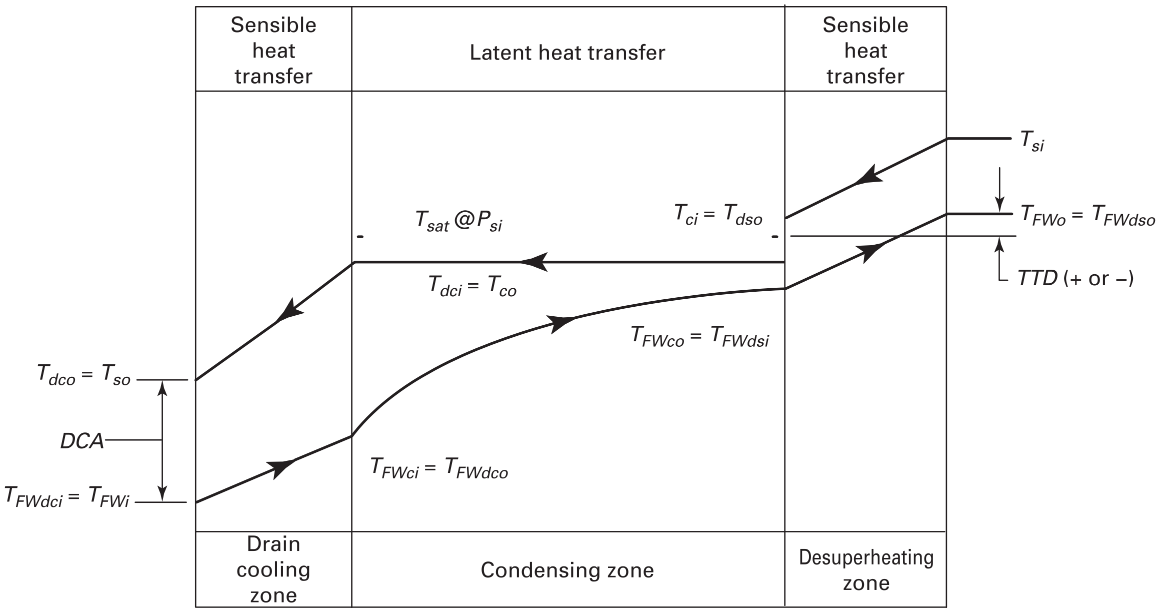
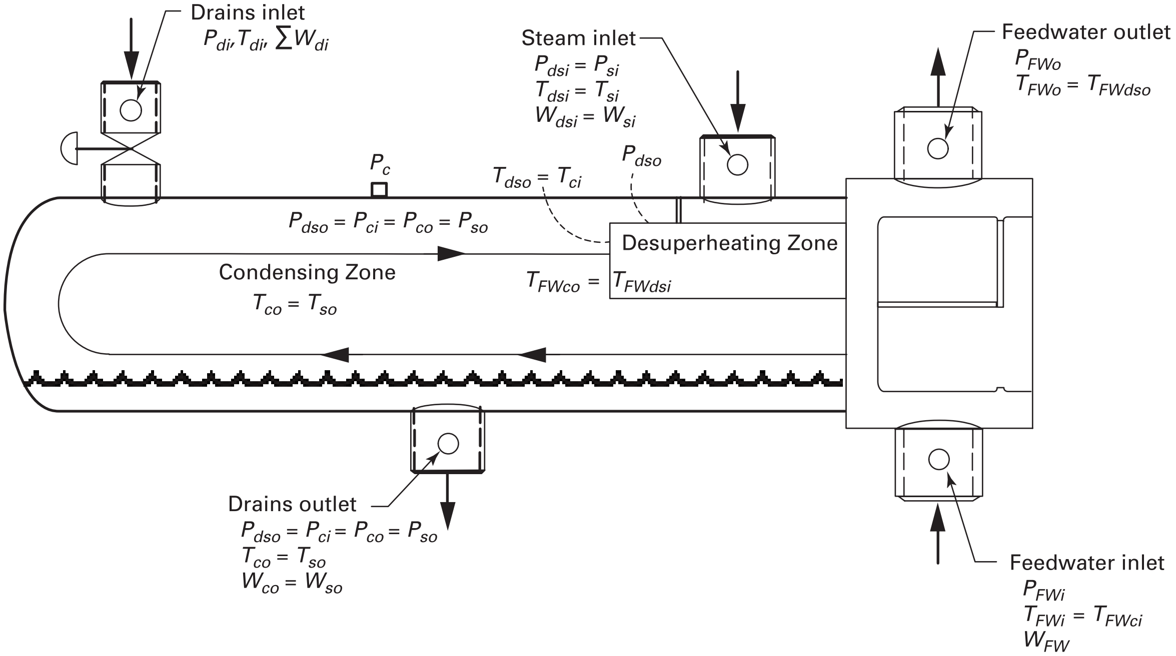


Fig. 3-8-3 Two-Zone Heater Test Points: Desuperheating and Condensing Zones



GENERAL NOTES:

(a) Measured parameters are: W_{FW}, T_{FWi}, P_{FWi}, T_{FWo}, P_{FWo}, T_{Si}, P_{Si}, T_{So}, P_{So}, W_{di}, T_{di}, and P_{di}.

(b) Tube Side

(1) The feedwater inlet parameters (subscript "*FWi*") are equal to the condensing zone inlet parameters (subscript "*FWci*").

(2) The condensing zone outlet parameters (subscript "*FWco*") are equal to the desuperheating zone inlet parameters (subscript "*FWdsi*").

(3) The desuperheating zone outlet parameters (subscript "*FWdso*") are equal to the feedwater outlet parameters (subscript "*FWo*").

(c) Shell Side

(1) The extraction steam shell inlet parameters (subscript "*si*") are equal to the desuperheating zone inlet parameters (subscript "*dsi*").

(2) The desuperheating zone outlet parameters (subscript "*dso*") are equal to the condensing zone inlet parameters (subscript "*ci*").

(3) The condensing zone outlet parameters (subscript "*co*") are equal to the drain (shell) outlet parameters (subscript "*so*").

(4) Multiple Drains Inputs. This figure depicts a single drain inlet. However, based on unit specific configurations there may be one or more drain inlets from one or more energy sources. These multiple streams shall be thermodynamically weighted and converted into resultant inputs in both the applicable vapor and liquid states based on their respective input parameters.

(5) Terminal temperature difference (TTD) may either be positive or negative for a two-zone heater with a desuperheating zone.

(6) The saturation temperature, T_{sat}, and the temperature at which the steam condenses, T_c, will differ due to the pressure drop across the desuperheating zone.

Fig. 3-8-4 Thermal Profile: Desuperheating and Condensing Zones

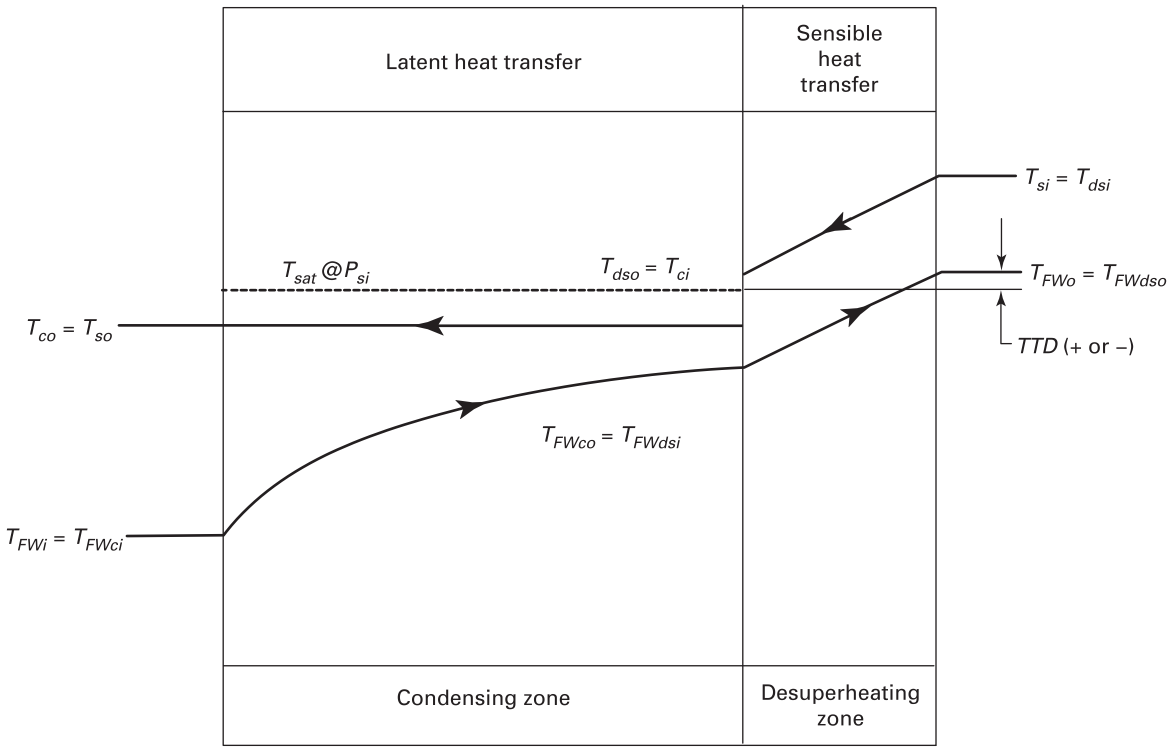
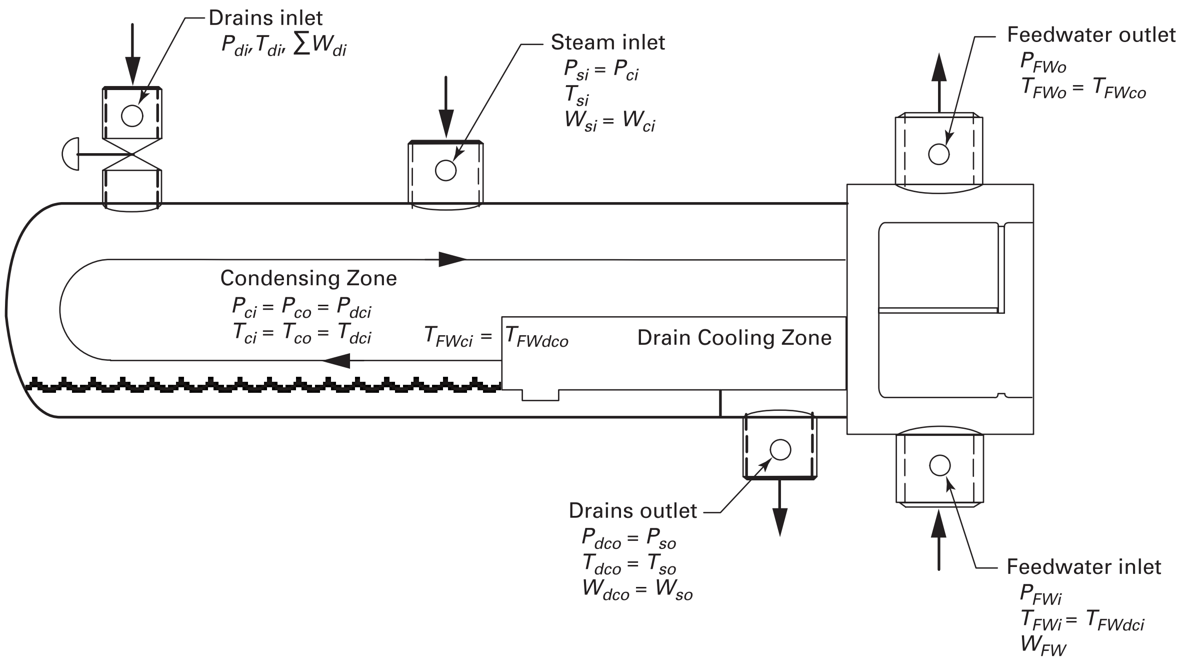


Fig. 3-8-5 Two-Zone Heater Test Points: Condensing and Drain Cooling Zones



GENERAL NOTES:

(a) Measured parameters are: W_{FW}, T_{FWi}, P_{FWi}, T_{FWo}, P_{FWo}, T_{Si}, P_{Si}, T_{So}, P_{So}, W_{di}, T_{di}, and P_{di}.

(b) Tube Side

(1) The feedwater inlet parameters (subscript "*FWi*") are equal to the drain cooling zone inlet parameters (subscript "*FWdci*").

(2) The drain cooling zone outlet parameters (subscript "*FWdco*") are equal to the condensing zone inlet parameters (subscript "*FWci*").

(3) The condensing zone outlet parameters (subscript "*FWco*") are equal to the feedwater outlet parameters (subscript "*FWo*").

(c) Shell Side

(1) The extraction steam shell inlet pressure (subscript "*si*") is equal to the condensing zone inlet pressure (subscript "*ci*").

(2) The condensing zone outlet parameters (subscript "*co*") are equal to the drain cooling zone inlet parameters (subscript "*dci*").

(3) The drain cooling zone outlet parameters (subscript "*dco*") are equal to the drain (shell) outlet parameters (subscript "*so*").

(4) Multiple Drains Inputs. This figure depicts a single drain inlet. However, based on unit specific configurations there may be one or more drain inlets from one or more energy sources. These multiple streams shall be thermodynamically weighted and converted into resultant inputs in both the applicable vapor and liquid states based on their respective input parameters.

(5) Multiple Steam Inlets. This figure depicts a single steam inlet. However, based on unit specific configurations there may be one or more steam inlets. Refer to subsection 4-6 for a discussion on this case.

(6) The steam temperature entering the heater may be superheated. Therefore it may not necessarily be equal to the condensing temperature, T_{ci}.

(7) The DCA will be significantly affected by the liquid level. Refer to para. 3-3.2(b).

(8) TTD for this type of heater configuration will be positive.

Fig. 3-8-6 Thermal Profile: Condensing and Drain Cooling Zones

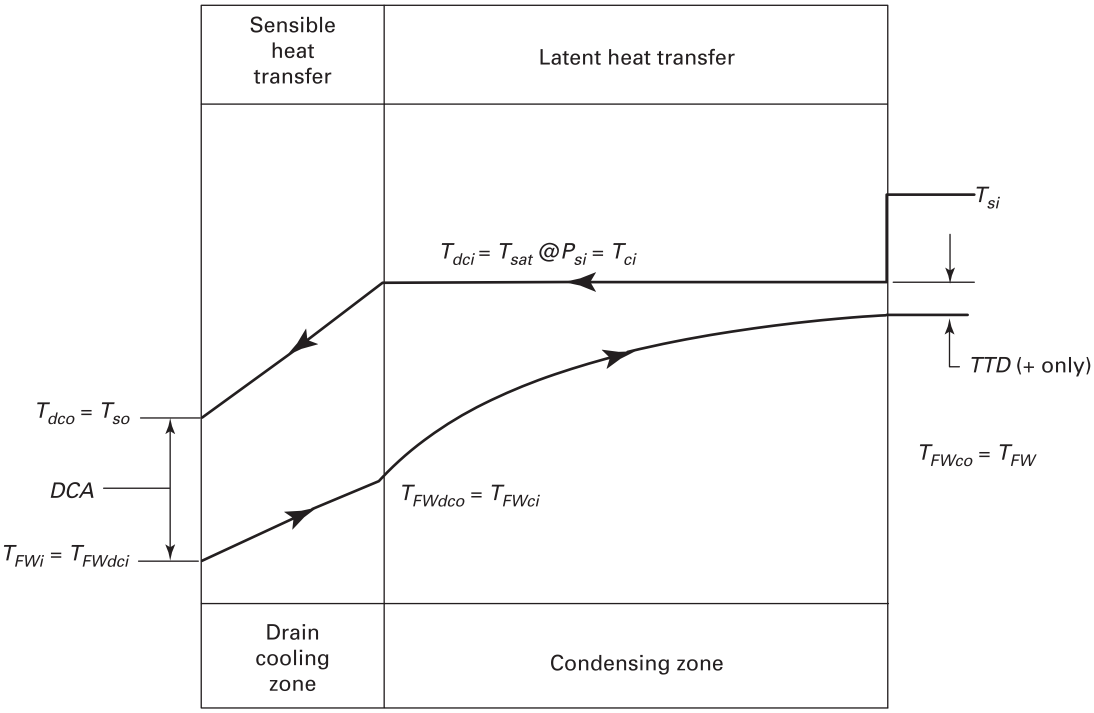
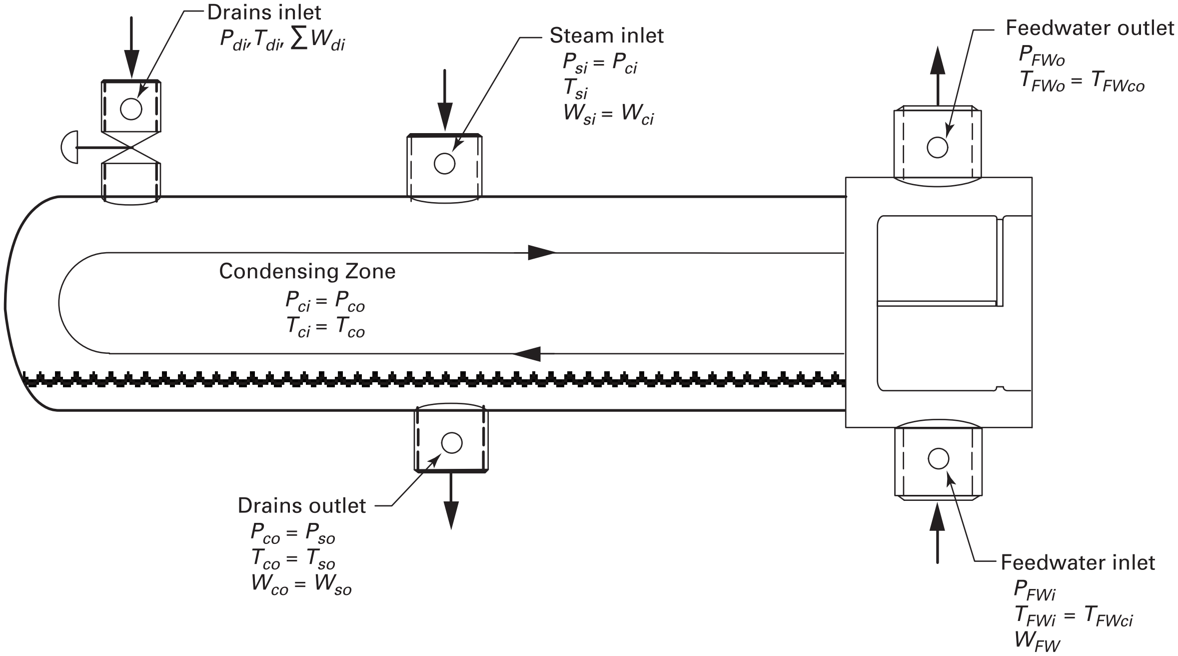


Fig. 3-8-7 Single-Zone Heater Test Points: Condensing Zone Only



GENERAL NOTES:

(a) Measured parameters are: W_{FW}, T_{FWi}, P_{FWi}, T_{FWo}, P_{FWo}, T_{Si}, P_{Si}, T_{So}, P_{So}, W_{di}, T_{di}, and P_{di}.

(b) Tube Side

(1) The feedwater inlet parameters (subscript "*FWi*") are equal to the condensing zone inlet parameters (subscript "*FWci*").

(2) The condensing zone outlet parameters (subscript "*FWco*") are equal to the feedwater outlet parameters (subscript "*FWo*").

(c) Shell Side

(1) The extraction steam shell inlet parameters (subscript "*si*") are equal to the condensing zone inlet parameters (subscript "*ci*").

(2) The condensing zone outlet parameters (subscript "*co*") are equal to the drain (shell) outlet parameters (subscript "*so*").

(3) Multiple Drains Inputs. This figure depicts a single drain inlet. However, based on unit specific configurations there may be one or more drain inlets from one or more energy sources. These multiple streams shall be thermodynamically weighted and converted into resultant inputs in both the applicable vapor and liquid states based on their respective input parameters.

(4) Multiple Steam Inlets. This figure depicts a single steam inlet. However, based on unit specific configurations there may be one or more steam inlets. Refer to subsection 4-6 for a discussion on this case.

(5) The steam temperature entering the heater may be superheated. Therefore it may not necessarily be equal to the condensing temperature, T_c.

(6) TTD for this type of heater will be positive.

Fig. 3-8-8 Thermal Profile: Condensing Zone

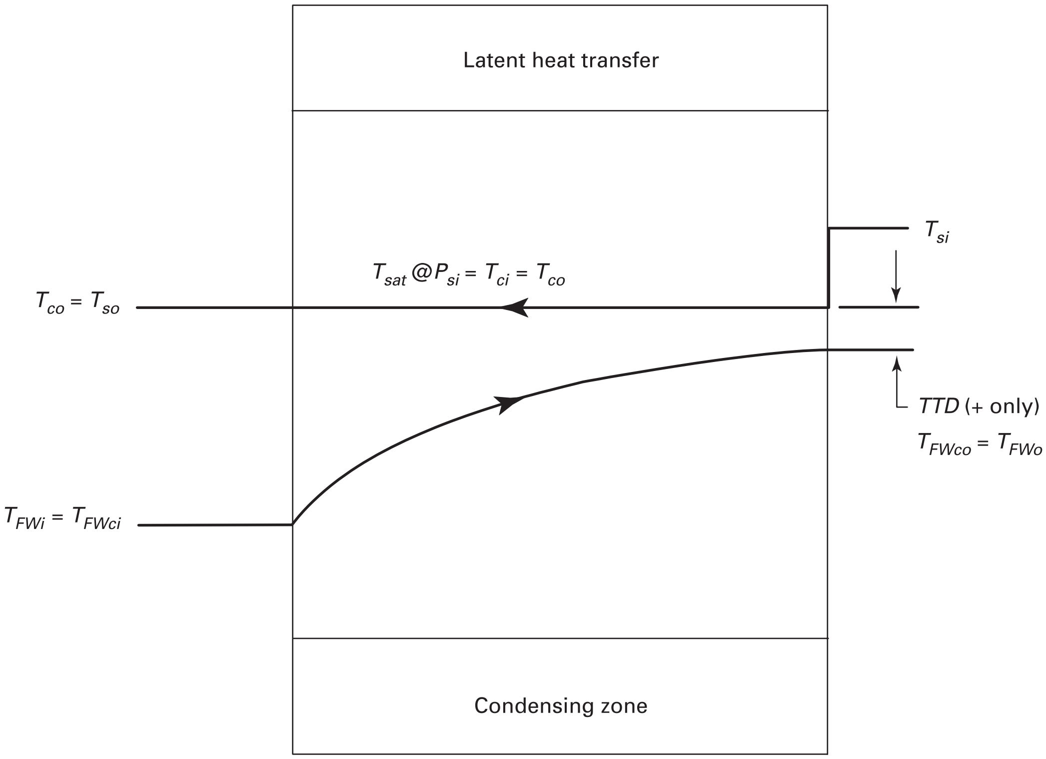
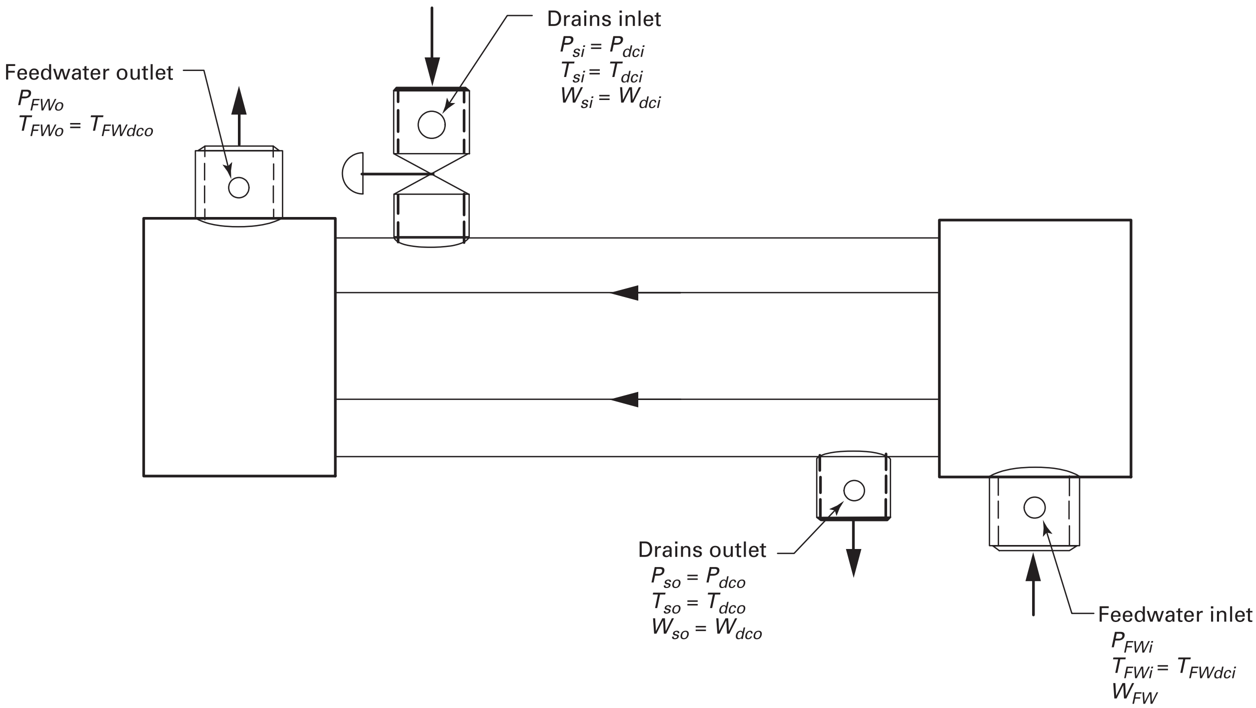
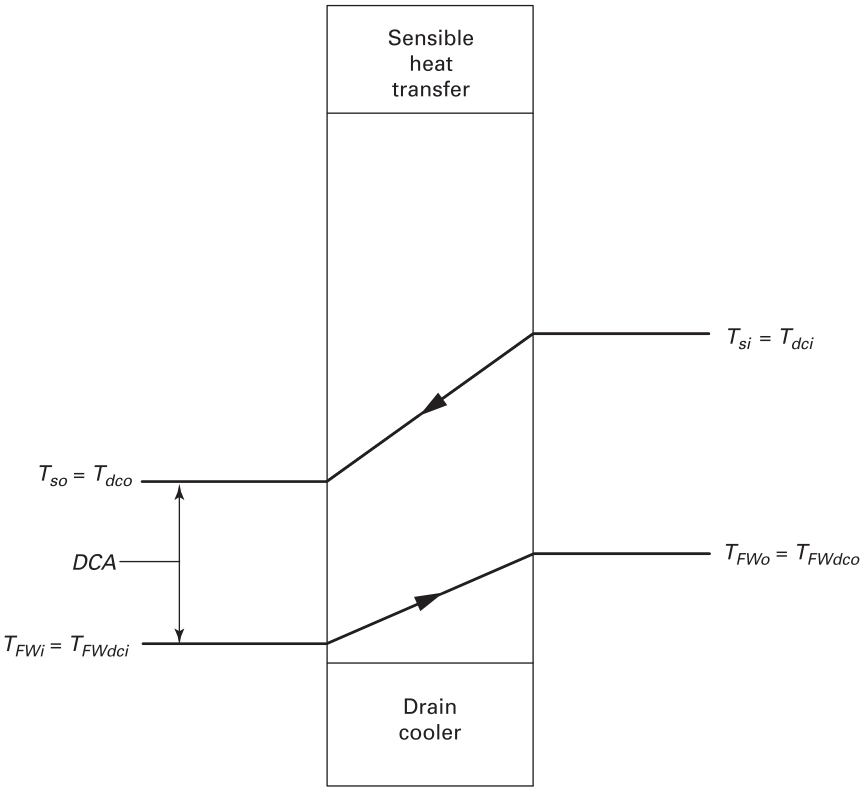


Fig. 3-8-9 Single-Zone Heater Test Points: External Drain Cooler



GENERAL NOTES:
(a) Measured parameters are: W_{FW}, T_{FWi}, P_{FWi}, T_{FWo}, P_{FWo}, T_{Si}, P_{Si}, T_{So}, and P_{So}.
(b) Tube Side
(1) The feedwater inlet parameters (subscript "*FWi*") are equal to the drain cooling zone inlet parameters (subscript "*FWdci*").
(2) The drain cooling zone outlet parameters (subscript "*FWdco*") are equal to the feedwater outlet parameters (subscript "*FWo*").
(c) Shell Side
(1) The condensate inlet shell parameters (subscript "*si*") are equal to the drain cooling zone inlet parameters (subscript "*dci*").
(2) The drain cooling zone outlet parameters (subscript "*dco*") are equal to the drain (shell) outlet parameters (subscript "*so*").
(3) This figure is shown as a single pass but it may have other configurations (i.e., multiple passes).
(4) Since the shell-side inlet flow (subscript "*si*") is equal to the shell side outlet flow (subscript "*so*"), either the inlet or outlet shell side flow may be measured, utilizing whichever location is more accessible.

Fig. 3-8-10 Thermal Profile: External Drain Cooler



Section 4
Instruments and Methods of Measurement

4-1 GENERAL

This Code presents the requirements for instruments and methods that shall be used. It emphasizes the use of "state of the art" instrumentation. General guidance on the selection and use of temperature, pressure, and flow instrumentation may be found in the PTC 19 series, Supplements on Instruments and Apparatus.

The instruments described in this Section are required for performance tests on feedwater heaters. Temperature and pressure measurements around a feedwater heater may be straightforward. Flow measurement, however, may be quite complex. In some configurations, it may be necessary to perform a heat balance or to collect data from several heaters in order to resolve feedwater, shell, and drain flows to the tested heater.

4-2 PRESSURE MEASUREMENT

Pressure measurements shall be taken at the locations shown in Figures 3-8-1 through 3-8-10. These pressures may range from the highest pressure in the cycle to below atmospheric pressure. This wide range of pressure measurements makes instrument selection heater-dependent. Absolute pressures are needed for steam calculations. If gage transmitters are used, it is necessary to convert the pressures to absolute values prior to using the test data in calculations. Outlet pressure measurements indicated in Figures 3-8-1 through 3-8-10 are needed to determine pressure loss through the feedwater side or shell side of the heater. The feedwater pressure loss is most accurately measured with a differential pressure device connected between feedwater inlet and outlet. Similarly, the desuperheating and drain cooling zone pressure drops could also be measured with a differential pressure device.

WARNING: If the pressure taps are at unequal elevations, a differential water leg correction is required to account for the static head. The water legs associated with the elevations of the high and low pressure taps need to be carefully reviewed to ensure the water leg correction is properly applied.

Other means of pressure testing of similar or higher accuracy and reliability may also be used, if the specific instruments are agreed upon prior to the test. See ASME PTC 19.2.

Regardless of the pressure measurement instrument selected, attention shall be given to how the instrument is installed and operated. Particular attention shall be paid to elevation differences in the source of the pressure and the instrument. The line connecting the pressure-sensing instrument is usually filled with fluid, causing the instrument to read high or low depending on the relative location of the instrument to the source. In instances where the instrument is below the source, the correction (known as a water leg correction) is subtracted from the reading. The water leg correction is added if the instrument is above the source, provided the existence of a full water leg is determined. In general, liquid-filled lines should be routed from the source to the instrument in a manner such that the line continuously slopes downward, and a low point drain should be available for purging the line. The opposite is true for vapor-filled lines with a vent located near the top of the line, just before the instrument. Some vapor legs will collect condensate and may require low-volume flow, continuous venting to stay dry. If the venting method is utilized, the flow rate shall be kept low [approximately 0.5 ft^3/hr (0.014 m^3/h)] enough to have an undetectable effect on pressure measurement. All pressure measuring devices shall be calibrated before and after the test to verify that the instruments meet the requirements of subsection 4-7. If the instrumentation does not satisfy these requirements, the test shall be rejected.

4-3 TEMPERATURE MEASUREMENT

Temperature measurement shall be taken at the locations shown in Figures 3-8-1 through 3-8-10. See subsection 3-8 where precautions on locations of feedwater and drain outlet measurements are discussed. Test grade temperature measuring devices shall be used (see ASME PTC 19.3).

The location of these devices is important. Temperature measuring devices shall be located at a point where the most uniform temperatures are found. They shall not be installed where there may be an air pocket or where they may be near a cold water manifold. When they are located near a large, uninsulated heat source, they shall be shielded from radiation. Elements that are too long for the thermowell or exposed thermowells should be insulated (see ASME PTC 19.3).

All temperature measuring instruments shall be calibrated before and after the test. Calibrations should be performed around the range of expected use and should include hysteresis checks.

At least five calibration temperatures should be used. Midspan temperature should be replicated in both heating and cooling runs. The total uncertainty, including the standard error of estimate (SEE), shall be less than or equal to the requirements of subsection 4-7. If this level of accuracy cannot be demonstrated, an agreement among the parties to the test is required prior to the test in order to use the instrumentation. If the post-test calibration does not meet the requirements of subsection 4-7, the test results shall be rejected.

4-4 WATER FLOW MEASUREMENT

(a) Laboratory-calibrated flowmeters, which may include ultrasonic transit-time flowmeters, shall be used for feedwater. For drain flow measurements calibrated flowmeters may be used or drain flow rates may be calculated by a heat balance. This Code does not recommend utilizing differential pressure (DP) type flow measurement devices for drain flow due to the possibility of inducing two-phase flow in the drain line, resulting from the pressure drop across the DP device. For proper use of nozzles, orifice meters, and venturi meters, see ASME PTC 19.5. This Section includes guidance for the use of ultrasonic transit-time flowmeters.

The accurate determination of flow is one of the most difficult field measurements. Flow measurements are affected by irregularities in the pipe wall, calibration of instrumentation, and the location of suitable runs of piping in which to install fluid meters.

There are two acceptable methods of testing feedwater heaters. The first method uses the existing plant flow nozzle that satisfies ASME PTC 19.5, Section 5 and utilizes temperature and pressure instrumentation required by this Code on the entire string of feedwater heaters. Use of a known feedwater flow and heat balance techniques allows the calculation of drain flows that then may be cascaded throughout the system. However, the following restrictions apply.

(1) Due to unknown flow distribution resulting from differences in piping, valves, and percentage of tubes plugged, this method cannot be utilized where a split-string feedwater heater setup exists unless each string has its own flow nozzle that meets the appropriate requirements.

(2) When using this method of calculating drain flows that cascade to the last feedwater heater, the uncertainty increases. The uncertainty calculation procedures specified in subsection 5-3 shall be performed to determine if this method meets the requirements of this Code.

The second method incorporates direct flow measurements utilizing ultrasonic technology. These devices are generally nonintrusive with respect to the piping systems and have the potential to be moved from one location to another with relative ease. Calibrated meters using the transit-time principle and transducers designed for high temperature have demonstrated Code-required accuracies consistent with other plant flow nozzles. A typical nonintrusive transducer installation on a pipe is illustrated in Figure 4-4-1.

In order to achieve the best possible accuracy using ultrasonic flow measuring equipment, several parameters shall be considered and some operational precautions shall be observed.

The most critical steps when installing the transducer array are proper alignment and selection of the couplant that bonds the transducers to the piping. Multiple couplant compounds are available and should be selected based on the temperature range expected for the process fluid. Templates or precise measurements shall be utilized to ensure good alignment of the transducers with respect to the piping.

Separate flow calibrations should be used for each different pipe size, and the flow rate should cover the range expected for the process fluid in the field.

With the proper use of ultrasonic flow-measuring equipment, it is possible to measure the actual feedwater and drain flows in real time. The feedwater and drain flows shall be monitored simultaneously at all times during the test.

Periodic equipment maintenance and recalibration of the flow transducer pairs may be necessary. Users will have to establish their own calibration cycles based on the temperatures, equipment usage, and brand.

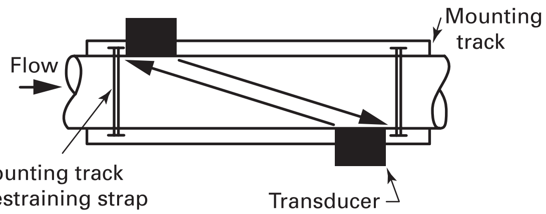
(b) Properly trained operators are required and site selection for the transducer location is critical. There are several known factors that may influence flow measurement under field conditions using ultrasonic equipment. The major factors are as follows:

(1) Piping configuration is critical when measuring flows. Most equipment vendors recommend that transducers be located in a straight length of pipe of at least 15 pipe diameters with at least 10 pipe diameters upstream and 5 pipe diameters downstream from any bends, elbows, valves, joint weld seams, points of aeration, and other items that could distort the flow profile. Field measurements should duplicate or exceed this piping criteria for maximum accuracy.

Flow measurement using ultrasonics is possible with less than an ideal number of pipe diameters, but the accuracy has the potential to be reduced by an unknown factor. One technique that has proven useful in compensating for nonsymmetrical flow profiles, when less than an ideal number of pipe diameters is available, is transducer rotation. Using this technique, the transducers are installed in one location and a flow reading is obtained. The transducers are then rotated around the circumference of the pipe, and additional flow measurements are made.

The final location of the transducers is determined by averaging the indicated flows and selecting the location closest to the calculated average flow value. A typical rotation is 120 deg, but accuracy has the potential to be increased with a smaller angle of rotation. This procedure is somewhat cumbersome but it may improve the accuracy of flow measurement if the required straight

Fig. 4-4-1 Typical Transducer Installation



length of unobstructed piping is not available. Multiple-path flow measurement is more accurate than single-path measurement under this condition.

(2) It is necessary both to stop the flow and maintain a full pipe in the section under consideration in order to set an appropriate zero-offset compensation factor. Without this ability, flow will be offset by some constant amount. Bypasses and emergency drain lines may usually be utilized to stop the flow.

(3) The zeroing of the flow measuring equipment shall be done as close to normal operating temperature as possible. Otherwise, this procedure will not produce an appropriate zero offset.

(4) If pressure regimes within the piping are such that flashing occurs or excessive aeration is present, ultrasonic equipment will receive a signal too weak to function. This may be a continuous process, occurring only under certain conditions, or intermittently.

(5) Internal/external pipe scale and unbonded pipe liners may cause ultrasonic flow-detection equipment to be unusable or to give false flow indications.

(6) Operation of ultrasonic equipment in the proximity of other ultrasonic flow measuring equipment may cause cross talk and inaccurate readings. Likewise, both electrical and radio interferences may invalidate flow readings. These problems are generally solved by shielding the electrical components and routing flow meter transducer cables away from high-voltage lines and other instrumentation cables.

(7) Most ultrasonic flow-measuring devices require that the pipe material, outside dimensions, and exact wall thickness be known in order to correct the indicated flows to actual ones. Digital thickness gages based on ultrasonic technology are generally used to provide wall thickness information. Other information is usually obtained from drawings and piping specifications. The following equation may be used to correct mathematically for different pipe wall thicknesses if the appropriate data from the flow meter calibration runs is available.

To correct for different thicknesses, multiply measured flow rate by the following:

$$(d_A/d_N)^2$$

where

d_A = actual pipe internal diameter
d_N = nominal pipe internal diameter

(8) Sources of Error. With regard to sources of error, the four main contributors to error when using ultrasonic flow meters are uncertainty of the pipe dimensions, coupling of the transducers, uneven velocity profiles of the flow, and "drift" of the electronics during the period of the test.

To reduce the uncertainty due to pipe dimensions, careful measurements of the pipe dimensions including wall thickness at the point of flow measurement shall be made.

To reduce the uncertainty due to transducer coupling, trained, experienced technicians should install the transducers securely on the pipe according to the manufacturer's instructions. If the coupling is completely inadequate, a loss of signal will occur. Many ultrasonic meters have warning signals incorporated into their design to alert the operators to a loss of signal.

The effect of uneven velocity profiles, which may be expected downstream from convoluted piping typically found in feedwater heaters, may best be reduced by measuring flow across several axial planes dissecting the pipe. Therefore, it is recommended to record flow measurements after transducers are rotated about the pipe axis, to as many positions as practical or necessary depending on the variation of flow indications. A comparison of the flow indications at these different planes will provide a practical indication of the effect of nonuniformity of the velocity profile. The difference between the indications at different planes should be treated as a systematic uncertainty.

4-5 SPLIT STREAM FEEDWATER HEATER TESTING

Due to economic considerations, most plants have only one final feedwater flow nozzle measuring the combined flow from all heaters that are operating in parallel. This causes uncertainty in the actual flow distribution through each heater. Uncertainty in the feedwater flow also directly affects the calculation of the drain flow for that particular feedwater heater.

Table 4-7-1 Maximim Uncertainty Values

Flow Rate	Pressure	Temperature
Feedwater at heater: ±1%	Desuperheater pressure loss: ±1%	Steam inlet: ±1.00°F
Drains: ±1%	Steam inlet: ±0.25%	Drains inlet: ±0.25°F
	Feedwater inlet: ±2%	Drain outlet: ±0.25°F
	Feedwater pressure loss: ±1%	Feedwater inlet: ±0.25°F
	Drain cooler pressure loss: ±1%	Feedwater outlet: ±0.25°F

GENERAL NOTE: Uncertainties expressed in terms of percentage are based on measured values.

Since flow inequalities may exist due to differences in valve coefficients, piping configuration, and number of tubes plugged in each heater, split-stream feedwater heaters cannot be tested according to this Code unless at least one of the following conditions exists:

(a) Each heater has its own flow element to measure feedwater flow that meets the requirements of this Code, and the calculated values for the cascaded drains using the heat balance method meet the uncertainty limitations imposed by subsection 4-7.

(b) Flow instrumentation may be installed to measure directly both the feedwater and drain flow(s) simultaneously for each feedwater heater to be tested. Overall uncertainty calculations referenced in subsection 3-7 shall be made to ensure that the final results are within the required limitations.

4-6 MULTIPLE INLET STEAM NOZZLES

Some designs incorporate multiple steam inlet nozzles. Typically these designs are found in low pressure heaters. The potential differences in thermal and hydraulic conditions from each nozzle may make accurate heater extraction steam pressure and enthalpy determination challenging. For these cases it is recommended that TTD calculations be based on a shell pressure gauge measurement instead of measuring the extraction steam pressure at the individual nozzles. The extraction steam enthalpy utilized in the calculations should be based on agreement by the parties to the test. Uncertainty calculations may help determine the overall quality of the test under these conditions.

4-7 INSTRUMENT UNCERTAINTIES

Primary instruments selected for the test shall have total uncertainties equal to or less than the values shown in Table 4-7-1. The use of instrumentation providing total uncertainties exceeding the limits indicated in Table 4-7-1 shall be subject to mutual agreement by the parties to the test.

Section 5
Computation of Results

5-1 INTRODUCTION

The feedwater heater performance test is to be conducted under the conditions specified in section 3. The following points are important to the accuracy and documentation of the test:

(a) Design and test data shall be tabulated on the Test Report Form 6-1 (see section 6) or a similar type of form used to document the test results.

(b) Compressed water enthalpies shall be used in the calculations for feedwater.

(c) The latest edition of the ASME Steam Tables shall be used in the calculations of the test results.

(d) The calculation procedure shall be based on all resistances to heat transfer being corrected to the outside diameter of the tube.

(e) The calculation procedure shall be based on the reheat factor being applied by the manufacturer to the condensate film resistance of the drain cooling zone r_{sdc}.

Test Report Form 6-1 provides a convenient means for recording the design and the test data. The heater manufacturer shall supply the design data for the heater. Test Report Form 6-1 provides a form for recording data during the test if using manual readings. Similar forms may be used or, preferentially, the data may be recorded with a data acquisition system.

Since steam surrounds the drain cooler shrouds, drain coolers are subject to reheat (horizontal heaters with short type drain coolers or vertical channel up heaters). Therefore, steam condenses on the lower temperature drain cooler shrouds injecting heat back into the condensate inside the drain cooler. In order to compensate for this condition, the heater manufacturer applies a reheat factor to either the shell-side heat transfer coefficient or to the log mean temperature difference (LMTD). See Nonmandatory Appendix A for a definition of LMTD. Since the majority of heater manufacturers use the true LMTD, this Code uses the method of a modified shell-side heat transfer coefficient based on a "corrected" shell-side film resistance. The user of this Code should make certain that the shell-side film resistance, r_{sdc}, provided by the manufacturer includes the reheat factor. A separate reheat factor is not required. When the shell-side film resistance is back-calculated from the overall drain-cooling zone heat-transfer coefficient, the reheat factor is included.

The terms and symbols shown in the following Tables and data sheets are defined in Section 2. The performance calculation procedures are given in subsection 5-2. The results of these calculations are the basis for the evaluations of the performance of the heater being tested.

5-2 PERFORMANCE CALCULATION PROCEDURES

This subsection contains five paragraphs covering performance calculation procedures for feedwater heaters with various configurations. Calculations shall be performed for each of the test runs. Paragraph 5-2.1 covers a three-zone feedwater heater with integral desuperheating zone, condensing zone, and drain cooling zone. Paragraph 5-2.2 covers a two-zone feedwater heater with desuperheating zone and condensing zone. Paragraph 5-2.3 covers a two-zone feedwater heater with condensing zone and drain cooling zone. Paragraph 5-2.4 covers a feedwater heater with condensing zone only. Paragraph 5-2.5 covers an external drain cooler.

It is not feasible to expect that the test will be conducted exactly at the design point. In addition, it is not possible to measure the internal shell-side or tube-side temperatures at the transitions between zones (drain cooling zone to condensing zone and/or condensing zone to desuperheating zone) because there is insufficient test data to adjust the test results to design conditions. Therefore, performance comparisons are made by predicting the heater performance by adjusting the design parameters (including the internal transition temperatures) to the test conditions. The predicted values for TTD, DCA, tube-side ΔP, drain cooling zone ΔP, and desuperheating zone ΔP, shall be compared to the measured test values.

The calculation determines the feedwater outlet temperature and the drain cooling zone outlet temperature by iteration. These iterations should continue until the old and new computed values of feedwater outlet temperature differ by no more than 0.1°F.

The resistance summation and effectiveness/NTU methods are used in the calculation procedures. Individual resistance for each zone may be obtained from the heater manufacturer, or calculated based on the manufacturer's design specification data sheet. The basic heat transfer equations and examples on how to use the calculation procedures are included in the Nonmandatory Appendices.

In cases where the incoming steam is less than 100% quality, the saturated steam enthalpy at the tested extraction pressure should ideally be taken from the turbine

Table 5-2.1-1 Manufacturer Design Data

Parameter	Performance Data: Shell Side: Steam	Shell Side: Drains	Tube Side: Feedwater
Fluid circulated	Steam	Drains	Feedwater
Total fluid entering	W_{si_G}	W_{di_G}	W_{FW_G}
Inlet enthalpy	h_{si_G}	h_{di_G}	h_{FWi_G}
Outlet enthalpy	. . .	h_{so_G}	h_{FWo_G}
Inlet temperature	T_{si_G}	. . .	T_{FWi_G}
Outlet temperature	. . .	T_{so_G}	T_{FWo_G}
Operating pressure	P_{si_G}	. . .	P_{FWi_G}
Number of passes	3 zones		2 passes
Velocity (at average temperature)	. . .	. . .	$v_{\_G}$
Pressure drop (at operating temperature)	ΔP_{ds_G}	ΔP_{dc_G}	ΔP_{FW_G}

Parameter	Heat Exchanged	Effective Area	Heat Transfer Rate	Reference Temperature Differences
Desuperheating zone	Q_{ds_G}	A_{ds_G}	U_{ds_G}	$\mathrm{TTD}_{\_G}$
Condensing zone	Q_{c_G}	A_{c_G}	U_{c_G}	$\mathrm{DCA}_{\_G}$
Drain Cooling zone	Q_{dc_G}	A_{dc_G}	U_{dc_G}	. . .
Tube material	. . .	Tube $OD_{\_G}$	. . .	Average tube wall thickness, $t_{\_G}$

expansion line that satisfies a cycle energy balance at the time of the test. However, subject to agreement by the parties to the test, the steam quality at the design condition, along with the measured steam temperature/pressure, may be utilized to obtain the extraction steam enthalpy. This condition could apply to any feedwater heater referenced in paras. 5-2.3 and 5-2.4.

5-2.1 Three-Zone Heater (Integral Desuperheating Zone, Condensing Zone, and Drain Cooling Zone)

In this heater, the feedwater enters the heater in the drain cooling zone and exits through the desuperheating zone. The steam enters the heater in the desuperheating zone and passes through the condensing zone where it condenses, and then flows through the drain cooling zone and exits as condensate. Refer to Figs 3-8-1 and 3-8--2.

Table 5-2.1-1 contains the minimum required data from the heater manufacturer to utilize this Code to calculate performance. Note that the data assumes a three-zone design but in reality the data would be presented specific to the actual heater design mentioned above. This Table may be utilized with paras. 5-2.1 to 5-2.5 to represent the data supplied by the manufacturer. Typically the data in Table 5-2.1-1 is a subset of what the manufacturer actually provides since it only lists the heat transfer data for clarity.

NOTE: For clarity and brevity, the units used are U.S. Customary. The SI constants will be different. U.S. Customary and SI equivalents on heat transfer resistances are provided in Nonmandatory Appendix A. Nonmandatory Appendix B uses an example that converts all results to SI units, and all unit conversion factors are listed in Nonmandatory Appendix B.

Step 1: Calculate the assumed feedwater outlet temperature based on the given terminal temperature difference, $\mathrm{TTD}_{\_G}$, and saturation temperature, T_{sat}, corresponding to the measured shell-side inlet steam pressure (psi).

$$T_{FWo\_a} = T_{sat\_G} - \mathrm{TTD}_{\_G}$$

Calculate the assumed drain cooling zone outlet temperature based on the given drain cooler approach, $\mathrm{DCA}_{\_G}$, and the measured feedwater inlet temperature, T_{FWi}.

$$T_{so\_a} = T_{FWi} + \mathrm{DCA}_{\_G}$$

These temperatures serve as a starting point for the calculations. During the reiteration process, use the following convergence criteria.

If $| T_{FWo\_a} - T_{FWo\_X} | > 0.1$, then let $T_{FWo\_a} = T_{FWo\_X}$ using T_{FWo_X} as calculated in Step 28.

Step 2: Calculate the total heat transferred, $Q_{\_X}$, based on the measured feedwater flow, W_{FW}, the feedwater outlet enthalpy, h_{FWo_X} determined using T_{FWo_a} in Step 1 and the measured feedwater pressure, P_{FWo}, and the feedwater inlet enthalpy, h_{FWi}, determined using the measured feedwater inlet temperature, T_{FWi}, and pressure, P_{FWi}.

$$Q_{\_X} = W_{FW}\,(h_{FWo\_X} - h_{FWi})$$

Step 3: Calculate the drain inlet energy, Q_{di_X}, as follows:

(a) Obtain the sum of the drain inlet flows, W_{di}, if necessary. See Nonmandatory Appendix A.

(b) Obtain the drain inlet enthalpy, h_{di}, based on P_{di} and T_{di} for a single-drain stream or by the flow weighted average of enthalpies for multiple drain streams. Note that the pressure(s) and temperature(s) are measured upstream of the drain control valve(s).

(c) Obtain the drain cooling zone shell-side outlet enthalpy, h_{so_X}, based on the assumed shell-side outlet temperature, T_{so_a}, and measured pressure, P_{so}, and calculate the total energy from the inlet drains.

$$Q_{di\_X} = W_{di}\,(h_{di} - h_{so\_X})$$

Step 4: Calculate the steam flow to the heater by energy balance (see Nonmandatory Appendix A). The shell-side steam inlet enthalpy, h_{si}, is based on the measured temperature, T_{si}, and pressure, P_{si}.

$$W_{si\_X} = \frac{Q_{\_X} - Q_{di\_X}}{h_{si} - h_{so\_X}}$$

Step 5: Calculate the total shell-side outlet flow.

$$W_{so\_X} = W_{si\_X} + W_{di}$$

Step 6: Calculate the desuperheating zone, drain cooling zone, and feedwater pressure losses based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{ds\_X} = \Delta P_{ds\_G}\left(\frac{W_{si\_X}}{W_{si\_G}}\right)^{1.8}$$

$$\Delta P_{dc\_X} = \Delta P_{dc\_G}\left(\frac{W_{so\_X}}{W_{so\_G}}\right)^{1.8}$$

$$\Delta P_{FW\_X} = \Delta P_{FW\_G}\left(\frac{W_{FW}}{W_{FW\_G}}\right)^{1.8}$$

Step 7: Calculate the shell-side pressure, P_{c_X}, inside the condensing zone, and determine the saturation temperature, T_{c_X}, corresponding to this pressure.

$$P_{c\_X} = P_{si} - \Delta P_{ds\_X}$$

Step 8: If not available from the heat exchanger manufacturer, calculate the desuperheating and drain cooling zone resistances. These will be needed for the overall heat transfer coefficient calculation in Step 9. See Nonmandatory Appendix A for more information.

If the tube-side fouling and shell-side fouling resistances are not available from the manufacturer, Heat Exchange Institute (HEI) recommends utilizing the following:

$$r_{fsds\_G} = r_{fsdc\_G} = 0.0003\left[\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right]$$

$$r_{fsc\_G} = 0$$

$$r_{ftds\_G} = r_{ftc\_G} = r_{ftdc\_G} = 0.0002\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\left[\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right]$$

If the metal and tube-side film resistances are not available from the manufacturer, calculate each as per the formulas in Nonmandatory Appendix A.

$$r_{tds\_G} = 0.0378\left[\frac{\mu_{ds}^{\,0.4}}{k_{FWds}^{\,0.6} \times \rho_{FWds}^{\,0.8} \times c_{pFWds}^{\,0.4}}\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{\,0.8}}\right)\left(\frac{1}{v^{0.8}}\right)$$

$$r_{tc\_G} = 0.0378\left[\frac{\mu_{c}^{\,0.4}}{k_{FWc}^{\,0.6} \times \rho_{FWc}^{\,0.8} \times c_{pFWc}^{\,0.4}}\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{\,0.8}}\right)\left(\frac{1}{v^{0.8}}\right)$$

$$r_{tdc\_G} = 0.0378\left[\frac{\mu_{dc}^{\,0.4}}{k_{FWdc}^{\,0.6} \times \rho_{FWdc}^{\,0.8} \times c_{pFWdc}^{\,0.4}}\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{\,0.8}}\right)\left(\frac{1}{v^{0.8}}\right)$$

Metal resistance is calculated at average temperature and the same values are used for the entire heater.

$$r_{mds\_G} = r_{mc\_G} = r_{mdc\_G} = \frac{\text{OD}_{\_G}}{24k_m}\left[\ln\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\right]$$

Calculate the shell-side film resistance as the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as follows:

$$r_{sds\_G} = \left(\frac{1}{U_{ds\_G}}\right) - (r_{fsds\_G} + r_{mds\_G} + r_{ftds\_G} + r_{tds\_G})$$

$$r_{sc\_G} = \left(\frac{1}{U_{c\_G}}\right) - (r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G})$$

$$r_{sdc\_G} = \left(\frac{1}{U_{dc\_G}}\right) - (r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G})$$

Step 9: Calculate the desuperheating, condensing and drain cooling zone overall heat transfer coefficients based on the inverse of the sum of the individual resistances. All resistances are calculated as shown in Nonmandatory Appendix A. Note that the shell- and tube-side film resistances are adjusted based on flow proportionalities. The fouling resistances utilized are not adjusted and remain as reported by the manufacturer or assumed. The tube-side metal resistance is referenced to the outer tube diameter.

$$U_{ds\_X} = \frac{1}{\left[r_{sds\_G}\left(\frac{W_{si\_G}}{W_{si\_X}}\right)^{0.6} + r_{fsds\_G} + r_{mds\_G} + r_{ftds\_G} + r_{tds\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

$$U_{c\_X} = \frac{1}{\left[r_{sc\_G} + r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

where the shell-side heat transfer coefficient is not adjusted for steam flow in the condensing zone. The tube-side film resistances are adjusted based on flow proportionalities as shown in Nonmandatory Appendix A.

$$U_{dc\_X} = \frac{1}{\left[r_{sdc\_G}\left(\frac{W_{so\_G}}{W_{so\_X}}\right)^{0.6} + r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

Step 10: Using T_{FWi_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWdc}, and the feedwater temperature leaving the drain cooling zone as shown in Nonmandatory Appendix A under effectiveness/NTU method.

$$T_{FWdco\_G} = T_{FWi\_G} + \frac{Q_{dc\_G}}{W_{FW\_G} \times c_{pFWdc}}$$

Step 11: Calculate the drain cooling zone condensate (shell-side) hourly heat capacity flow rate.

$$C_{dc\_X} = \frac{W_{so\_X} \times Q_{dc\_G}}{W_{so\_G}\,(T_{c\_G} - T_{so\_G})}$$

where

T_{c_G} = saturation temperature at P_{c_G}

$P_{c\_G} = P_{si\_G} - \Delta P_{ds\_G}$

Step 12: Calculate the drain cooling zone feedwater (tube-side) hourly heat capacity flow rate.

$$C_{FWdc\_X} = \frac{W_{FW} \times Q_{dc\_G}}{W_{FW\_G}\,(T_{FWdco\_G} - T_{FWi\_G})}$$

Step 13: Calculate the drain cooling zone heat capacity ratio.

$$R_{dc\_X} = \frac{C_{FWdc\_X}}{C_{dc\_X}}$$

Step 14: Calculate the drain cooling zone number of transfer units.

$$(\mathrm{NTU})_{dc\_X} = \frac{U_{dc\_X} \times A_{dc\_G}}{C_{FWdc\_X}}$$

Step 15: Calculate the drain cooling zone effectiveness.

$$\epsilon_{dc\_X} = \frac{1 - \exp[(\mathrm{NTU})_{dc\_X}\,(R_{dc\_X} - 1)]}{1 - R_{dc\_X}\exp[(\mathrm{NTU})_{dc\_X}\,(R_{dc\_X} - 1)]}$$

Step 16: Calculate the feedwater temperature leaving the drain cooling zone.

$$T_{FWdco\_X} = \epsilon_{dc\_X}\,(T_{c\_X} - T_{FWi}) + T_{FWi}$$

where T_{c_X} is calculated in Step 7.

Step 17: Using T_{FWdco_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWc}, and the manufacturer's feedwater temperature leaving the condensing zone as shown in Nonmandatory Appendix A under effectiveness/NTU method.

$$T_{FWco\_G} = T_{FWdco\_G} + \frac{Q_{c\_G}}{W_{FW\_G} \times c_{pFWc}}$$

Step 18: Considering that the shell-side heat capacity flow rate in the condensing zone is zero (see Nonmandatory Appendix A), calculate the feedwater hourly heat capacity flow rate in the condensing zone.

$$C_{FWc\_X} = \frac{W_{FW} \times Q_{c\_G}}{W_{FW\_G}\,(T_{FWco\_G} - T_{FWci\_G})}$$

Step 19: Considering that the heat capacity ratio in the condensing zone is zero (see Nonmandatory Appendix A), calculate the number of transfer units in the condensing zone $(\mathrm{NTU})_{c\_X}$.

$$(\mathrm{NTU})_{c\_X} = \frac{U_{c\_X} \times A_{c\_G}}{C_{FWc\_X}}$$

Step 20: Calculate the condensing zone effectiveness.

$$\epsilon_{c\_X} = 1 - \exp[-(\mathrm{NTU})_{c\_X}]$$

Step 21: Calculate the feedwater temperature leaving the condensing zone.

$$T_{FWco\_X} = \epsilon_{c\_X}(T_{c\_X} - T_{FWdco\_X}) + T_{FWdco\_X}$$

Step 22: If not provided by the manufacturer, calculate the steam temperature leaving the desuperheating zone.

$$T_{dso\_G} = T_{si\_G} - \left(\frac{Q_{ds\_G}}{W_{si\_G} \times c_{pds\_G}}\right)$$

Step 23: Calculate the desuperheating zone steam (shell-side) hourly heat capacity flow rate.

$$C_{ds\_X} = \frac{W_{si\_X} \times Q_{ds\_G}}{W_{si\_G} \times (T_{si\_G} - T_{dso\_G})}$$

where
T_{si_G} = extraction steam inlet temperature

Step 24: Calculate the desuperheating zone feedwater hourly heat capacity flow rate.

$$C_{FWds\_X} = \frac{W_{FW} \times Q_{ds\_G}}{W_{FW\_G}\ (T_{FWdso\_G} - T_{FWdsi\_G})}$$

where
$T_{FWdsi\_G} = T_{FWco\_G}$
$T_{FWdso\_G} = T_{FWo\_G}$

Step 25: Calculate the desuperheating zone heat capacity ratio.

$$R_{ds\_X} = \frac{C_{FWds\_X}}{C_{ds\_X}}$$

Step 26: Calculate the desuperheating zone number of transfer units.

$$(\mathrm{NTU})_{ds\_X} = \frac{U_{ds\_X} \times A_{ds\_G}}{C_{FWds\_X}}$$

Step 27: Calculate the desuperheating zone effectiveness.

$$\epsilon_{ds\_X} = \frac{1 - \exp[(\mathrm{NTU})_{ds\_X}(R_{ds\_X} - 1)]}{1 - R_{ds\_X} \exp[(\mathrm{NTU})_{ds\_X}(R_{ds\_X} - 1)]}$$

Step 28: Calculate the final feedwater temperature leaving the desuperheating zone.

$$T_{FWdso\_X} = \epsilon_{ds\_X}\,(T_{si} - T_{FWco\_X}) + T_{FWco\_X}$$

where
$T_{FWdso\_X} = T_{FWo\_X}$
$T_{FWco\_X} = T_{FWdsi\_X}$

Step 29: Check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$|\,T_{FWo\_X} = T_{FWo\_a}\,| > 0.1$$

Step 30: Calculate the drain outlet temperature.

$$T_{so\_X} = T_{c\_X} - (R_{dc\_X} \times \epsilon_{dc\_X})(T_{c\_X} - T_{FWi})$$

where
$T_{FWdci} = \mathrm{T}_{FWi}$
$T_{dco\_X} = T_{so\_X}$

Step 31: Calculate the predicted terminal temperature difference (TTD$_{_X}$).

$$\mathrm{TTD}_{\_X} = T_{sat} - T_{FWo\_X}$$

Step 32: Calculate the predicted drain cooler approach (DCA$_{_X}$).

$$\mathrm{DCA}_{\_X} = T_{so\_X} - T_{FWi}$$

Step 33: Calculate the terminal temperature difference at the test point.

$$\mathrm{TTD} = T_{sat} - T_{FWo}$$

Step 34: Calculate the drain cooler approach at the test point.

$$\mathrm{DCA} = T_{so} - T_{FWi}$$

where
$T_{so} = T_{dco}$

Step 35: If directly measured differential pressure is not available, calculate the drain cooling and desuperheating zone pressure loss at the test point.

$$\Delta P_{dc} = P_c - P_{dco}$$

$$\Delta P_{ds} = P_{si} - P_{dso}$$

where
$P_{dso} = P_c$

Step 36: If directly measured differential pressure is not available, calculate the feedwater pressure loss at the test point.

$$\Delta P_{FW} = P_{FWi} - P_{FWo}$$

Step 37: Compare TTD$_{_X}$, DCA$_{_X}$, ΔP_{dc_X}, ΔP_{ds_X}, ΔP_{FW_X} with the measured values TTD, DCA, ΔP_{dc}, ΔP_{ds}, ΔP_{FW}.

5-2.2 Two-Zone Heater (Desuperheating and Condensing Heater)

In this heater, the feedwater enters the heater in the condensing zone and exits through the desuperheating zone. The steam enters the heater in the desuperheating zone and passes through the condensing zone where it condenses and exits as saturated condensate. There is no drain cooling zone, and therefore, no drain cooler approach is calculated. Refer to Figs. 3-8-3 and 3-8-4.

Step 1: Calculate the assumed feedwater outlet temperature based on the given terminal temperature difference, TTD$_{_G}$, and T_{sat} corresponding to the cooling zone measured shell-side inlet steam pressure (P_{si}).

$$T_{FWo\_a} = T_{sat} - \mathrm{TTD}_{\_G}$$

This temperature serves as a starting point for the calculations. During the reiteration process, use the following convergence criteria.

If $|T_{FWo\_a} - T_{FWo\_X}| > 0.1$, then let $T_{FWo\_a} = T_{FWo\_X}$ using T_{FWo_X} as calculated in Step 20.

Step 2: Calculate the total heat transferred, $Q_{\_X}$, based on the measured feedwater flow, W_{FW}, the feedwater outlet enthalpy, h_{FWo_X}, determined using T_{FWo_a} in Step 1 and the measured feedwater pressure, P_{FWo}, and the feedwater inlet enthalpy, h_{FWi}, determined using the measured feedwater inlet temperature, T_{FWi}, and pressure, P_{FWi}.

$$Q_{\_X} = W_{FW}\,(h_{FWo\_X} - h_{FWi})$$

Step 3: Calculate the drain inlet energy, Q_{di}, as follows:

(a) Obtain the sum of the drain inlet flows, W_{di}, if necessary. See Nonmandatory Appendix A.

(b) Obtain the drain inlet enthalpy, h_{di}, based on P_{di} and T_{di} for a single-drain stream or by the flow weighted average of enthalpies for multiple drain streams. Note that the pressure(s) and temperature(s) are measured upstream of the drain control valve(s).

(c) Obtain the condensing zone shell-side outlet enthalpy, h_{so}, based on the measured shell-side outlet temperature, T_{so}, and measured pressure, P_{so}. In the event the condensate outlet is determined to be saturated, h_{so} may be calculated based on the measured pressure, P_{so}. The total energy from the inlet drains is then calculated as follows:

$$Q_{di} = W_{di}\,(h_{di} - h_{so})$$

Step 4: Calculate the steam flow to the heater by the energy balance (see Nonmandatory Appendix A). The shell-side steam inlet enthalpy, h_{si}, is based on the measured temperature, T_{si}, and pressure, P_{si}.

$$W_{si\_X} = \frac{(Q_{\_X} - Q_{di})}{(h_{si} - h_{so})}$$

Step 5: Calculate the total shell-side outlet flow.

$$W_{so\_X} = W_{si\_X} + W_{di}$$

Step 6: Calculate the desuperheating zone and feedwater pressure losses based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{ds\_X} = \Delta P_{ds\_G}\left[\frac{W_{si\_X}}{W_{si\_G}}\right]^{1.8}$$

$$\Delta P_{FW\_X} = \Delta P_{FW\_G}\left[\frac{W_{FW}}{W_{FW\_G}}\right]^{1.8}$$

Step 7: Calculate the shell-side pressure, P_{c_X}, inside the condensing zone, and determine the saturation temperature, T_{c_X}, corresponding to this pressure.

$$P_{c\_X} = P_{si} - \Delta P_{ds\_X}$$

Step 8: If not available from the heat exchanger manufacturer, calculate the desuperheating zone resistance. This will be needed for the overall heat transfer coefficient calculation in Step 9. See Nonmandatory Appendix A for more information.

(a) If the tube-side fouling and shell-side fouling resistances are not available from the manufacturer, HEI recommends utilizing the following:

$$r_{fsds\_G} = \left[0.0003\left(\frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}\right)\right]$$

$$r_{fsc\_G} = 0$$

$$r_{ftds\_G} = r_{ftc\_G} = \left[0.0002\left(\frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}\right)\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)$$

(b) If the metal and tube-side film resistances are not available from the manufacturer, calculate each as per the formulas in Nonmandatory Appendix A.

$$r_{tds\_G} = 0.0378\left[\frac{\mu_{ds}^{\,0.4}}{k_{FWds}^{\,0.6} \times \rho_{FWds}^{\,0.8} \times c_{pFWds}^{\,0.4}}\right]\left[\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{\,0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

For condensing zone:

$$r_{tc\_G} = 0.0378\left[\frac{\mu_{c}^{\,0.4}}{k_{FWc}^{\,0.6} \times \rho_{FWc}^{\,0.8} \times c_{pFWc}^{\,0.4}}\right]\left[\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{\,0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

(c) Metal resistance is calculated at average temperature and the same values are used for the entire heater.

$$r_{mds\_G} = r_{mc\_G} = \frac{\text{OD}_{\_G}}{24\,k_m}\left[\ln\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\right]$$

(d) Calculate the shell-side film resistance as the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as follows:

$$r_{sds\_G} = \left(\frac{1}{U_{ds\_G}}\right) - (r_{fsds\_G} + r_{mds\_G} + r_{ftds\_G} + r_{tds\_G})$$

$$r_{sc\_G} = \left(\frac{1}{U_{c\_G}}\right) - (r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G})$$

Step 9: Calculate the desuperheating and condensing zone overall heat transfer coefficients based on the inverse of the sum of the individual resistances. All resistances are calculated as shown in Nonmandatory Appendix A. Note that the shell-side and tube-side film resistances are adjusted based on flow proportionalities. The fouling resistances utilized are not adjusted and remain as reported by the manufacturer or assumed. The tube-side metal resistance is referenced to the outer tube diameter.

$$U_{ds\_X} = \frac{1}{\left[r_{sds\_G}\left(\frac{W_{si\_G}}{W_{si\_X}}\right)^{0.6} + r_{fsds\_G} + r_{rmds\_G} + r_{ftds\_G} + r_{tds\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

$$U_{c\_X} = \frac{1}{\left[r_{sc\_G} + r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

where the shell-side heat transfer coefficient is not adjusted for steam flow in the condensing zone. The tube-side film resistances are adjusted based on flow proportionalities as shown in Nonmandatory Appendix A.

Step 10: Using T_{FWi_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWc}, and calculate the temperature of the feedwater leaving the condensing zone as shown in Nonmandatory Appendix A. The heat transferred in the condensing zone, Q_{c_G}, is either supplied by the manufacturer or calculated using the formulations in Nonmandatory Appendix A.

$$T_{FWco\_G} = T_{FWi\_G} + \frac{Q_{c\_G}}{W_{FW\_G} \times c_{pFWc}}$$

Step 11: Calculate the condensing zone feedwater hourly heat capacity flow rate.

$$C_{FWc\_X} = \frac{W_{FW} \times Q_{c\_G}}{W_{FW\_G}\,(T_{FWco\_G} - T_{FWi\_G})}$$

where

$T_{FWci\_G} = T_{FWi\_G}$

Step 12: Considering that the heat capacity ratio in the condensing zone is zero (see Nonmandatory Appendix A), calculate the number of transfer units in the condensing zone $(\mathrm{NTU})_{c\_X}$.

$$(\mathrm{NTU})_{c\_X} = \frac{U_{c\_X} \times A_{c\_G}}{C_{FWc\_X}}$$

Step 13: Calculate the condensing zone effectiveness.

$$\epsilon_{c\_X} = 1 - \exp[-(\mathrm{NTU})_{c\_X}]$$

Step 14: Calculate the feedwater temperature leaving the condensing zone.

$$T_{FWco\_X} = \epsilon_{c\_X}(T_{c\_X} - T_{FWci\_X}) + T_{FWci\_X}$$

Step 15: Calculate the desuperheating zone steam (shell-side) hourly heat capacity flow rate.

$$C_{ds\_X} = \frac{W_{si\_X} \times Q_{ds\_G}}{W_{si\_G}\,(T_{si\_G} - T_{dso\_G})}$$

where

T_{si_G} = extraction steam inlet temperature

Step 16: Calculate the desuperheating zone feedwater hourly heat capacity flow rate.

$$C_{FWds\_X} = \frac{W_{FW} \times Q_{ds\_G}}{W_{FW\_G}\,(T_{FWdso\_G} - T_{FWdsi\_G})}$$

where

$T_{FWdsi\_G} = T_{FWco\_G}$

$T_{FWdso\_G} = T_{FWo\_G}$

Step 17: Calculate the desuperheating zone heat capacity ratio, which is the ratio of the feedwater side to shell-side hourly heat capacity flow rates.

$$R_{ds\_X} = \frac{C_{FWds\_X}}{C_{ds\_X}}$$

Step 18: Calculate the desuperheating zone number of transfer units.

$$(\mathrm{NTU})_{ds\_X} = \frac{U_{ds\_X} \times A_{ds\_G}}{C_{FWds\_X}}$$

Step 19: Calculate the desuperheating zone effectiveness.

$$\epsilon_{ds\_X} = \frac{1 - \exp[(\mathrm{NTU})_{ds\_X}\,(R_{ds\_X} - 1]}{1 - R_{ds\_X}\exp[(\mathrm{NTU})_{ds\_X}\,(R_{ds\_X} - 1)]}$$

Step 20: Calculate the final feedwater temperature leaving the desuperheating zone and check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$T_{FWdso\_X} = \epsilon_{ds\_X}(T_{si} - T_{FWco\_X}) + T_{FWco\_X}$$

where

$T_{FWdso\_X} = T_{FWo\_X}$

$T_{FWco\_X} = T_{FWdsi\_X}$

Step 21: Check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$|T_{FWo\_X} - T_{FWo\_a}| > 0.1$$

Step 22: Calculate the predicted terminal temperature difference ($\text{TTD}_{\_X}$).

$$\text{TTD}_{\_X} = T_{sat} - T_{FWo\_X}$$

Step 23: Calculate the terminal temperature difference at the test point.

$$\text{TTD} = T_{sat} - T_{FWo}$$

Step 24: If the desuperheating zone differential pressure is not directly measured, calculate the pressure loss at the test point.

$$\Delta P_{ds} = P_{si} - P_{dso}$$

where
$P_{dso} = P_c$

Step 25: If the feedwater differential pressure is not directly measured, calculate the pressure loss at the test point.

$$\Delta P_{FW} = P_{FWi} - P_{FWo}$$

Step 26: Compare $\text{TTD}_{\_X}$, ΔP_{ds_X}, ΔP_{FW_X} with the measured values TTD, ΔP_{ds}, ΔP_{FW}.

5-2.3 Two-Zone Heater (Condensing and Drain Cooling)

In this heater, the feedwater enters the heater in the drain cooling zone and exits through the condensing zone. The steam enters the heater in the condensing zone where it condenses, and then flows through the drain cooling zone and exits as subcooled condensate. Refer to Figs. 3-8-5 and 3-8-6.

Step 1: Calculate the assumed feedwater outlet temperature based on the given terminal temperature difference, $\text{TTD}_{\_G}$, and saturation temperature, T_{sat}, corresponding to measured shell-side inlet steam pressure, P_{si}.

$$T_{FWo\_a} = T_{sat} - \text{TTD}_{\_G}$$

Calculate the assumed drain cooling zone outlet temperature based on the given drain cooler approach, $\text{DCA}_{\_G}$, and the measured feedwater inlet temperature, T_{FWi}.

$$T_{so\_a} = T_{FWi} + \text{DCA}_{\_G}$$

These temperatures serve as a starting point for the calculations. During the reiteration process, use the following convergence criteria:

If $|T_{FWo\_a} - T_{FWo\_X}| > 0.1$, = then let $T_{FWo\_a} = T_{FWo\_X}$ using T_{FWo_X} as calculated in Step 21.

Step 2: Calculate the total heat transferred, $Q_{\_X}$, based on the measured feedwater flow, W_{FW}, the feedwater outlet enthalpy, h_{FWo_X}, determined using T_{FWo_a} in Step 1 and the measured feedwater pressure, P_{FWo}, and the feedwater inlet enthalpy, h_{FWi} determined using the measured feedwater inlet temperature T_{FWi} and pressure P_{FWi}.

$$Q_{\_X} = W_{FW}\,(h_{FWo\_X} - h_{FWi})$$

Step 3: Calculate the drain inlet energy, Q_{di_X}, as follows:

(a) Obtain the sum of the drain inlet flows, W_{di}, if necessary. See Nonmandatory Appendix A.

(b) Obtain the drain inlet enthalpy, h_{di}, based on P_{di} and T_{di} for a single-drain stream or by the flow weighted average of enthalpies for multiple drain streams. Note that the pressure(s) and temperature(s) are measured upstream of the drain control valve(s).

(c) Obtain the drain cooling zone shell-side outlet enthalpy, h_{so_X}, based on the assumed shell-side outlet temperature, T_{so_a}, and measured pressure, P_{so}, and calculate the total energy from the inlet drains.

$$Q_{di\_X} = W_{di}\,(h_{di} - h_{so\_X})$$

Step 4: Calculate the steam flow to the heater by energy balance (see Nonmandatory Appendix A). The shell-side steam inlet enthalpy, h_{si} is based on the measured temperature, T_{si}, and pressure, P_{si}.

$$W_{si\_X} = \frac{(Q_{\_X} - Q_{di\_X})}{h_{si} - h_{so\_X}}$$

Step 5: Calculate the total shell-side outlet flow.

$$W_{so\_X} = W_{si\_X} + W_{di}$$

Step 6: Calculate the drain cooling zone and feedwater pressure losses based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{dc\_X} = \Delta P_{dc\_G}\left(\frac{W_{so\_X}}{W_{so\_G}}\right)^{1.8}$$

$$\Delta P_{FW\_X} = \Delta P_{FW\_G}\left(\frac{W_{FW}}{W_{FW\_G}}\right)^{1.8}$$

Step 7: Determine the saturation temperature, T_{sat}, corresponding to shell-side pressure, P_c, inside the condensing zone, where $P_c = P_{si}$.

Step 8: If not available from the heat exchanger manufacturer, calculate the drain cooling zone resistance. This will be needed for the overall heat transfer coefficient calculation in Step 9. See Nonmandatory Appendix A for more information.

(a) If the tube-side fouling and shell-side fouling resistances are not available from the manufacturer, HEI recommends utilizing the following:

(1) shell-side resistance for condensing zone:

$$r_{fsc\_G} = 0$$

(2) shell-side resistance for drain cooling zone

$$r_{fsdc\_G} = 0.0003 \left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right)$$

$$r_{ftc\_G} = r_{ftdc\_G} = \left[0.0002 \left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right)\right]$$

(b) If the metal and tube-side film resistances are not available from the manufacturer, calculate each as per the formulas in Nonmandatory Appendix A.

$$r_{tc\_G} = 0.0378 \left[\frac{{\mu_c}^{0.4}}{{k_{FWc}}^{0.6} \times {\rho_{FWc}}^{0.8} \times {c_{pFWc}}^{0.4}}\right]\left[\frac{\text{OD}_{\_G}}{{\text{ID}_{\_G}}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

$$r_{tdc\_G} = 0.0378 \left[\frac{{\mu_{dc}}^{0.4}}{{k_{FWdc}}^{0.6} \times {\rho_{FWdc}}^{0.8} \times {c_{pFWdc}}^{0.4}}\right]\left[\frac{\text{OD}_{\_G}}{{\text{ID}_{\_G}}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

(c) Metal resistance is calculated at average temperature and the same values are used for the entire heater.

$$r_{mc\_G} = r_{mdc\_G} = \left[\frac{\text{OD}_{\_G}}{24k_m}\right]\left[\ln\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\right]$$

(d) Calculate the shell-side film resistance as the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as follows:

$$r_{sc\_G} = \left(\frac{1}{U_{c\_G}}\right) - (r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G})$$

$$r_{sdc\_G} = \left(\frac{1}{U_{dc\_G}}\right) - (r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G})$$

Step 9: Calculate the overall heat transfer coefficients in the drain cooling and condensing zones based on the inverse of the sum of the individual resistances. All resistances are calculated as shown in Nonmandatory Appendix A. Note that the shell-side and tube-side film resistances are adjusted based on flow proportionalities in the drain cooling zone. The shell-side heat transfer coefficient is not adjusted for steam flow in the condensing zone. The fouling resistances utilized are not adjusted and remain as reported by the manufacturer or assumed. The tube-side metal resistance is referenced to the outer tube diameter.

$$U_{c\_X} = \frac{1}{\left[r_{sc\_G} + r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

$$U_{dc\_X} = \frac{1}{\left[r_{sdc\_G}\left(\frac{W_{so\_G}}{W_{so\_X}}\right)^{0.6} + r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

Step 10: Using T_{FWi_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWdc} and the feedwater temperature leaving the drain cooling zone as shown in Appendix A under effectiveness/NTU method.

$$T_{FWdco\_G} = T_{FWi\_G} + \frac{Q_{dc\_G}}{W_{FW\_G} \times c_{pFWdc}}$$

Step 11: Calculate the drain cooling zone condensate (shell-side) hourly heat-capacity flow rate.

$$C_{dc\_X} = \frac{W_{so\_X} \times Q_{dc\_G}}{W_{so\_G}\,(T_{c\_G} - T_{so\_G})}$$

where

T_{c_G} = saturation temperature at P_{c_G}
P_{c_G} = P_{si_G}

Step 12: Calculate the drain cooling zone feed water (tube-side) hourly heat capacity flow rate.

$$C_{FWdc\_X} = \frac{W_{FW} \times Q_{dc\_G}}{W_{FW\_G}\,(T_{FWdco\_G} - T_{FWi\_G})}$$

Step 13: Calculate the drain cooling zone heat capacity ratio.

$$R_{dc\_X} = \frac{C_{FWdc\_X}}{C_{dc\_X}}$$

Step 14: Calculate the drain cooling zone number of transfer units.

$$(\text{NTU})_{dc\_X} = \frac{U_{dc} \times A_{dc\_G}}{C_{FWdc\_X}}$$

Step 15: Calculate the drain cooling zone effectiveness.

$$\epsilon_{dc\_X} = \frac{1 - \exp\,[(\text{NTU})_{dc\_X}\,(R_{dc\_X} - 1)]}{1 - R_{dc\_X}\exp[(\text{NTU})_{dc\_X}\,(R_{dc\_X} - 1)]}$$

Step 16: Calculate the feedwater temperature leaving the drain cooling zone.

$$T_{FWdco\_X} = \epsilon_{dc\_X}(T_{c\_X} - T_{FWi}) + T_{FWi}$$

Step 17: Using T_{FWdco_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWc}, and the feedwater temperature leaving the condensing zone as shown in Nonmandatory Appendix A under effectiveness/NTU method.

$$T_{FWco\_G} = T_{FWdco\_G} + \frac{Q_{c\_G}}{W_{FW\_G} \times c_{pFWc}}$$

Step 18: Considering that the shell-side heat capacity flow rate in the condensing zone is zero (see Nonmandatory Appendix A), calculate the feedwater hourly heat capacity flow rate in the condensing zone.

$$C_{FWc\_X} = \frac{W_F \times Q_{c\_G}}{[W_{FW\_G}(T_{FWco\_G} - T_{FWci\_G})]}$$

Step 19: Considering that the heat capacity ratio in the condensing zone is zero (see Nonmandatory Appendix A), calculate the number of transfer units in the condensing zone $(\mathrm{NTU})_{c\_X}$.

$$(\mathrm{NTU})_{c\_X} = \frac{U_{c\_X} \times A_{c\_G}}{C_{FWc\_X}}$$

where

$T_{FWci\_G} = T_{FWdco\_G}$

Step 20: Calculate the condensing zone effectiveness.

$$\epsilon_{c\_X} = 1 - \exp[-(\mathrm{NTU})_{c\_X}]$$

Step 21: Calculate the final feedwater temperature leaving the condensing zone and check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$T_{FWco\_X} = \epsilon_{c\_X}(T_{c\_X} - T_{FWdco\_X}) + T_{FWdco\_X}$$

where

$T_{FWco\_X} = T_{FWo\_X}$

Step 22: Check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$|T_{FWo\_X} - T_{FWo\_a}| > 0.1$$

Step 23: Calculate the drain outlet temperature.

$$T_{so\_X} = T_{c\_X} - (R_{dc\_X})(\epsilon_{dc\_X})(T_{c\_X} - T_{FWi})$$

where

$T_{FWdci} = T_{FWi}$

$T_{dco\_X} = T_{so\_X}$

Step 24: Calculate the predicted terminal temperature difference ($\mathrm{TTD}_{\_X}$).

$$\mathrm{TTD}_{\_X} = T_{sat} - T_{FWo\_X}$$

Step 25: Calculate the predicted drain cooler approach ($\mathrm{DCA}_{\_X}$).

$$\mathrm{DCA}_{\_X} = T_{so\_X} - T_{FWi}$$

Step 26: Calculate the terminal temperature difference at the test point.

$$\mathrm{TTD} = T_{sat} - T_{FWo}$$

Step 27: Calculate the drain cooler approach at the test point.

$$\mathrm{DCA} = T_{so} - T_{FWi}$$

where

$T_{so} = T_{dco}$

Step 28: If directly measured differential pressure is not available, calculate the drain cooling zone pressure loss at the test point.

$$\Delta P_{dc} = P_c - P_{dco}$$

Step 29: If directly measured differential pressure is not available, calculate the feedwater pressure loss at the test point.

$$\Delta P_{FW} = P_{FWi} - P_{FWo}$$

Step 30: Compare $\mathrm{TTD}_{\_X}$, $\mathrm{DCA}_{\_X}$, ΔP_{dc_X}, ΔP_{FW_X} with the measured values TTD, DCA, ΔP_{dc}, and ΔP_{FW}.

5-2.4 One-Zone Heater (Condensing Only)

This is a one-zone heater with condensing only. In this heater, the feedwater and steam enters and exits the heater in the condensing zone. There is no drain cooling zone and therefore, no drain cooler approach is calculated. Refer to Figs. 3-8-7 and 3-8-8.

Step 1: Calculate the total heat transferred, Q, based on the measured feedwater flow, W_{FW}, the feedwater outlet enthalpy, h_{FWo}, determined using T_{FWo} and the measured feedwater pressure, P_{FWo}, and the feedwater inlet enthalpy, h_{FWi}, determined using the measured feedwater inlet temperature, T_{FWi} and pressure, P_{FWi}.

$$Q = W_{FW}(h_{FWo} - h_{FWi})$$

Step 2: Calculate the drain inlet energy, Q_{di}, as follows:

(a) Obtain the sum of the drain inlet flows, W_{di}, if necessary. See Nonmandatory Appendix A.

(b) Obtain the drain inlet enthalpy, h_{di}, based on P_{di} and T_{di} for a single-drain stream or by the flow weighted average of enthalpies for multiple drain streams. Note that the pressure(s) and temperature(s) are measured upstream of the drain control valve(s).

(c) Obtain the condensing zone shell-side outlet enthalpy, h_{so}, based on the measured shell-side outlet temperature, T_{so}, and pressure, P_{so}. In the event the condensate outlet is determined to be saturated, then h_{so} may be calculated based on the measured pressure, P_{so}. The total energy from the inlet drains is then calculated as follows:

$$Q_{di} = W_{di}\left(h_{di} - h_{so}\right)$$

Step 3: Calculate the steam flow to the heater by energy balance (see Nonmandatory Appendix A). The shell-side steam inlet enthalpy, h_{si}, is based on the measured temperature, T_{si}, and pressure, P_{si}.

$$W_{si} = \frac{(Q - Q_{di})}{h_{si} - h_{so}}$$

Step 4: Calculate the total shell-side outlet flow.

$$W_{so} = W_{si} + W_{di}$$

Step 5: Calculate the feedwater pressure loss based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{FW\_X} = \Delta P_{FW\_G}\left(\frac{W_{FW}}{W_{FW\_G}}\right)^{1.8}$$

NOTE: Steps 1 through 4 are not necessary for calculation of adjusted guaranteed parameters but are included for completeness.

Step 6: Determine the saturation temperature, T_{sat}, corresponding to shell-side pressure, P_c, where $P_c = P_{si}$.

Step 7: If the tube-side fouling resistance is not available from the manufacturer, the following is recommended:

$$r_{fsc\_G} = 0$$

$$r_{ftc\_G} = \left[0.0002\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right)\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)$$

If the tube-side film resistance is not available from the manufacturer, calculate per the formulas in Nonmandatory Appendix A.

$$r_{tc\_G} = 0.0378\left[\frac{\mu_c^{0.4}}{k_{FWc}^{0.6} \times \rho_{FWc}^{0.8} \times c_{pFWc}^{0.4}}\right]\left[\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

If the metal resistance is not available from the manufacturer, calculate it per the formula in Nonmandatory Appendix A.

$$r_{mc\_G} = \frac{\text{OD}}{24k_m}\left[\ln\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)\right]$$

Calculate the shell-side film resistance as the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as shown below.

$$r_{sc\_G} = \left(\frac{1}{U_{c\_G}}\right) - (r_{fs\_G} + r_{mc\_G} + r_{ft\_G} + r_{tc\_G})$$

Step 8: Calculate the condensing zone overall heat transfer coefficients based on the inverse of the sum of the individual resistances. The tube-side metal resistance, r_{mc_G}, is referenced to the outer tube diameter. The tube-side film resistances are adjusted based on flow proportionalities as shown in Nonmandatory Appendix A.

$$U_{c\_X} = \frac{1}{\left[r_{sc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

Step 9: Using T_{FWi_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWc_G}, and the feedwater temperature leaving the condensing zone as shown in Nonmandatory Appendix A under effectiveness/NTU method.

$$T_{FWco\_G} = T_{FWi\_G} + \frac{Q_{c\_G}}{W_{FW\_G} \times c_{pFWc\_G}}$$

Step 10: Calculate the condensing zone feedwater hourly heat capacity flow rate.

$$C_{FWc\_X} = \frac{W_{FW} \times Q_{c\_G}}{W_{FW\_G}\,(T_{FWco\_G} - T_{FWci\_G})}$$

where

$T_{FWci\_G} = \text{T}_{FWi\_G}$

$T_{FWco\_G} = \text{T}_{FWo\_G}$

Step 11: Considering that the heat capacity ratio in the condensing zone is zero (see Nonmandatory Appendix A), calculate the number of transfer units in the condensing zone $(\text{NTU})_{c\_X}$.

$$(\text{NTU})_{c\_X} = \frac{U_{c\_X} \times A_{c\_G}}{C_{FWc\_X}}$$

Step 12: Calculate the condensing zone effectiveness.

$$\epsilon_{c\_X} = 1 - \exp[-(\mathrm{NTU})_{c\_X}]$$

Step 13: Calculate the final feedwater temperature leaving the condensing zone.

$$T_{FWco\_X} = \epsilon_{c\_X}\left(T_{sat} - T_{FWi}\right) + T_{FWi}$$

where

$$T_{FWco\_X} = T_{FWo\_X}$$

Step 14: The drain outlet temperature is the temperature exiting the condensing zone.

$$T_{so} = T_{co} = T_{sat}$$

Step 15: Calculate the predicted terminal temperature difference ($\mathrm{TTD}_{\_X}$).

$$\mathrm{TTD}_{\_X} = T_{so} - T_{FWo\_X}$$

Step 16: Calculate the terminal temperature difference at the test point.

$$\mathrm{TTD} = T_{sat} - T_{FWo}$$

Step 17: If directly measured differential pressure is not available, calculate the feedwater pressure loss at the test point.

$$\Delta P_{FW} = P_{FWi} - P_{FWo}$$

Step 18: Compare $\mathrm{TTD}_{\_X}$, ΔP_{FW_X} with the measured values TTD and ΔP_{FW}.

5-2.5 Drain Cooler Only

In this heater, the feedwater enters the heater in one end and exits at either the same end or the other end. The drains enter the shell-side in one end and exit at the other end. There are no zones inside the shell and the shell is totally filled with condensate. Terminal temperature difference (TTD) is not calculated. Refer to Figs. 3-8-9 and 3-8-10.

Step 1: Calculate the shell-side pressure loss based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{dc\_X} = \Delta P_{dc\_G}\left(\frac{W_{so}}{W_{so\_G}}\right)^{1.8}$$

where

$$W_{so} = W_{si}$$
$$W_{so\_G} = W_{si\_G}$$

Step 2: Calculate the feedwater side pressure loss based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\Delta P_{FW\_X} = \Delta P_{FW\_G}\left(\frac{W_{FW}}{W_{FW\_G}}\right)^{1.8}$$

Step 3: Calculate the overall heat transfer coefficient. If the tube-side fouling and shell-side fouling resistances are not available from the manufacturer, the following values are recommended:

$$r_{fsdc\_G} = \left[0.0003\,\frac{(\text{hr-ft}^2\text{-}^\circ\text{F})}{\text{Btu}}\right]$$

$$r_{ftdc\_G} = \left[0.0002\,\frac{(\text{hr-ft}^2\text{-}^\circ\text{F})}{\text{Btu}}\right]\left[\left(\frac{\mathrm{OD}_{\_G}}{\mathrm{ID}_{\_G}}\right)\right]$$

If the metal and tube-side film resistances are not available from the manufacturer, calculate each as per the formulas in Nonmandatory Appendix A.

$$r_{mdc\_G} = \frac{\mathrm{OD}_{\_G}}{24\,k_m}\left[\ln\left(\frac{\mathrm{OD}_{\_G}}{\mathrm{ID}_{\_G}}\right)\right]$$

$$r_{tdc\_G} = 0.0378\left[\frac{\mu_{dc}{}^{0.4}}{k_{FWdc}{}^{0.6} \times \rho_{FWdc}{}^{0.8} \times c_{pFWdc}{}^{0.4}}\right]\left[\frac{\mathrm{OD}_{\_G}}{\mathrm{ID}_{\_G}{}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$

Calculate the drain cooler resistances if they are not available from the manufacturer. These will be needed for the overall heat transfer coefficient calculation below. Calculate the shell-side film resistance by difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as follows:

$$r_{sdc\_G} = \left(\frac{1}{U_{dc\_G}}\right) - \left(r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G}\right)$$

where r_{tdc_G} will be calculated per the formulas in Nonmandatory Appendix A.

Step 4: Calculate overall heat transfter coefficient in drain cooler.

$$U_{dc\_X} = \frac{1}{\left[r_{sdc\_G}\left(\frac{W_{so\_G}}{W_{so}}\right)^{0.6} + r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}\right]}$$

Step 5: Calculate the (shell-side) of the drain cooling zone condensate hourly heat capacity flow rate.

$$C_{dc\_X} = \frac{W_{so} \times Q_{dc\_G}}{W_{so\_G}\left(T_{si\_G} - T_{so\_G}\right)}$$

Step 6: Calculate the hourly heat capacity flow rate of the drain cooling zone feedwater.

$$C_{FWdc\_X} = \frac{W_{FW} \times Q_{dc\_G}}{W_{FW\_G}(T_{FWo\_G} - T_{FWi\_G})}$$

Step 7: Calculate the drain cooling zone heat capacity ratio.

$$R_{dc\_X} = \frac{C_{FWdc\_X}}{C_{dc\_X}}$$

Step 8: Calculate the number of transfer units.

$$(\mathrm{NTU})_{dc\_X} = \frac{U_{dc\_X} \times A_{dc\_G}}{C_{FWdc}}$$

Step 9: Calculate the effectiveness.

$$\epsilon_{dc\_X} = \frac{1 - \exp\left[(\mathrm{NTU})_{dc\_X}\,(R_{dc\_X} - 1)\right]}{1 - R_{dc\_X}\exp[(\mathrm{NTU})_{dc\_X}\,(R_{dc\_X} - 1)]}$$

Step 10: Calculate the drain outlet temperature.

$$T_{so\_X} = T_{si} - \left[(R_{dc\_X}\epsilon_{dc\_X})(T_{si} - T_{FWi})\right]$$

Step 11: Calculate the predicted drain cooler approach ($\mathrm{DCA}_{\_X}$).

$$\mathrm{DCA}_{\_X} = T_{so\_X} - T_{FWi}$$

Step 12: Calculate the drain cooler approach at the test point.

$$\mathrm{DCA} = T_{so} - T_{FWi}$$

Step 13: If directly measured differential pressure is not available, calculate the drain cooling zone pressure loss at the test point.

$$\Delta P_{dc} = P_c - P_{dco}$$

Step 14: If directly measured differential pressure is not available, calculate the feedwater pressure loss at the test point.

$$\Delta P_{FW} = P_{FWi} - P_{FWo}$$

Step 15: Compare $\mathrm{DCA}_{\_X}$, ΔP_{dc_X}, ΔP_{FW_X} with the measured values DCA, ΔP_{dc}, ΔP_{FW}.

5-3 UNCERTAINTY CALCULATION PROCEDURES

This subsection discusses the procedures for calculating the effects of measurement uncertainties on the test results. A numerical example is provided in Nonmandatory Appendix C. Refer to ASME PTC 19.1 for a more complete description of the required calculations.

The effects of measurement uncertainty on the results may be analyzed using the following four steps.

Step 1: Calculate the sensitivity of the final results to uncertainties of the measured variables.

Step 2: Use the calculated sensitivities to determine the effects of random uncertainties of the measured variables on the results.

Step 3: Use the calculated sensitivities to determine the effects of systematic uncertainties of the measured variables on the results.

Step 4: Determine the combined effects of random and systematic uncertainties.

Measurement uncertainties include random uncertainties and systematic uncertainties as discussed in subsection 3-7.

5-3.1 Calculation of Sensitivity Factors

The sensitivity of a result from a measurement parameter i, θ_i is the ratio of the change in the result, ΔR, caused by a unit change in the value of the sample mean $\Delta\overline{X}_i$. In equation form:

$$\theta_i = \frac{\Delta R}{\Delta\overline{X}_i}$$

Calculation of the sensitivity factors uses the procedures described in subsection 5-2. For each measured variable the calculation procedure is repeated twice, once with the measured parameter i increased by a unit value and once with the measured value i decreased by a unit value. (For temperature measurements, the unit is typically 1.0°F. For flows, pressures, and pressure losses, the unit change is typically 1.0%.) More rigorous analytical methods may be used, if desired, to more accurately determine the sensitivity factors using smaller incremental increases/decreases for each measured parameter. The sensitivity factor is then calculated by taking the average of the change in the result (e.g., the difference between the calculated and measured TTD) resulting from the unit increase and the unit decrease in the measured value.

5-3.2 Calculation of the Random Standard Uncertainty of the Result

The first step is to calculate the random standard uncertainty of the sample mean, i.e., $s_{\bar{X}i}$, for each measurement parameter i, as follows:

$$s_{\overline{X}i} = \frac{s_{Xi}}{\sqrt{N}}$$

where

N = number of observations available for a single measurement parameter (i.e., sample size)

$s_{\bar{X}i}$ = the standard deviation of a data sample for measurement parameter i

$$s_{Xi} = \left[\frac{\sum_{k=1}^{N}(X_k - \overline{X}_i)^2}{N - 1}\right]^{1/2}$$

where

$N - 1$ = degrees of freedom

X_k = k^{th} value of the variable

X = an individual observation in a data sample

$\overline{X}_i$ = the sample mean; the average of a set of N individual observations as follows:

$$\overline{X}_i = \frac{1}{N} \sum_{k=1}^{N} X_k$$

The random standard uncertainty of the result, s_R, is then calculated by taking the square root of the sum of the squares of the products of the sensitivity factors (θ_i) and random standard uncertainties of the sample means ($s_{\bar{X}i}$) for all measurements that impact the result. In equation form:

$$s_R = \left[\sum_{i=1}^{I} \left(\theta_i s_{\overline{X}i} \right)^2 \right]^{1/2}$$

5-3.3 Calculation of the Systematic Standard Uncertainty of the Result

The first step is to determine the systematic standard uncertainty for each measurement, denoted by $b_{\overline{X}i}$. A measurement may contain several elemental systematic error sources k; the systematic standard uncertainty of the measurement is the square root of the sum of the squares of the elemental systematic standard uncertainties $b_{\bar{X}k}$ for all sources:

$$b_{\overline{X}i} = \left[\sum_{k=1}^{K} (b_{\overline{X}k})^2 \right]^{1/2}$$

Note that the elemental systematic standard uncertainty $b_{\bar{X}k}$ for error source k is equal to the following:

$$b_{\overline{X}k} = \frac{B_{\overline{X}k}}{2}$$

The variable $B_{\bar{X}k}$ in the equation represents the 95% confidence-level estimate of the symmetric limits of error associated with the k^{th} elemental error source.

The systematic standard uncertainty of the result, b_R, is then calculated by taking the square root of the sum of the squares of the products of the sensitivity factors, θ_i, and systematic standard uncertainties of the measurements, $b_{\overline{X}i}$, for all the measurements that impact the result. In equation form:

$$b_R = \left[\sum_{i=1}^{I} (\theta_i b_{\overline{X}i})^2 \right]^{1/2}$$

5-3.4 Calculation of the Combined Effect of Random and Systematic Standard Uncertainties

The combined standard uncertainty of the result, u_R, is determined as the square root of the sum of the squares of the random and systematic standard uncertainties, as follows:

$$u_R = [(b_R)^2 + (s_R)^2]^{1/2}$$

where

s_R = the random standard uncertainty as calculated in para. 5-3.2

b_R = the systematic standard uncertainty as calculated in para. 5-3.3

The expanded uncertainty in the result at approximately 95% confidence, i.e. $U_{R,\,95}$, is determined as follows:

$$U_{R,\,95} = t_{95}\, u_R$$

The term t_{95} is the Student t for the 95% confidence interval, which is equal to 2 if the value for the degrees of freedom ($N - 1$) is 30 or higher. ASME PTC 19.1 may be consulted for finding Student t values at other confidence intervals and smaller degrees of freedom. The calculated result of interest is determined to be within $\pm U_{R,\,95}$ of the true value, with 95% confidence.

Note that this methodology for determining the expanded uncertainty of the result may also be applied for each individual measurement, as follows:

$$u_{\overline{X}} = [(b_{\overline{X}})^2 + (s_{\overline{X}})^2]^{1/2}$$

$$U_{\overline{X},95} = t_{95} u_{\overline{X}}$$

The expanded uncertainty for each measurement, $U_{\bar{X},\,95}$, should not exceed the maximum uncertainty values prescribed in this Code (Table 4-7-1).

Section 6
Report of Results

The following outlines the report of test results. Only relevant items need to be reported in any particular case. The report should be complete in all respects and should be signed by the lead test engineer.

(a) Brief Summary of Test

(1) owner

(2) name and location of plant

(3) designation of unit and heater(s)

(4) feedwater heater manufacturer and heater identification number

(5) feedwater heater description

(6) brief history of the feedwater heater(s)

(7) object of test

(8) date and time of test

(9) key test personnel and relevant observers and their affiliations

(10) stipulated agreements

(11) executive summary of test results and conclusions (a tabular or graphical presentation may be used to show essential findings)

(b) Discussion of Test

(1) test procedure

(2) data acquisition and instrumentation summary, including method of measurement, calibration, and location of test points

(3) all other pertinent information

(c) Heater Data

(1) tabulation of operating conditions, feedwater heater design data, and test data (after application of all calibration corrections).

(2) the required data shall be entered on tables similar to Test Report Form 6-1 as applicable, for each run. Test Report Form 6-1 is provided in the case of manual data acquisition during FWH testing.

(3) the format for automated data acquisition of test parameters and reporting should be decided prior to starting the test.

(d) Feedwater Heater Performance Computations

(1) computed data format for each test run report shall be decided prior to starting the test.

(2) supporting calculations for reference.

(3) electronic data transfer (CD, DVD, memory stick, external hard drive, etc.) is also acceptable, and desired data transfer formats shall be determined prior to completion of the test report.

(e) Overall Uncertainty of Test Results

(1) specified instrument and measurement uncertainties, and relevant sensitivities

(2) calculation of overall uncertainty of final test results, similar to the example in Nonmandatory Appendix C

(f) Conclusion. Statement of the conclusions.

(g) Appendices and Illustrations. Any appendices and illustrations necessary to clarify description of the equipment or method and circumstances of the test.

Test Report Form 6-1 Performance Testing of Closed Feedwater Heaters

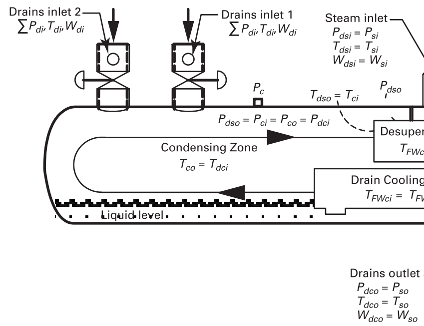
Heater Information

Name of plant and unit number __________
Unit guarantee point (MW) __________
Unit test point (MW) __________
Test Engineer __________
Date of test __________
Heater designation __________
Heater manufacturer __________
Heater orientation ☐ Horizontal ☐ Vertical (Check applicable orientation)
Heater zones ☐ Desuperheating ☐ Condensing ☐ Drain cooling (Check applicable orientation)

Channel up __________
Channel down __________

Tube Data

Tube material __________
Number of tubes __________
Wall thickness __________
Tube pitch __________



GENERAL NOTE: This sketch symbolically represents a horizontal three-way feedwater heater. Please refer to Figures 3-8-1, 3-8-3, 3-8-5, 3-8-7, and 3-8-9.

				Test Run Data							
				Reading Number							
				1	2	3	4	5	6	7	8
				Date/Time							
Data		**Units**	**Design Data**								
Plant MW output		MW									
Feedwater inlet	P_{FWi}	psig (kPa)									
	T_{FWi}	°F (°C)									
	W_{FW}	lbm/hr (kg/s)									
Feedwater outlet	P_{FWo}	psig (kPa)									
	T_{FWo}	°F (°C)									
	W_{FW}	lbm/hr (kg/s)									
Steam inlet	P_{si}	psig (kPa)									
	T_{si}	°F (°C)									
	W_{si}	lbm/hr (kg/s)									
Drains outlet	P_{dco}	psig (kPa)									
	T_{dco}	°F (°C)									
	W_{dco}	lbm/hr (kg/s)									
Drains inlet 1 (if applicable)	P_{di}	psig (kPa)									
	T_{di}	°F (°C)									
	W_{di}	lbm/hr (kg/s)									
Drains inlet 2 (if applicable)	P_{di}	psig (kPa)									
	T_{di}	°F (°C)									
	W_{di}	lbm/hr (kg/s)									
Shell	P_{SAT}	psig (kPa)									
	T_{SAT}	°F (°C)									
Liquid Level in FWH	L.L.	in. (mm)									
Atmospheric pressure	P_a	psi (kPa)									
Calculated	DCA	°F (°C)									
	TTD	°F (°C)									

Section 7
References

Clemmer, A. B., and S. Lemezis, "Selection and Design of Closed Feedwater Heaters," ASME Paper No. 65-WA/PTC-S.

Johnson, S. C., W. A. Thomas, Jr., and J. V. Hoobler, "Review of Closed Feedwater Heater Design," ASME Paper No. 88-JPGC/PWR-24.

Tsou, J., "Feedwater Heater Performance Prediction Calculation Procedure," ASME PWR-Vol. 6, 1989.

ASME MFC-3M–1989, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi

ASME PTC 19.1-2013, Test Uncertainty

ASME PTC 19.2-2010, Pressure Measurement

ASME PTC 19.3-1974, Temperature Measurement

ASME PTC 19.5-2004, Flow Measurement

ASME Steam Tables, 6th edition, 1993

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016 (www.asme.org)

Standards for Closed Feedwater Heaters, 8th edition (2009)

Publisher: Heat Exchange Institute (HEI), 1300 Sumner Avenue, Cleveland, OH 44115 (www.heatexchange.org)

Holman J. P., "Heat Transfer," McGraw-Hill Book Co., New York, NY, 1963.

Karac, S., A. E. Bergles, and F. Mayinger, "Heat Exchanger — Thermal-Hydraulic Fundamentals and Design," Hemisphere Publishing Corp., Washington, D.C., 1981.

Kays, W. M., and A. L. London, "Compact Heat Exchangers," second edition, McGraw-Hill Book Co., New York, NY, 1955.

Linley, F., "Feedwater Heater Operation," Annual Conference Engineering and Operation Division, New Orleans, LA; April 1983.

McAdams, W. H., "Heat Transmission," third edition, McGraw-Hill Book Co., New York, NY, 1954.

Thompson, N., "Heat Exchanger Testing Using Ultrasonic Flow Meters," Joint JSME-ASME International Conference on Power Engineering, 1993.

NONMANDATORY APPENDIX A
BASIC HEAT TRANSFER EQUATIONS

A-1 INTRODUCTION

This Appendix consists of basic heat transfer equations. Examples of how to use the performance calculation procedures are provided in Nonmandatory Appendix B.

The basic heat transfer equations include commonly used heat transfer equations and the effectiveness/NTU method. The subscript *z* stands for the respective zone, where *dc* represents the drain cooling zone, *c* the condensing zone, and *ds* the desuperheating zone. The subscript *FW* refers to the feedwater or tube side, and *s* refers to the steam/condensate or shell-side. The subscript *i* stands for inlet, *o* for outlet, and *d* for drain.

The nomenclature listed in Table A-1-1 is used in Nonmandatory Appendices A and B in addition to the nomenclature shown in subsection 2-1.

Table A-1-1 Nomenclature

Symbol	Term	Units U.S. Customary	Units SI
c_p	Specific heat	Btu/(lbm-°F)	J/(kg-K)
k	Thermal conductivity	Btu/(hr-ft-°F)	W/(m-K)
μ	Dynamic viscosity	lbm/(hr-ft)	Pa-s
ρ	Density	lbm/ft^3	kg/m^3
v	Velocity	ft/sec	m/s
OD	Tube outside diameter	in.	mm
ID	Tube inside diameter	in.	mm

A-2 BASIC THERMODYNAMIC HEAT BALANCE FOR THE ENTIRE HEATER

(a) The total heat transfer from the shell side, Q_s equals the total heat transfer to the feedwater side, Q_{FW}.

$$Q_{FW} = Q_s \tag{A-1}$$

$$Q_s = \Sigma Q_{sz} = Q_{sdc} + Q_{sc} + Q_{sds} \tag{A-2}$$

which is dependent on shell-side zones

$$Q_s = Q_{si} + Q_{di} \tag{A-3}$$

(b) Balance of Mass Flow Rates. Cascading drains from higher energy heater stages may be directed into the condensing zone, affecting steam demand for a given heater duty. Extraction steam from the turbine and incoming drains, if applicable, is the heating medium of the feedwater in the condensing zone and desuperheating zone. The heating sources in the drain cooling zone are the condensed steam and the incoming drains.

The total shell-side flow leaving the heater equals the sum of the steam inlet and drain inlet flows. Note that there could be multiple drain inlet flows.

$$W_{so} = W_{si} + W_{di} \tag{A-4}$$

(c) Weighted Enthalpy for Multiple Inlet Drain Flows

$$h_{di\_X} = \frac{\Sigma(W_{di\_X}\, h_{di\_X})}{\Sigma W_{di\_X}} \tag{A-5}$$

A-3 HEAT BALANCE FOR EACH ZONE

Heat balance for each zone is calculated as follows:

$$Q_{FWz} = Q_{sz} \tag{A-6}$$

(a) Governing Heat Transfer Equations

$$Q_{FWz} = W_{FW}\, c_{pFWz}\, (T_{FWzo} - T_{FWzi}) = W_{FW}\, (h_{FWzo} - h_{FWzi}) = U_z A_z\, (\text{LMTD})_z \tag{A-7}$$

$$Q_{sz} = W_s c_{psz}\, (T_{szi} - T_{szo}) = W_s\, (h_{szi} - h_{szo}) = U_z A_z\, (\text{LMTD})_z \tag{A-8}$$

Where the log mean temperature difference (LMTD) parameter represents a proportionality of the temperature differences in the counterflow streams on the shell-side and tube-side and serves as a natural log multiplier to the heat transfer coefficient and the area available for heat transfer per zone.

$$\text{LMTD}_z = \frac{(T_{szi} - T_{FWzo}) - (T_{szo} - T_{FWzi})}{\ln\left[\dfrac{(T_{szi} - T_{FWzo})}{(T_{szo} - T_{FWzi})}\right]} \tag{A-9}$$

(b) Overall Heat Transfer Coefficient per Zone:

$$U_z = \frac{1}{r_{sz} + r_{fsz} + r_{mz} + r_{fFWz} + r_{FWz}} \tag{A-10}$$

A-4 RESISTANCES

If not provided by the heat exchanger manufacturer, the desuperheating and drain-cooling zone resistances will need to be calculated. These are needed for the overall heat transfer coefficient calculation shown above.

Tube-side fouling and shell-side fouling resistances may not be available from the manufacturer. HEI recommends a tube-side fouling resistance (r_{ftds_G}, r_{ftc_G}, and r_{ftdc_G}) be applied to the tube surface and corrected from the inside surface to the outside surface for all zones. These values may be found in Nonmandatory Appendix B. Additionally, shell-side fouling resistance should be applied to surfaces in the desuperheating and drains subcooling zones (r_{fsds_G} and r_{fsdc_G}). The shell-side fouling resistance for the condensing section should be considered to have no resistance value (r_{fsc_G}). The value for these resistances may be found below.

If the metal and tube-side film resistances (r_{tds_G}, r_{tc_G}, and r_{tdc_G}) are not available from the manufacturer, calculate each as per the formulas below. The metal resistances (r_{mds_G}, r_{mc_G}, and r_{mdc_G}) should be calculated using the average temperature. These values may be determined for all zones.

The shell-side film resistances (r_{sds_G} and r_{sdc_G}) are calculated by the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances. Examples are shown in Nonmandatory Appendix B.

(a) Metal Resistance

(U.S. Customary Units)

$$r_{mz} = \frac{\text{OD}}{24k}\left[\ln\frac{\text{OD}}{\text{ID}}\right]\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-11}$$

(SI Units)

$$r_{mz} = \frac{\text{OD}}{1.36 \times 10^2 k}\left[\ln\frac{\text{OD}}{\text{ID}}\right]\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

(b) Fouling Resistances as per HEI Standards

(1) Shell Side

(U.S. Customary Units)

$$r_{fsz} = 0.0003\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-12}$$

(SI Units)

$$r_{fsz} = 0.00005\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

NOTE: Condensing zone fouling = 0.

(2) Tube Side

(U.S. Customary Units)

$$r_{fFWz} = 0.0002\left[\frac{\text{OD}}{\text{ID}}\right]\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-13}$$

(SI Units)

$$r_{fFWz} = 0.000035\left[\frac{\text{OD}}{\text{ID}}\right]\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

(3) Tube-Side Film Resistance

(U.S. Customary Units)

$$r_{FWz} = 0.0378\left[\left(\frac{\mu^{0.4}}{k^{0.6}\rho^{0.8}c_p^{0.4}}\right)\left(\frac{\text{OD}}{\text{ID}^{0.8}}\right)\left(\frac{1}{v^{0.8}}\right)\right]\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-14}$$

(SI Units)

$$r_{FWz} = [0.023\ (Re)^{0.8}(Pr)^{0.4}]^{-1}\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

where

Re = Reynolds number

Pr = Prandtl number

For the first iteration, the properties of the feedwater (in particular, the value for specific heat) should be determined using the inlet feedwater temperature for the drain cooling zone. Use the average of inlet and outlet feedwater temperatures for the condensing zone, and the feedwater outlet temperature for the desuperheating zone. For subsequent iteration steps adjust the properties at the average temperature for that zone for exactness.

(4) Shell-Side Film Resistance

NOTE: Design DSH zone and DC zone shell-side film resistances are typically obtained from the OEM or calculated as follows:

$$r_{sz} = \left(\frac{1}{U_z}\right) - (r_{fsz} + r_{fFWz} + r_{mz} + r_{FWz}) \tag{A-15}$$

In the condensing zone, the shell-side film resistance may be determined using the following formula:

(U.S. Customary Units)

$$r_{sc} = 0.06834\ (T)^{-0.8912}\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-16}$$

(SI Units)

$$r_{sc} = 0.01204\ (1.8T + 32)^{-0.8912}\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

where T is the condensate film temperature defined as follows:

$$T = T_{sat} - 0.2 \times \text{LMTD} \tag{A-17}$$

If $T > 320$°F, then use

(U.S. Customary Units)

$$r_{sc} = 0.0004\left(\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}\right) \tag{A-18}$$

(SI Units)

$$r_{sc} = 0.00007\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)$$

A-5 BASIC PERFORMANCE ACCEPTANCE EQUATIONS

Basic performance acceptance equations are as follows:

$$\text{TTD} = T_{sat} - T_{FWo} \tag{A-19}$$

$$\text{DCA} = T_{so} - T_{FWi} \tag{A-20}$$

A-6 PRESSURE DROP RATIOS

$$\Delta P_{z\_X} = \Delta P_{z\_G} \left(\frac{W_{z\_X}}{W_{z\_G}}\right)^{1.8} \tag{A-21}$$

$$\Delta P_{FW\_X} = \Delta P_{FW\_G} \left(\frac{v_{FW\_X}}{v_{FW\_G}}\right)^{1.8} \tag{A-22}$$

NOTE: Velocity ratios may be alternately used to compensate for tube plugging.

A-7 RESISTANCE RATIOS

In order to adjust shell-side and tube-side resistances based on new flow rates use the following rules of thumb:

$$r_{sz\_X} = r_{sz\_G} \left(\frac{W_{s\_G}}{W_s}\right)^{0.6} \tag{A-23}$$

$$r_{FWz\_X} = r_{FWz\_G} \left(\frac{v_{FW\_G}}{v_{FW}}\right)^{0.8} \tag{A-24}$$

NOTE: Velocity ratios may be alternately used to compensate for tube plugging.

In order to calculate the drain cooling zone feedwater outlet temperature at the design condition (T_{FWdco_G}) as referenced in subsection 5-2, use the following equation:

$$T_{FWdco\_G} = T_{FWi\_G} + \left[\frac{Q_{dc\_G}}{(W_{FW\_G})\,(c_{pFWdc})}\right] \tag{A-25}$$

In order to calculate the desuperheating zone steam outlet temperature at the design condition (T_{dso_G}) as referenced in subsection 5-2, use the following equation:

$$T_{dso\_G} = T_{si\_G} - \left[\frac{Q_{ds\_G}}{(W_{si\_G})\,(c_{pds\_G})}\right] \tag{A-26}$$

A-8 EFFECTIVENESS/NTU METHOD

(a) Hourly heat capacity flow rate for feedwater

$$C_{FWz} = \frac{(W_{FW})\,(Q_{z\_G})}{W_{FW\_G}\,(T_{FWzo\_G} - T_{FWzi\_G})} \tag{A-27}$$

(b) Hourly heat capacity flow rate for shell-side flows

$$C_{sz} = \frac{(W_{z\_X})(Q_{z\_G})}{W_{z\_G}\,(T_{zi\_G} - T_{zo\_G})} \tag{A-28}$$

(c) Hourly heat capacity ratio for desuperheating and drain cooling zones (hourly heat capacity ratio for the condensing zone is zero):

$$R_z = \frac{C_{FWz}}{C_{sz}} \tag{A-29}$$

(d) Number of transfer units (NTU)

$$\text{NTU}_z = \frac{U_z A_z}{C_z} \tag{A-30}$$

(e) Effectiveness in terms of NTU for the desuperheating and drain cooling zones

$$\epsilon_z = \frac{1 - \exp\,[(\text{NTU}_z)(R_z - 1)]}{1 - R_z \exp\,[(\text{NTU}_z)(R_z - 1)]} \tag{A-31}$$

Since the heat capacity ratio in the condensing zone is zero, the effectiveness for this zone is

$$\epsilon_c = 1 - \exp\,[-(\text{NTU}_c)] \tag{A-32}$$

(f) Feedwater outlet temperature in terms of effectiveness

$$T_{FWzo} = \epsilon_z\,(T_{zi} - T_{FWzi}) + T_{FWzi} \tag{A-33}$$

NONMANDATORY APPENDIX B
HEATER PERFORMANCE CALCULATION EXAMPLES

B-1 INTRODUCTION

This example gives a step-by-step calculation using the procedure described in para. 5-2.1 for a three-zone heater. Hypothetical design data and test data are given in Tables B-1-1 and B-1-2. See Figures 3-8-1 and 3-8-2 for the instrumentation test points for a three-zone heater. This example is calculated in U.S. Customary units, and SI units follow in parentheses. See Nonmandatory Appendix D for a reference on conversion factors.

For this example, typical minimum performance data supplied by the heater manufacturer are shown in Table B-1-1.

For this example, a test differential pressure transmitter was installed to measure the desuperheating zone, drain cooling zone and feedwater pressure drops directly. Measuring these values directly significantly reduces the pressure drop measurement uncertainty.

For determining the thermal properties of the water such as specific heats, the average water temperature within the zone should be used. For the first interation, use the feedwater inlet temperature for the drain cooling zone, the average inlet and outlet temperatures in the condensing zone, and the feedwater outlet temperature in the desuperheating zone. For each subsequent iteration, use the average temperature for that zone from the previous iteration.

B-2 STEP-BY-STEP CALCULATION

Step 1: Calculate the assumed feedwater outlet temperature based on the given terminal temperature difference, $\mathrm{TTD}_{\_G}$, and saturation temperature, T_{sat}, corresponding to the measured shell-side inlet steam pressure, P_{si}. Using $P_{si} = 396.0$ psia, the ASME Steam Tables yields T_{sat} of 443.6°F.

$$\begin{aligned} T_{FWo\_a} &= T_{sat} - \mathrm{TTD}_{\_G} \\ &= 443.6 - (-3.9) \\ &= 447.5°\mathrm{F} \\ &= (230.8°\mathrm{C}) \end{aligned}$$

Calculate the assumed drain cooling zone outlet temperature based on the given drain cooler approach, $\mathrm{DCA}_{\_G}$, and the measured feedwater inlet temperature.

$$\begin{aligned} T_{so\_a} &= T_{FWi} + \mathrm{DCA}_{\_G} \\ &= 375.4 + 10 = 385.4°\mathrm{F} \\ &= (196.3°\mathrm{C}) \end{aligned}$$

These temperatures serve as a starting point for the calculations. During the reiteration process, use the following convergence criteria:

If $|T_{FWo\_a} - T_{FWo\_X}| > 0.1$, then let $T_{FWo\_a} = T_{FWo\_X}$ using T_{FWo_X} as calculated in Step 28.

Step 2: Calculate the total heat transferred, $Q_{\_X}$, based on the measured feedwater flow, W_{FW}, the feedwater outlet enthalpy, h_{FWo_X}, determined using T_{FWo_a} in Step 1 and the measured feedwater pressure, P_{FWo}, and the feedwater inlet enthalpy, h_{FWi}, determined using the measured feedwater inlet temperature, T_{FWi} and pressure, P_{FWi}.

$$Q_{\_X} = W_{FW}\,(h_{FWo\_X} - h_{FWi})$$

Using 1,786.5 psia and 447.5°F, the ASME Steam Tables yields $h_{FWo\_X} = 428.3$ Btu/lbm (996.2 kJ/kg). Using 1,790 psia and 375.4°F, the ASME Steam Tables yields $h_{FWi} = 350.9$ Btu/lbm (816.2 kJ/kg).

$$\begin{aligned} Q_{\_X} &= W_{FW}\,(h_{FWo\_X} - h_{FWi}) \\ &= (621{,}000)\,(428.3 - 350.9) \\ &= 48{,}065{,}400\ \mathrm{Btu/hr} \\ &= (14\,087\ \mathrm{W}) \end{aligned}$$

Table B-1-1 Manufacturer Design Data

Parameter	Performance Data — Shell Side		Tube Side
Fluid circulated	Steam	Drains	Feedwater
Total fluid entering, lb/hr	52,270	25,000	689,777
Inlet enthalpy, Btu/lb	1362.2	450.8	361.4
Outlet enthalpy, Btu/lb	. . .	370.4	439.8
Inlet temperature, °F	701.9	. . .	385.4
Outlet temperature, °F	. . .	395.4	457.9
Operating pressure, psia	440.1	. . .	1748.7
Number of passes	3 zones		2 passes
Velocity, ft/sec (at average temperature)	. . .	. . .	5.529
Pressure drop, psi	DS: 1.6	DC: 1.8	4.8

Parameter	Heat Exchanged, Btu/hr	Effective Area, ft^2	LMTD, °F	Heat Transfer Rate, Btu/hr-ft^2-°F	Reference Temperature Differences, °F
Desuperheating zone	5,268,816	353	143.2	104.2	TTD = −3.9
Condensing zone	43,861,331	3,185	18.8	732.6	DCA = 10
Drain cooling zone	4,948,370	464	28.4	375.2	
Tube material	Monel	$OD_{\_G}$ (in.) = 0.625	. . .	Avg wall thickness $t_{\_G}$ (in.) = 0.049	. . .

Table B-1-2 Test Run Data

Location	Parameter	Symbol	Average of Data for One Test Run — U.S. Customary	SI
Feedwater inlet	Pressure	P_{FWi}	1,790 psia	12,342 kPa
	Temperature	T_{FWi}	375.4°F	190.8°C
	Flow rate	W_{FW}	621,000 lbm/hr	78.2 kg/s
Feedwater outlet	Pressure	P_{FWo}	1,786.5 psia	12,318 kPa
	Pressure loss	ΔP_{FW}	3.5 psi	24.1 kPa
	Temperature	T_{FWo}	448.6°F	231.4°C
Drains inlet	Pressure	P_{di}	697.3 psia	4,807.7 kPa
	Temperature	T_{di}	476.1°F	246.7°C
	Flow rate	W_{di}	25,000 lbm/hr	3.15 kg/s
Drains outlet	Pressure	P_{do}	393.4 psia	2,712.4 kPa
	Temperature	T_{do}	384.1°F	195.6°C
Extraction steam	Pressure	P_{si}	396.0 psia	2,730 kPa
	Temperature	T_{si}	700.0°F	371.1°C
Heater shell	Pressure	P_c	394.9 psia	2,722.7 kPa
	DS zone pressure loss	ΔP_{ds}	1.1 psi	7.6 kPa
	DC zone pressure loss	ΔP_{dc}	1.5 psi	10.3 kPa

Step 3: Calculate the drain inlet energy, Q_{di_X} as follows:

(a) Obtain the sum of the drain inlet flows, W_{di}.

$$W_{di} = 25{,}000 \text{ lbm/hr}$$
$$= (3.15 \text{ kg/sec})$$

(b) Obtain the drain inlet enthalpy, h_{di}, based on P_{di} and T_{di} for a single drain stream or by the flow weighted average of enthalpies for multiple drain streams. Note that the pressure(s) and temperature(s) are measured upstream of the drain control valve(s).

$$h_{di} = 460.0 \text{ Btu/lb}$$
$$= (1\,070.0 \text{ kJ/kg})$$

(c) Obtain the drain cooling zone shell-side outlet enthalpy, h_{so_X}, based on the assumed shell-side outlet temperature, T_{so_a}, and measured pressure, P_{so}, and calculate the total energy from the inlet drains.

$$h_{so\_X} = 359.6 \text{ Btu/lb}$$
$$= (836.4 \text{ kJ/kg})$$

$$\begin{aligned} Q_{di\_X} &= W_{di}\,(h_{di} - h_{so\_X}) \\ &= (25{,}000)\,(460 - 359.6) \\ &= 2{,}510{,}000 \text{ Btu/hr} \\ &= (735\,606 \text{ W}) \end{aligned}$$

Step 4. Calculate the steam flow to the heater by energy balance (see Nonmandatory Appendix A). The shell-side steam inlet enthalpy, h_{si}, is based on the measured temperature, T_{si}, and pressure, P_{si}.

$$\begin{aligned} W_{si\_X} &= \frac{(Q_x - Q_{di\_X})}{(h_{si} - h_{so\_X})} \\ &= \frac{(48{,}065{,}400 - 2{,}510{,}000)}{(1{,}363.1 - 359.6)} \\ &= 45{,}374 \text{ lbm/hr} \\ &= (5.72 \text{ kg/s}) \end{aligned}$$

Step 5: Calculate the total shell-side outlet flow.

$$\begin{aligned} W_{so\_X} &= W_{si\_X} + W_{di} \\ &= 45{,}374 + 25{,}000 \\ &= 70{,}374 \text{ lbm/hr} \\ &= (8.87 \text{ kg/s}) \end{aligned}$$

Step 6: Calculate the desuperheating zone, drain cooling zone, and feedwater pressure losses based on flow proportionalities as shown in Nonmandatory Appendix A.

$$\begin{aligned} \Delta P_{ds\_X} &= \Delta P_{ds\_G}\,(W_{si\_X}/W_{si\_G})^{1.8} \\ &= 1.6\,(45{,}374/52{,}270)^{1.8} \\ &= 1.24 \text{ psi} \\ &= (8.56 \text{ kPa}) \end{aligned}$$

$$\begin{aligned} \Delta P_{dc\_X} &= \Delta P_{dc\_G}\,(W_{so\_X}/W_{so\_G})^{1.8} \\ &= 1.8\,(70{,}374/77{,}270)^{1.8} \\ &= 1.52 \text{ psi} \\ &= (10.50 \text{ kPa}) \end{aligned}$$

$$\begin{aligned} \Delta P_{FW\_X} &= \Delta P_{FW\_G}\,(W_{FW}/W_{FW\_G})^{1.8} \\ &= 4.8\,(621{,}000/689{,}777)^{1.8} \\ &= 3.97 \text{ psi} \\ &= (27.39 \text{ kPa}) \end{aligned}$$

Step 7: Calculate the shell-side pressure, P_{c_X}, inside the condensing zone, and determine the saturation temperature, T_{c_X}, corresponding to this pressure.

$$\begin{aligned} P_{c\_X} &= P_{si} - \Delta P_{ds\_X} \\ &= 396 - 1.24 = 394.76 \text{ psia} \\ &= (2\,721.8 \text{ kPa}) \end{aligned}$$

$$\begin{aligned} T_{c\_X} &= 443.3°\text{F} \\ &= (228.5°\text{C}) \end{aligned}$$

Step 8: If not available from the heat exchanger manufacturer, calculate the desuperheating and drain cooling zone resistances. These will be needed for the overall heat transfer coefficient calculation in Step 9. See Nonmandatory Appendix A for more information.

If the tube-side fouling and shell-side fouling resistances are not available from the manufacturer, HEI recommends utilizing the following:

$$r_{fsds\_G} = r_{fsdc\_G} = \left[0.0003\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right]$$
$$= \left[0.00005\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]$$

$$r_{fsc\_G} = 0$$

$$r_{ftds\_G} = r_{ftc\_G} = r_{ftdc\_G}$$
$$= \left[0.0002\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)$$
$$= \left[0.000035\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]\left(\frac{\text{OD}_{\_G}}{\text{ID}_{\_G}}\right)$$
$$= 0.0002\left(\frac{0.625}{0.527}\right)$$
$$= \left[0.000237\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right]$$
$$= \left[0.000042\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]$$

If the metal and tube-side film resistances are not available from the manufacturer, calculate each as per the formulas in Nonmandatory Appendix A.

$$r_{tds\_G} = 0.0378\left[\frac{{\mu_{ds}}^{0.4}}{{k_{FWds}}^{0.6}\times{\rho_{FWds}}^{0.8}\times{c_{pFWds}}^{0.4}}\right]\left[\frac{OD_{\_G}}{{ID_{\_G}}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$
$$= 0.0378\left[\frac{0.278^{0.4}}{0.373^{0.6}\times 51.6^{0.8}\times 1.11^{0.4}}\right]\left[\frac{0.625}{0.527^{0.8}}\right]\left[\frac{1}{5.529^{0.8}}\right]$$
$$= \left[0.000445\,\frac{(\text{hr}-\text{ft}^2-\text{°F})}{\text{Btu}}\right]$$
$$= \left[0.000078\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]$$

$$r_{tc\_G} = \left[0.0378\,\frac{{\mu_c}^{0.4}}{{k_{FWc}}^{0.6}\times{\rho_{FWc}}^{0.8}\times{c_{pFWc}}^{0.4}}\right]\left[\frac{\text{OD}_{\_G}}{{\text{ID}_{\_G}}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$
$$= 0.0378\left[\frac{0.305^{0.4}}{0.383^{0.6}\times 53.3^{0.8}\times 1.056^{0.4}}\right]\left[\frac{0.625}{0.527^{0.8}}\right]\left[\frac{1}{5.529^{0.8}}\right]$$
$$= \left[0.000448\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right]$$
$$= \left[0.000079\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]$$

$$r_{tdc\_G} = 0.0378\left[\frac{{\mu_{dc}}^{0.4}}{{k_{FWdc}}^{0.6}\times{\rho_{FWdc}}^{0.8}\times{c_{pFWdc}}^{0.4}}\right]\left[\frac{\text{OD}_{\_G}}{{\text{ID}_{\_G}}^{0.8}}\right]\left[\frac{1}{v^{0.8}}\right]$$
$$= 0.0378\left[\frac{0.338^{0.4}}{0.390^{0.6}\times 54.7^{0.8}\times 1.056^{0.4}}\right]\left[\frac{0.625}{0.527^{0.8}}\right]\left[\frac{1}{5.529^{0.8}}\right]$$
$$= \left[0.000456\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right]$$

$$= \left[0.000080 \left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]$$

Metal resistance is calculated at average temperature, and the same values are used for the entire heater.

$$\begin{aligned}
r_{mds_G} &= r_{mc_G} = r_{mdc_G} \\
&= \frac{\text{OD}_{_G}}{24 \times k_m}\left[\ln\left(\frac{\text{OD}_{_G}}{\text{ID}_{_G}}\right)\right] \\
&= \frac{(0.625)}{(24 \times 16)}\left[\ln\left(\frac{0.625}{0.527}\right)\right] \\
&= \left[0.000278\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right] \\
&= \left[0.000049\left(\frac{\text{m}^2\text{-K}}{\text{W}}\right)\right]
\end{aligned}$$

where

k_m = 16 Btu-ft/hr-ft^2-°F for monel tubing [obtained from the heater manufacturer or Standards for Closed Feedwater Heaters (HEI)]

Calculate the shell-side film resistance as the difference between the inverse of the overall design heat transfer coefficient and the sum of the other resistances as follows:

$$\begin{aligned}
r_{sds_G} &= \left(\frac{1}{U_{ds_G}}\right) - \left(r_{fsds_G} + r_{mds_G} + r_{ftds_G} + r_{tds_G}\right) \\
&= \left(\frac{1}{104.2}\right) - \left(0.000300 + 0.000278 + 0.000237 + 0.000445\right) \\
&= \left[0.008337\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right] \\
&= \left[0.001468\,\frac{\text{m}^2\text{-K}}{\text{W}}\right]
\end{aligned}$$

$$\begin{aligned}
r_{sc_G} &= \left(\frac{1}{U_{c_G}}\right) - \left(r_{fsc_G} + r_{mc_G} + r_{ftc_G} + r_{tc_G}\right) \\
&= \left(\frac{1}{732.6}\right) - (0.0 + 0.000278 + 0.000237 + 0.000448) \\
&= \left[0.000402\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right] \\
&= \left[0.000071\,\frac{\text{m}^2\text{-K}}{\text{W}}\right]
\end{aligned}$$

$$\begin{aligned}
r_{sdc_G} &= \left(\frac{1}{U_{dc_G}}\right) - (r_{fsdc_G} + r_{mdc_G} + r_{ftdc_G} + r_{tdc_G}) \\
&= \left(\frac{1}{375.2}\right) - (0.0003 + 0.000278 + 0.000237 + 0.000456) \\
&= \left[0.001396\,\frac{(\text{hr-ft}^2\text{-°F})}{\text{Btu}}\right] \\
&= \left[0.000246\,\frac{\text{m}^2\text{-K}}{\text{W}}\right]
\end{aligned}$$

Step 9: Calculate the desuperheating, condensing, and drain cooling zones overall heat transfer coefficients based on the inverse of the sum of the individual resistances. Note that in the following equations, the shell and tube film coefficients have been adjusted for the actual versus design flow proportionalities.

$$U_{ds\_X} = \frac{1}{r_{sds\_G}\left(\frac{W_{si\_G}}{W_{si\_X}}\right)^{0.6} + r_{fsds\_G} + r_{mds\_G} + r_{ftds\_G} + r_{ds\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}}$$

$$= \frac{1}{0.008337\left(\frac{52{,}270}{45{,}374}\right)^{0.6} + 0.0003 + 0.000278 + 0.000237 + 0.000445\left(\frac{689{,}777}{621{,}000}\right)^{0.8}}$$

$$= \left[96.4\ \frac{\text{Btu}}{(\text{hr-ft}^2\text{-°F})}\right]$$

$$= \left[547.4\ \frac{\text{W}}{\text{m}^2\text{-K}}\right]$$

$$U_{c\_X} = \frac{1}{r_{sc\_G} + r_{fsc\_G} + r_{mc\_G} + r_{ftc\_G} + r_{tc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}}$$

$$= \frac{1}{0.000402 + 0 + 0.000278 + 0.000237 + 0.000448\left(\frac{689{,}777}{621{,}000}\right)^{0.8}}$$

$$= \left[712.1\ \frac{\text{Btu}}{(\text{hr-ft}^2\text{-°F})}\right]$$

$$= \left[4043.5\ \frac{\text{W}}{\text{m}^2\text{-K}}\right]$$

$$U_{dc\_X} = \frac{1}{r_{sdc\_G}\left(\frac{W_{so\_G}}{W_{so\_X}}\right)^{0.6} + r_{fsdc\_G} + r_{mdc\_G} + r_{ftdc\_G} + r_{tdc\_G}\left(\frac{W_{FW\_G}}{W_{FW}}\right)^{0.8}}$$

$$= \frac{1}{0.001396\left(\frac{77{,}270}{70{,}374}\right)^{0.6} + 0.0003 + 0.000278 + 0.000237 + 0.000454\left(\frac{689{,}777}{621{,}000}\right)^{0.8}}$$

$$= \left[359.0\ \frac{\text{Btu}}{(\text{hr-ft}^2\text{-°F})}\right]$$

$$= \left[2\,038.6\ \frac{\text{W}}{\text{m}^2\text{-K}}\right]$$

Step 10: If the manufacturer's feedwater temperature leaving the drain cooling zone, T_{FWdco_G}, is not available, it may be calculated by the following:

Using T_{FWi_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWdc}, and calculate T_{FWdco_G}.

$$T_{FWdco\_G} = T_{FWi\_G} + \left(\frac{Q_{dc\_G}}{W_{FW\_G} \times c_{pFWdc}}\right)$$

$$= 385.4 + \left[\frac{4{,}948{,}370}{(689{,}777 \times 1.056)}\right]$$

$$= 392.2\text{°F}$$

$$= (200.1\text{°C})$$

Step 11: If the saturation temperature in the condensing zone, T_{c_G} is not available from the manufacturer, calculate the pressure in the condensing zone using $P_{c\_G} = P_{ds\_G} - \Delta P_{ds\_G}$ and its corresponding saturation temperature, then calculate the hourly heat capacity flow rate of the drain cooling zone condensate.

$$C_{dc\_X} = \frac{W_{so\_X} \times Q_{dc\_G}}{W_{so\_G}\,(T_{c\_G} - T_{so\_G})}$$

$$= \frac{70{,}374 \times 4{,}948{,}370}{77{,}270\,(453.7 - 395.4)}$$

$$= 77{,}330\ \text{Btu/hr-°F}$$

$$= (40\,794\ \text{W/°C})$$

Step 12: Calculate the drain cooling zone feedwater (tube-side) hourly heat capacity flow rate.

$$
\begin{aligned}
C_{FWdc\_X} &= \frac{W_{FW} \times Q_{dc\_G}}{W_{FW\_G}\,(T_{FWdco\_G} - T_{FWi\_G})} \\
&= \frac{621{,}000 \times 4{,}948{,}370}{689{,}777\ (392.2 - 385.4)} \\
&= 655{,}143\ \text{Btu/hr-°F} \\
&= (345\ 606\ \text{W/°C})
\end{aligned}
$$

Step 13: Calculate the drain cooling zone heat capacity ratio.

$$
\begin{aligned}
R_{dc\_X} &= \frac{C_{FWdc\_X}}{C_{dc\_X}} \\
&= \frac{655{,}143}{77{,}330} = 8.472
\end{aligned}
$$

Step 14: Calculate the drain cooling zone number of transfer units.

$$
\begin{aligned}
(NTU)_{dc\_X} &= \frac{U_{dc\_X} \times A_{dc\_G}}{C_{FWdc\_X}} \\
&= \frac{359 \times 464}{655{,}143} = 0.2543
\end{aligned}
$$

Step 15: Calculate the drain cooling zone effectiveness.

$$
\begin{aligned}
\epsilon_{dc\_X} &= \frac{1 - \exp\,[(NTU)_{dc\_X} \times (R_{dc\_X} - 1)]}{1 - (R_{dc\_X})\exp\,[(NTU)_{dc\_X} \times (R_{dc\_X} - 1)]} \\
&= \frac{1 - \exp\,(0.254)\,(8.472 - 1)}{1 - 8.47\exp\,[(0.254)\,(8.472 - 1]} = 0.1022
\end{aligned}
$$

Step 16: Calculate the feedwater temperature leaving the drain cooling zone.

$$
\begin{aligned}
T_{FWdco\_X} &= \epsilon_{dc\_X}\,(T_{c\_X} - T_{FWi}) + T_{FWi} \\
&= (0.1022)\,(443.3 - 375.4) + 375.4 \\
&= 382.3\text{°F} \\
&= (194.6\text{°C})
\end{aligned}
$$

Step 17: Using T_{FWdco_G} and P_{FWi_G}, obtain the feedwater specific heat, c_{pFWc}, and the manufacturer's feedwater temperature leaving the condensing zone as shown in Nonmandatory Appendix A under effectiveness/NTU method.

$$
\begin{aligned}
T_{FWco\_X} &= T_{FWdco\_G} + \frac{Q_{c\_G}}{W_{FW\_G} \times c_{pFWc}} \\
&= 392.2 + \frac{43{,}861{,}331}{(689{,}777 \times 1.079)} \\
&= 451.1\text{°F} \\
&= (232.8\text{°C})
\end{aligned}
$$

Step 18: Considering that the shell-side heat capacity flow rate in the condensing zone is zero (see Nonmandatory Appendix A), calculate the feedwater hourly heat capacity flow rate in the condensing zone.

$$
\begin{aligned}
C_{FWc\_X} &= \frac{W_{FW} \times Q_{c\_G}}{W_{FW\_G}\,(T_{FWco\_G} - T_{FWci\_G})} \\
&= \frac{(621{,}000 \times 43{,}861{,}331)}{689{,}777\ (451.1 - 392.2)} \\
&= 670{,}424\ \text{Btu/hr-°F} \\
&= (353.7\ \text{kW/°C})
\end{aligned}
$$

Step 19: Calculate the number of transfer units in the condensing zone, $(NTU)_{c\_X}$.

$$(NTU)_{c\_X} = \frac{U_{c\_X} \times A_{c\_G}}{C_{FWc\_X}} = \frac{712.1 \times 3{,}185}{670{,}424} = 3.383$$

Step 20: Calculate the condensing zone effectiveness.

$$\begin{aligned}\epsilon_{c\_X} &= 1 - \exp\,[-(NTU)_{c\_X}]\\ &= 1 - \exp\,[-(3.383)] = 0.966\end{aligned}$$

Step 21: Calculate the feedwater temperature leaving the condensing zone.

$$\begin{aligned}T_{FWco\_X} &= \epsilon_{c\_X}\,(T_{c\_X} - T_{FWdco\_X}) + T_{FWdco\_X}\\ &= 0.966\,(443.3 - 382.3) + 382.3\\ &= 441.3°\text{F}\\ &= (227.4°\text{C})\end{aligned}$$

Step 22: If not provided by the manufacturer, calculate the steam temperature leaving the desuperheating zone.

$$\begin{aligned}T_{dso\_G} &= T_{si\_G} - \frac{Q_{ds\_G}}{W_{si\_G} \times c_{pds\_G}}\\ &= 701.9 - \frac{5{,}268{,}816}{52{,}270 \times 0.605}\\ &= 535.3°\text{F}\\ &= (279.6°\text{C})\end{aligned}$$

Step 23: Calculate the hourly heat capacity flow rate of the desuperheating zone steam.

$$\begin{aligned}C_{ds\_X} &= \frac{W_{si\_X} \times Q_{ds\_G}}{W_{si\_G}\,(T_{si\_G} - T_{dso\_G})}\\ &= \frac{45{,}374 \times 5{,}268{,}816}{52{,}270\,(701.9 - 535.3)}\\ &= 27{,}453\ \text{Btu/hr-°F}\\ &= (14\,482\ \text{W/°C})\end{aligned}$$

Step 24: Calculate the hourly heat capacity flow rate of the desuperheating zone feedwater.

$$\begin{aligned}C_{FWds\_X} &= \frac{W_{FW} \times Q_{ds\_G}}{W_{FW\_G}\,(T_{FWdso\_G} - T_{FWdsi\_G})}\\ &= \frac{621{,}000 \times 5{,}268{,}816}{689{,}777\,(457.9 - 451.1)}\\ &= 697{,}568\ \text{Btu/hr-°F}\\ &= (367{,}987\ \text{W/°C})\end{aligned}$$

Step 25: Calculate the desuperheating zone heat capacity ratio.

$$\begin{aligned}R_{ds\_X} &= \frac{C_{FWds\_X}}{C_{ds\_X}}\\ &= \frac{697{,}568}{27{,}453} = 25.40\end{aligned}$$

Step 26: Calculate the desuperheating zone number of transfer units.

$$\begin{aligned}(NTU)_{ds\_X} &= \frac{U_{ds\_X} \times A_{ds\_G}}{C_{FWds\_X}}\\ &= \frac{96.4 \times 353}{697{,}568} = 0.0488\end{aligned}$$

Step 27: Calculate the desuperheating zone effectiveness.

$$\epsilon_{ds\_X} = \frac{1 - \exp\left[(NTU)_{ds\_X}\,(R_{ds\_X} - 1)\right]}{1 - (R_{ds\_X})\exp\left[(NTU)_{ds\_X}\,(R_{ds\_X} - 1)\right]}$$
$$= \frac{1 - \exp\left[(0.0488)\,(25.40 - 1)\right]}{1 - 25.40\exp\left[(0.0488)\,(25.40 - 1)\right]} = 0.0277$$

Step 28: Calculate the final feedwater temperature leaving the desuperheating zone.

$$T_{FWdso\_X} = \epsilon_{ds\_X}\,(T_{si} - T_{FWco\_X}) + T_{FWco\_X}$$

where

$$T_{FWdso\_X} = T_{FWo\_X}$$

$$\begin{aligned} T_{FWco\_X} &= T_{FWdsi\_X} \\ &= (0.0277)\,(700.0 - 441.3) + 441.3 = 448.5°\text{F} \\ &= (231.4°\text{C}) \end{aligned}$$

Step 29: Check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new T_{FWo_X}.

$$\left|T_{FWo\_X} - T_{FWo\_a}\right| > 0.1$$

Since the difference between the calculated feedwater outlet temperature [448.5°F (231.4°C)] and the initially assumed feedwater outlet temperature [447.5°F (230.8°C)] is greater than 0.1°F, another iteration is necessary. Calculations continue at this point to illustrate the procedure.

Step 30: Calculate the drain outlet temperature.

$$\begin{aligned} T_{so\_X} &= T_{c\_X} - R_{dc\_X}\,\epsilon_{dc\_X}\,(T_{c\_X} - T_{FWi}) \\ &= 443.3 - (8.47)\,(0.1022)\,(443.3 - 375.4) \\ &= 384.5°\text{F} \\ &= (195.8°\text{C}) \end{aligned}$$

where

$$T_{FWdci} = T_{FWi}$$

$$T_{dco\_X} = T_{so\_X}$$

Step 31: Calculate the predicted terminal temperature difference ($\text{TTD}_{\_X}$).

$$\begin{aligned} \text{TTD}_{\_X} &= T_{sat} - T_{FWo\_X} \\ &= 443.6 - 448.5 \\ &= -4.9°\text{F} \\ &= (-2.7°\text{C}) \end{aligned}$$

Step 32: Calculate the predicted drain cooler approach ($\text{DCA}_{\_X}$).

$$\begin{aligned} \text{DCA}_{\_X} &= T_{so\_X} - T_{FWi} \\ &= 384.5 - 375.4 \\ &= 9.1°\text{F} \\ &= (5.1°\text{C}) \end{aligned}$$

Using 448.5°F as the initial feedwater outlet temperature, repeat the calculation from Step 2 through Step 30, which yields the following:

$$\begin{aligned} W_{si\_X} &= 46{,}003 \text{ lbm/hr} \\ &= (5.796 \text{ kg/s}) \end{aligned}$$

$$\begin{aligned} T_{FWo\_X} &= 448.5°\text{F} \\ &= (231.4°\text{C}) \end{aligned}$$

$$\begin{aligned} T_{so\_X} &= 443.3 - (8.43)(0.1025)(443.3 - 375.4) \\ &= 384.6°\text{F} \\ &= (195.9°\text{C}) \end{aligned}$$

$$\begin{aligned} \text{TTD}_{\_X} &= 443.6 - 448.5 \\ &= -4.9°\text{F} \\ &= (-2.7°\text{C}) \end{aligned}$$

$$\begin{aligned} \text{DCA}_{\_X} &= 384.6 - 375.4 \\ &= 9.2°\text{F} \\ &= (5.1°\text{C}) \end{aligned}$$

Step 33: Calculate the terminal temperature difference at the test point.

$$\begin{aligned} \text{TTD} &= T_{sat} - T_{FWo} \\ &= 443.6 - 448.6 \\ &= -5.0°\text{F} \\ &= (-2.8°\text{C}) \end{aligned}$$

Step 34: Calculate the drain cooler approach at the test point.

$$\text{DCA} = T_{so} - T_{FWi}$$

$$\begin{aligned} \text{where } T_{so} &= T_{dco} \\ &= 384.1 - 375.4 \\ &= 8.7°\text{F} \\ &= (4.8°\text{C}) \end{aligned}$$

Step 35: If directly measured differential pressure is not available, calculate the drain cooling and desuperheating zone pressure loss at the test point (measured directly in this example using a differential pressure transmitter).

$$\begin{aligned} \Delta P_{dc} = P_c - P_{dco} &= 1.5 \text{ psia} \\ &= (10.3 \text{ kPa}) \end{aligned}$$

$$\begin{aligned} \Delta P_{ds} &= P_{si} - P_{dso} \\ &= 1.1 \text{ psia} \\ &= (7.6 \text{ kPa}) \end{aligned}$$

$$\text{where } P_{dso} = P_c$$

Step 36: In this example, the feedwater pressure loss is measured directly. If directly measured differential pressure is not available, calculate the feedwater pressure loss at the test point.

$$\begin{aligned} \Delta P_{FW} &= P_{FWi} - P_{FWo} \\ &= 3.5 \text{ psi} \\ &= (24.1 \text{ kPa}) \end{aligned}$$

Step 37: Compare TTD$_{_X}$, DCA$_{_X}$, ΔP_{dc_X}, ΔP_{ds_X}, ΔP_{FW_X} with the measured values TTD, DCA, ΔP_{dc}, ΔP_{ds}, ΔP_{FW} as follows:

(a) TTD < TTD$_{_X}$: −5.0°F < −4.9°F (−2.8°C < −2.7°C)
(b) DCA < DCA$_{_X}$: 8.7°F < 9.2°F (4.8°C < 5.1°C)
(c) $\Delta P_{ds} < \Delta P_{ds\_X}$: 1.1 psi < 1.27 psi (7.6 kPa < 8.76 kPa)
(d) $\Delta P_{dc} < \Delta P_{dc\_X}$: 1.5 psi < 1.54 psi (10.3 kPa < 10.62 kPa)
(e) $\Delta P_{FW} < \Delta P_{FW\_X}$: 3.5 psi < 3.97 psi (24.1 kPa < 27.4 kPa)

In this example, the as-tested values for TTD, DCA, ΔP_{ds}, ΔP_{dc}, and ΔP_{FW} are all lower than the corresponding design values adjusted to test conditions. Therefore, the heater would "pass" for each of these five parameters.

NONMANDATORY APPENDIX C UNCERTAINTY CONSIDERATIONS

C-1 SAMPLE CALCULATION OF TEST UNCERTAINTY

This Nonmandatory Appendix contains a sample calculation of sensitivity coefficients, random standard uncertainty, systematic standard uncertainty, and combined standard uncertainty using the methods described in subsection 5-3 and the typical test data used in Nonmandatory Appendix B. For simplicity, the example assumes that the elemental systematic uncertainties are symmetrical. In cases where unsymmetrical elemental systematic uncertainties are expected, the example calculations in para. C-3.3 would need to be done twice, once for the upper elemental systematic uncertainty (i.e., positive direction) and once for the lower elemental systematic uncertainty (i.e., negative direction).

For this sample calculation, Table C-1-1 shows the 95% confidence level estimate of the limits associated with the systematic error source for each of the measurands, i.e., $B_{\bar{X}}$, and also the standard deviations of the data samples for each of the measurands, i.e., s_X. These values were selected to meet the maximum uncertainty value criteria in subsection 4-7 for each measured parameter. Also for this example, the number of measurements for the test run is assumed to be $N = 40$.

Subsection C-2 calculates the sensitivity of the results to uncertainties in the measured value of feedwater inlet temperature, as an illustration of the sensitivity analysis procedure discussed in para. 5-3.1. Subsection C-3 describes the calculation of the effects of uncertainties for all the measured values.

Table C-1-1 Sample Calculation Inputs For Systematic Error and Standard Deviation

Measured Parameter	Systematic Error, $B_{\bar{X}}$	Standard Deviation, s_X
Feedwater flow rate, W_{FW}	0.949%	1.00%
Drains inlet flow rate, W_{di}	0.949%	1.00%
Feedwater inlet temperature, T_{FWi}	0.231°F	0.30°F
Feedwater outlet temperature, T_{FWo}	0.231°F	0.30°F
Feedwater inlet pressure, P_{FWi}	1.897%	1.00%
Steam inlet temperature, T_{si}	0.949°F	1.00°F
Steam inlet pressure, P_{si}	0.237%	0.25%
Drain inlet temperature, T_{di}	0.231°F	0.30°F
Drain inlet pressure, P_{di}	1.897%	2.00%
Drain outlet temperature, T_{do}	0.231°F	0.30°F
Desuperheating zone pressure loss, ΔP_{ds}	0.949%	1.00%
Drain cooling zone pressure loss, ΔP_{dc}	0.949%	1.00%
Feedwater pressure loss across heater, ΔP_{FW}	0.949%	1.00%

C-2 SENSITIVITY OF THE RESULTS TO FEEDWATER INLET TEMPERATURE MEASUREMENT UNCERTAINTY

The calculations in Appendix B were done using a measured value of feedwater inlet temperature of 375.4°F. To determine the sensitivity of the results to variations in feedwater inlet temperature, those calculations are repeated twice using 376.4°F and 374.4°F for the measured feedwater inlet temperature. Table C-2-1 shows the results.

C-3 COMBINED UNCERTAINTY DUE TO ALL MEASUREMENTS

C-3.1 Sensitivity

In subsection C-2 only feedwater inlet temperature was perturbed. By perturbing each of the measurements, it is possible to determine the sensitivity of each of the results to unit uncertainties (1% or 1.0°F) in the measured parameters. The sensitivity values calculated for the example in Nonmandatory Appendix B appear in Tables C-3.1-1 through C-3.1-5.

C-3.2 Random Standard Uncertainty

Table C-1-1 shows that the standard deviation of the data sample for the feedwater inlet temperature is 0.30°F. Table C-2-1 shows that the sensitivity of the TTD to the feedwater inlet temperature is 0.038°F/°F. For this example, $N = 40$ measurements were made during the test run. Therefore, the random standard uncertainty of the difference between the predicted and measured TTD due to feedwater inlet temperature random error is calculated as follows:

$$s_{\bar{X}i} = \frac{s_{Xi}}{\sqrt{N}} = \frac{0.30°\text{F}}{\sqrt{40}} = 0.047°\text{F}$$

The random standard uncertainty contribution from feedwater inlet temperature to the random standard uncertainty of the result is calculated as follows:

$$(\theta_i \, s_{\bar{X}i})^2 = [(0.038°\text{F}/°\text{F})\,(0.047°\text{F})]^2 = 3.24\text{E} - 06$$

The contributions of the other measured parameters are calculated in the same way.

Table C-2-1 Sensitivity of the Results to Feedwater Inlet Temperature Measurement Uncertainty

Parameter	−Δ	Average	+Δ	Sensitivity, θ
Measured feedwater inlet temperature	374.4	375.4	376.4	. . .
Difference between calculated TTD and measured TTD	0.046	0.083	0.121	0.038
Difference between calculated DCA and measured DCA	−0.220	0.53	1.276	0.748
Difference between calculated FW ΔP and measured FW ΔP	0.47	0.47	0.47	0.0
Difference between calculated drain cooler ΔP and measured drain cooler ΔP	0.070	0.046	0.022	0.024
Difference between calculated desuperheater ΔP and measured desuperheater ΔP	0.202	0.17	0.141	0.031

Table C-3.1-1 Uncertainty Analysis for the Difference Between Predicted and Measured Terminal Temperature Difference (TTD) in Three-Zone Feedwater Heater

Variable	Variable Symbol	Sensitivity		Systematic Standard Uncertainty		Systematic Standard Uncertainty Contribution,	Random Standard Uncertainty		Random Standard Uncertainty Contribution,
		θ_i	Units	$b_{\bar{X}i}$	Units	$(\theta_i b_{\bar{X}i})^2$	$s_{\bar{X}i}$	Units	$(\theta_i s_{\bar{X}i})^2$
Feedwater flow rate	W_{FW}	0.074	°F/%	0.475	%	1.22E−03	0.158	%	1.36E−04
Drains inlet flow rate	W_{di}	0.002	°F/%	0.475	%	8.16E−07	0.158	%	9.06E−08
Feedwater inlet temperature	T_{FWi}	0.038	°F/°F	0.116	°F	1.92E−05	0.047	°F	3.24E−06
Feedwater outlet temperature	T_{FWo}	1.000	°F/°F	0.116	°F	1.33E−02	0.047	°F	2.25E−03
Feedwater inlet pressure	P_{FWi}	0.001	°F/%	0.949	%	7.86E−07	0.316	%	8.74E−08
Steam inlet temperature	T_{si}	0.027	°F/°F	0.475	°F	1.68E−04	0.158	°F	1.87E−05
Steam inlet pressure	P_{si}	0.996	°F/%	0.119	%	1.39E−02	0.040	%	1.55E−03
Drain inlet temperature	T_{di}	0.003	°F/°F	0.116	°F	1.57E−07	0.047	°F	2.65E−08
Drain inlet pressure	P_{di}	0.000	°F/%	0.949	%	1.67E−12	0.316	%	1.86E−13
Drain outlet temperature	T_{do}	0.000	°F/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Desuperheating zone pressure loss	ΔP_{ds}	0.000	°F/%	0.475	%	3.13E−15	0.158	%	3.48E−16
Drain cooling zone pressure loss	ΔP_{dc}	0.000	°F/%	0.475	%	5.82E−15	0.158	%	6.46E−16
Feedwater pressure loss across heater	ΔP_{FW}	0.000	°F/%	0.475	%	0.00E+00	0.158	%	0.00E+00
					(b_R)	0.1693		(s_R)	0.0629
Combined Standard Uncertainty of the Results, u_R, °F = 0.181									
Expanded Uncertainty of the Results, $U_{R,\,95}$, °F = 0.361									

The total random standard uncertainty of the difference between the predicted and measured TTD is calculated by taking the square root of the sum of the calculated values of $(\theta_i s_{\bar{X}i})^2$ for each measured parameter. The value calculated, which is s_R as defined in para. 5-3.2, is 0.0629°F and appears in Table C-3.1-1. The calculations for the other results of interest appear in Tables C-3.1-2 through C-3.1-5. Note that this is simply an example, and the standard deviations shown in Table C-1-1 shall be calculated on the basis of actual test data, and the number of measurements N shall be based on the actual frequency of test measurements.

C-3.3 Systematic Standard Uncertainty

Table C-1-1 shows that the systematic error of the feedwater inlet temperature is 0.231°F. Table C-2-1 shows that the sensitivity of the TTD to the feedwater inlet temperature is 0.038°F/°F. Therefore, the systematic standard uncertainty of the difference between the predicted and measured TTD due to feedwater inlet temperature is calculated as follows for a 95% confidence interval:

$$b_{\bar{X}i} = \frac{B_{\bar{X}i}}{2} = \frac{0.231°\text{F}}{2} = 0.116°\text{F}$$

The systematic standard uncertainty contribution from feedwater inlet temperature to the systematic standard uncertainty of the result is calculated as follows:

$$(\theta_i\, b_{\bar{X}i})^2 = [(0.038°\text{F}/°\text{F})\ (0.116°\text{F})]^2 = 1.92\text{E} - 05$$

The contributions of the other measured parameters are calculated in the same way. The total systematic standard uncertainty of the difference between the predicted and measured TTD is the square root of the sum of the calculated values of $(\theta_i b_{\bar{X}i})^2$ for each measured parameter. The value calculated, b_R, as defined in para. 5-3.3, is 0.1693°F and appears in Table C-3.1-1. The calculations for other results are in Tables C-3.1-2 through C-3.1-5. Note that this is simply an example, and the

Table C-3.1-2 Uncertainty Analysis for the Difference Between Predicted and Measured Drain Cooler Approach (DCA) in Three-Zone Feedwater Heater

Variable	Variable Symbol	Sensitivity		Systematic Standard Uncertainty		Systematic Standard Uncertainty Contribution,	Random Standard Uncertainty		Random Standard Uncertainty Contribution,
		θ_i	Units	$b_{\bar{x}i}$	Units	$(\theta_i b_{\bar{x}i})^2$	$s_{\bar{x}i}$	Units	$(\theta_i s_{\bar{x}i})^2$
Feedwater flow rate	W_{FW}	0.043	°F/%	0.475	%	4.26E−04	0.158	%	4.73E−05
Drains inlet flow rate	W_{di}	0.043	°F/%	0.475	%	4.11E−04	0.158	%	4.56E−05
Feedwater inlet temperature	T_{FWi}	0.748	°F/°F	0.116	°F	7.47E−03	0.047	°F	1.26E−03
Feedwater outlet temperature	T_{FWo}	0.000	°F/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Feedwater inlet pressure	P_{FWi}	0.002	°F/%	0.949	%	2.44E−06	0.316	%	2.72E−07
Steam inlet temperature	T_{si}	0.001	°F/°F	0.475	°F	3.32E−07	0.158	°F	3.69E−08
Steam inlet pressure	P_{si}	0.265	°F/%	0.119	%	9.88E−04	0.040	%	1.10E−04
Drain inlet temperature	T_{di}	0.006	°F/°F	0.116	°F	4.63E−07	0.047	°F	7.81E−08
Drain inlet pressure	P_{di}	0.000	°F/%	0.949	%	4.94E−12	0.316	%	5.49E−13
Drain outlet temperature	T_{do}	1.000	°F/°F	0.116	°F	1.33E−02	0.047	°F	2.25E−03
Desuperheating zone pressure loss	ΔP_{ds}	0.000	°F/%	0.475	%	9.24E−15	0.158	%	1.03E−15
Drain cooling zone pressure loss	ΔP_{dc}	0.000	°F/%	0.475	%	1.72E−14	0.158	%	1.91E−15
Feedwater pressure loss across heater	ΔP_{FW}	0.000	°F/%	0.475	%	0.00E+00	0.158	%	0.00E+00
					(b_R)	0.1504		(s_R)	0.0609
Combined Standard Uncertainty of the Results, u_R, °F = 0.162									
Expanded Uncertainty of the Results, $U_{R,\,95}$, °F = 0.325									

Table C-3.1-3 Uncertainty Analysis for the Difference Between Predicted and Measured Tube Side Pressure Loss in Three-Zone Feedwater Heater

Variable	Variable Symbol	Sensitivity		Systematic Standard Uncertainty		Systematic Standard Uncertainty Contribution,	Random Standard Uncertainty		Random Standard Uncertainty Contribution,
		θ_i	Units	$b_{\bar{x}i}$	Units	$(\theta_i b_{\bar{x}i})^2$	$s_{\bar{x}i}$	Units	$(\theta_i s_{\bar{x}i})^2$
Feedwater flow rate	W_{FW}	0.071	psi/%	0.475	%	1.14E−03	0.158	%	1.27E−04
Drains inlet flow rate	W_{di}	0.000	psi/%	0.475	%	0.00E+00	0.158	%	0.00E+00
Feedwater inlet temperature	T_{FWi}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Feedwater outlet temperature	T_{FWo}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Feedwater inlet pressure	P_{FWi}	0.000	psi/%	0.949	%	0.00E+00	0.316	%	0.00E+00
Steam inlet temperature	T_{si}	0.000	psi/°F	0.475	°F	0.00E+00	0.158	°F	0.00E+00
Steam inlet pressure	P_{si}	0.000	psi/%	0.119	%	0.00E+00	0.040	%	0.00E+00
Drain inlet temperature	T_{di}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Drain inlet pressure	P_{di}	0.000	psi/%	0.949	%	0.00E+00	0.316	%	0.00E+00
Drain outlet temperature	T_{do}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Desuperheating zone pressure loss	ΔP_{ds}	0.000	psi/%	0.475	%	0.00E+00	0.158	%	0.00E+00
Drain cooling zone pressure loss	ΔP_{dc}	0.000	psi/%	0.475	%	0.00E+00	0.158	%	0.00E+00
Feedwater pressure loss across heater	ΔP_{FW}	0.035	psi/%	0.475	%	2.73E−04	0.158	%	3.03E−05
					(b_R)	0.0376		(s_R)	0.0125
Combined Standard Uncertainty of the Results, u_R, psi = 0.040									
Expanded Uncertainty of the Results, $U_{R,\,95}$, psi = 0.079									

Table C-3.1-4 Uncertainty Analysis for the Difference Between Predicted and Measured Desuperheater Pressure Loss in Three-Zone Feedwater Heater

Variable	Variable Symbol	Sensitivity θ_i	Sensitivity Units	Systematic Standard Uncertainty $b_{\bar{x}i}$	Systematic Standard Uncertainty Units	Systematic Standard Uncertainty Contribution, $(\theta_i b_{\bar{x}i})^2$	Random Standard Uncertainty $s_{\bar{x}i}$	Random Standard Uncertainty Units	Random Standard Uncertainty Contribution, $(\theta_i s_{\bar{x}i})^2$
Feedwater flow rate	W_{FW}	0.022	psi/%	0.475	%	1.06E−04	0.158	%	1.18E−05
Drains inlet flow rate	W_{di}	0.001	psi/%	0.475	%	2.98E−07	0.158	%	3.31E−08
Feedwater inlet temperature	T_{FWi}	0.031	psi/°F	0.116	°F	1.26E−05	0.047	°F	2.13E−06
Feedwater outlet temperature	T_{FWo}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Feedwater inlet pressure	P_{FWi}	0.000	psi/%	0.949	%	1.70E−07	0.316	%	1.89E−08
Steam inlet temperature	T_{si}	0.000	psi/°F	0.475	°F	2.34E−08	0.158	°F	2.60E−09
Steam inlet pressure	P_{si}	0.035	psi/%	0.119	%	1.75E−05	0.040	%	1.94E−06
Drain inlet temperature	T_{di}	0.002	psi/°F	0.116	°F	3.26E−08	0.047	°F	5.50E−09
Drain inlet pressure	P_{di}	0.000	psi/%	0.949	%	3.48E−13	0.316	%	3.87E−14
Drain outlet temperature	T_{do}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Desuperheating zone pressure loss	ΔP_{ds}	0.011	psi/%	0.475	%	2.70E−05	0.158	%	3.00E−06
Drain cooling zone pressure loss	ΔP_{dc}	0.000	psi/%	0.475	%	1.21E−15	0.158	%	1.34E−16
Feedwater pressure loss across heater	ΔP_{FW}	0.000	psi/%	0.475	%	0.00E+00	0.158	%	0.00E+00
					(b_R)	0.0128		(s_R)	0.0043

Combined Standard Uncertainty of the Results, u_R, psi = 0.014

Expanded Uncertainty of the Results, $U_{R,\,95}$, psi = 0.027

Table C-3.1-5 Uncertainty Analysis for the Difference Between Predicted and Measured Drain Cooler Pressure Loss in Three-Zone Feedwater Heater

Variable	Variable Symbol	Sensitivity θ_i	Sensitivity Units	Systematic Standard Uncertainty $b_{\bar{x}i}$	Systematic Standard Uncertainty Units	Systematic Standard Uncertainty Contribution, $(\theta_i b_{\bar{x}i})^2$	Random Standard Uncertainty $s_{\bar{x}i}$	Random Standard Uncertainty Units	Random Standard Uncertainty Contribution, $(\theta_i s_{\bar{x}i})^2$
Feedwater flow rate	W_{FW}	0.017	psi/%	0.475	%	6.57E−05	0.158	%	7.30E−06
Drains inlet flow rate	W_{di}	0.009	psi/%	0.475	%	1.76E−05	0.158	%	1.95E−06
Feedwater inlet temperature	T_{FWi}	0.024	psi/°F	0.116	°F	7.84E−06	0.047	°F	1.32E−06
Feedwater outlet temperature	T_{FWo}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Feedwater inlet pressure	P_{FWi}	0.000	psi/%	0.949	%	1.06E−07	0.316	%	1.17E−08
Steam inlet temperature	T_{si}	0.000	psi/°F	0.475	°F	1.45E−08	0.158	°F	1.61E−09
Steam inlet pressure	P_{si}	0.028	psi/%	0.119	%	1.08E−05	0.040	%	1.20E−06
Drain inlet temperature	T_{di}	0.001	psi/°F	0.116	°F	2.02E−08	0.047	°F	3.41E−09
Drain inlet pressure	P_{di}	0.000	psi/%	0.949	%	2.16E−13	0.316	%	2.40E−14
Drain outlet temperature	T_{do}	0.000	psi/°F	0.116	°F	0.00E+00	0.047	°F	0.00E+00
Desuperheating zone pressure loss	ΔP_{ds}	0.000	psi/%	0.475	%	4.04E−16	0.158	%	4.48E−17
Drain cooling zone pressure loss	ΔP_{dc}	0.015	psi/%	0.475	%	5.02E−05	0.158	%	5.57E−06
Feedwater pressure loss across heater	ΔP_{FW}	0.000	psi/%	0.475	%	0.00E+00	0.158	%	0.00E+00
					(b_R)	0.0123		(s_R)	0.0042

Combined Standard Uncertainty of the Results, u_R, psi = 0.013

Expanded Uncertainty of the Results, $U_{R,\,95}$, psi = 0.026

systematic errors shown in Table C-1-1 shall be based on instruments and calibration of equipment used in the test.

C-3.4 Combined Standard Uncertainty and Expanded Uncertainty

The combined standard uncertainty of the difference between the predicted and measured TTD is calculated using the equation in para. 5-3.4, as follows:

$$u_R = [(b_R)^2 + (s_R)^2]^{1/2}$$

Using the calculated value of $s_R = 0.0629°F$ in para. C-3.2, and $b_R = 0.1693°F$ in para. C-3.3, the combined standard uncertainty is $u_R = 0.181°F$.

$$u_R = [(0.1693°F)^2 + (0.0629°F)^2]^{1/2} = 0.181°F$$

Finally, the expanded uncertainty of the difference between the predicted and measured TTD is calculated as described in para. 5-3.4:

$$U_{R,\,95} = t_{95} u_R$$

For $N = 40$ measurements, the student t at 95% confidence interval is $t_{95} = 2$, therefore the expanded uncertainty is:

$$U_{R,\,95} = 2 \times 0.181°F = 0.361°F$$

Therefore, for this example, there is 95% confidence that the calculated value for the difference between the predicted and measured TTD is within ± 0.361°F of the true value.

The calculated values for u_R and $U_{R,\,95}$ appear at the bottom of Table C-3.1-1. The calculations for other results are in Tables C-3.1-2 through C-3.1-5.

NONMANDATORY APPENDIX D
PRINCIPAL QUANTITIES AND COMMONLY USED CONVERSION FACTORS IN HEAT TRANSFER (SI UNITS)

Table D-1 lists commonly used conversion factors in heat transfer.

Table D-1 Conversion Factors

Multiply	By	To Obtain
Length		
in.	2.54×10^{1} [Note (1)]	mm
ft	3.048×10^{-1} [Note (1)]	m
Area		
in.^{2}	$6.451\,600 \times 10^{-4}$	m^2
ft^2	$9.290\,304 \times 10^{-2}$	m^2
Volume		
ft^3	$2.831\,685 \times 10^{-2}$	m^3
Mass		
lbm	$4.535\,924 \times 10^{-1}$	kg
Temperature		
°F	(°F − 32)/1.8	°C
Power (Energy/Time)		
Btu/hr	$2.930\,711 \times 10^{-1}$	W
Pressure		
lbm/in.^{2} (psi)	$6.894\,757 \times 10^{3}$	Pa
lbm/in.^{2} (psi)	6.894 757	kPa
lbm/in.^{2} (psi)	$7.030\,696 \times 10^{-2}$	kgf/cm^2
Velocity		
ft/sec	3.048×10^{-1} [Note (1)]	m/s
Mass Flow Rate		
lbm/hr	$1.259\,979 \times 10^{-4}$	kg/s
Density		
lbm/ft^3	$1.601\,846 \times 10^{1}$	kg/m^3
Enthalpy		
Btu/lbm	2.326×10^{3} [Note (1)]	J/kg
Btu/lbm	2.326 [Note (1)]	kJ/kg
Specific Heat		
Btu/(lbm-°F)	$4.186\,8 \times 10^{3}$ [Note (1)]	J/(kg-K)
Btu/(lbm-°F)	4.186 8 [Note (1)]	kJ/(kg-K)
Thermal Conductivity		
(Btu-ft)/(hr-ft^2-°F)	1.730 735	W/(m-K)
Dynamic Viscosity		
lbm/(hr-ft)	$4.133\,789 \times 10^{-4}$	Pa-s
Heat Transfer Coefficient		
Btu/(hr-ft^2-°F)	5.678 263	W/(m^2-K)
Fouling Resistance		
(hr-ft^2-°F)/Btu	$1.761\,102 \times 10^{-1}$	(m^2-K)/W

NOTE:
(1) Exact relationship in terms of the base unit.

PERFORMANCE TEST CODES (PTC)

General Instructions . . . . . . PTC 1-2015
Definitions and Values . . . . . . PTC 2-2001 (R2014)
Fired Steam Generators. . . . . . PTC 4-2013
Coal Pulverizers . . . . . . PTC 4.2-1969 (R2009)
Air Heaters . . . . . . PTC 4.3-1968 (R1991)
Gas Turbine Heat Recovery Steam Generators. . . . . . PTC 4.4-2008 (R2013)
Steam Turbines . . . . . . PTC 6-2004 (R2014)
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 (R2014)
Centrifugal Pumps . . . . . . PTC 8.2-1990
Compressors and Exhausters . . . . . . PTC 10-1997 (R2014)
Fans . . . . . . PTC 11-2008
Closed Feedwater Heaters. . . . . . PTC 12.1-2015
Steam Surface Condensers . . . . . . PTC 12.2-2010 (R2015)
Deaerators . . . . . . PTC 12.3-1997 (R2014)
Moisture Separator Reheaters. . . . . . PTC 12.4-1992 (R2014)
Single Phase Heat Exchangers . . . . . . PTC 12.5-2000 (R2015)
Reciprocating Internal-Combustion Engines. . . . . . PTC 17-1973 (R2012)
Hydraulic Turbines and Pump-Turbines . . . . . . PTC 18-2011
Test Uncertainty . . . . . . PTC 19.1-2013
Pressure Measurement . . . . . . PTC 19.2-2010 (R2015)
Temperature Measurement . . . . . . PTC 19.3-1974 (R2004)
Thermowells. . . . . . PTC 19.3 TW-2016
Flow Measurement . . . . . . PTC 19.5-2004 (R2013)
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 (R2013)
Data Acquisition Systems . . . . . . PTC 19.22-2007 (R2012)
Guidance Manual for Model Testing. . . . . . PTC 19.23-1980 (R1985)
Particulate Matter Collection Equipment . . . . . . PTC 21-1991
Gas Turbines . . . . . . PTC 22-2014
Atmospheric Water Cooling Equipment . . . . . . PTC 23-2003 (R2014)
Ejectors . . . . . . PTC 24-1976 (R1982)
Pressure Relief Devices . . . . . . PTC 25-2014
Speed-Governing Systems for Hydraulic Turbine-Generator Units . . . . . . PTC 29-2005 (R2015)
Air Cooled Heat Exchangers . . . . . . PTC 30-1991 (R2011)
Air-Cooled Steam Condensers. . . . . . PTC 30.1-2007 (R2012)
High-Purity Water Treatment Systems. . . . . . PTC 31-2011
Waste Combustors With Energy Recovery . . . . . . PTC 34-2007
Measurement of Industrial Sound . . . . . . PTC 36-2004 (R2013)
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 46-2015
Integrated Gasification Combined Cycle Power Generation Plants . . . . . . PTC 47-2006 (R2011)
Fuel Cell Power Systems Performance . . . . . . PTC 50-2002 (R2014)
Gas Turbine Inlet Air-Conditioning Equipment . . . . . . PTC 51-2011
Gas Turbine Aircraft Engines . . . . . . PTC 55-2013
Ramp Rates . . . . . . PTC 70-2009 (R2014)

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 Customer Care, 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	Member Services & Benefits	Public Information
Codes & Standards	Other ASME Programs	Self-Study Courses
Credit Card Orders	Payment Inquiries	Shipping Information
IMechE Publications	Professional Development Short Courses	Subscriptions/Journals/Magazines
Meetings & Conferences	Publications	Symposia Volumes
Member Dues Status		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 a Customer Care representative will handle your request.

Mail
ASME
150 Clove Road, 6th Floor
Little Falls, New Jersey
07424-2139

Call Toll Free
US & Canada: 800-THE-ASME
(800-843-2763)
Mexico: 95-800-THE-ASME
(95-800-843-2763)

Fax—24 hours
973-882-1717
973-882-5155

E-Mail—24 hours
customercare@asme.org

* Customer Care 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.

ASME PTC 12.1-2015

ISBN 978-0-7918-7050-1

9 780791 870501

C 0 1 3 1 5