



Standard Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers¹

This standard is issued under the fixed designation C1041; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the in-situ measurement of heat flux through industrial thermal insulation using a heat flux transducer (HFT).

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 This practice estimates the thermal transport properties of thermal insulation materials in-situ in field applications under pseudo steady-state conditions. It is not intended that this practice should be used as a substitute for more precise laboratory procedures such as Test Methods C177, C335, or C518.

1.4 This practice is limited by the relatively small area that can be covered by an HFT and by the transient effects of environmental conditions.

1.5 Temperature limitations shall be as specified by the manufacturer of the HFT.

1.6 While accurate values of heat flux are highly dependent upon proper calibrations under the conditions of use, it is acceptable to use the calibrations provided by the manufacturer of the HFT for comparative work between similar materials, aging, or other conditions of use.

NOTE 1—Further information may be found in the literature (1-6).²

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

¹ This practice is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

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² The boldface numbers in parentheses refer to the list of references at the end of this standard.

2. Referenced Documents

2.1 ASTM Standards:³

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C335 Test Method for Steady-State Heat Transfer Properties of Pipe Insulation

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

E220 Test Method for Calibration of Thermocouples By Comparison Techniques

E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

3. Terminology

3.1 Definitions:

3.1.1 *heat flux transducer (HFT)*—a rigid or flexible transducer in a durable housing comprised of a thermopile or equivalent for sensing the temperature drop across a thin thermal resistance layer which gives a voltage output proportional to the heat flux through the transducer.

3.1.1.1 *belt HFT*—a heat flux transducer having a belt-like configuration such that the unit can be wrapped helically around a section of pipe insulation (see Fig. 1).

3.1.1.2 *spot HFT*—a small heat flux transducer having a round, square, rectangular or other configuration for the sensitive area (see Fig. 1).

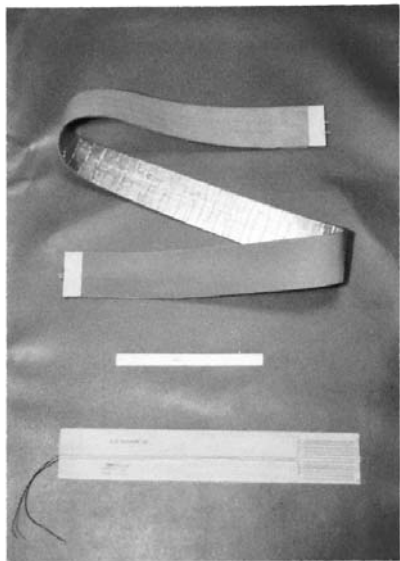
3.1.2 *pseudo steady state of HFT*—the criterion for pseudo steady-state condition is that the average HFT reading over two consecutive 5-min periods does not differ by more than 2 %. Since the time constant of an HFT is typically less than or of the order of 1 min, using a time interval of 5 min ensures that the transient effects in the HFT are averaged.

3.2 Symbols:

3.2.1 Q —heat flow, W (Btu/h).

3.2.2 q —heat flux, W/m² (Btu/h·ft²).

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



NOTE 1—Belt wraps around exterior; shim slips under jacketing (spot HFT).

FIG. 1 Flexible Heat Flux Transducers for Pipes

3.2.3 C —overall conductance of the insulated section, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot ^\circ F$).

3.2.4 t_o —process surface temperature, $^\circ C$ ($^\circ F$).

3.2.5 t_1 —insulation inside surface temperature. For purposes of this standard, t_o and t_1 shall be considered to be identical.

3.2.6 t_2 —insulation outside surface temperature, $^\circ C$ ($^\circ F$).

3.2.7 R —areal resistance of the insulating section,

$$\frac{m^2 \cdot K}{W} \left(\frac{h \cdot ft^2 \cdot ^\circ F}{Btu} \right) \quad (1)$$

3.2.8 λ (k)—apparent thermal conductivity, $W/m \cdot K$ ($Btu \cdot in \cdot h \cdot ft^2 \cdot ^\circ F$).

3.2.9 D —thickness of test section, m (in.).

3.2.10 r_2 —outer radius of pipe insulation, m (in.).

3.2.11 r_1 —inner radius of pipe insulation, m (in.).

3.2.12 r_o —outer radius of pipe, m (in.).

3.2.13 V —HFT output in millivolts or other chosen unit.

4. Summary of Practice

4.1 This practice is a guide to the proper use of heat flux transducers for estimating the thermal transport properties of thermal insulation in-situ in field applications under pseudo steady-state conditions.

5. Significance and Use

5.1 The major contribution of this practice is that it enables a measurement of the real-time energy loss or gain through a chosen surface of an existing process insulation with minimal disturbance to the heat flux through the insulating body.

5.2 The primary use of this practice will be for the in-situ estimation of thermal transport properties of industrial insula-

tion such as used on pipes, tanks, ovens, and boilers, operating under normal process conditions.

5.3 Errors attributable to heat flow measurements over a small area or short term testing can be misleading and this practice is intended to minimize such errors.

5.4 Insulation processes with large temperature differences across the insulation are best suited to HFT measurements because modest changes in ambient conditions have but minimal effects on HFT output.

5.5 While it would be ideal for the HFT and attachment system to have zero thermal resistance, this factor is insignificant to the measured result if kept to 5 % or less of the resistance of the insulating section being tested.

6. Apparatus

6.1 *Heat Flux Transducer*, as described in 3.1.1.

6.2 *Voltmeter/Recorder*—A voltage-measuring recording instrument accurate to within 0.5 % of the lowest HFT output anticipated during the test. An integrating voltmeter is even more appropriate for reading the output of the HFT.

6.3 *Temperature Sensor*—A thermocouple or other device of a type suitable for the temperatures being measured.

6.3.1 For measuring the temperature of an insulated surface, such as a pipe under insulation, a 1.5-mm diameter or smaller, flexible ungrounded thermocouple probe 500 mm long is recommended.

6.3.2 For measuring the temperature of surfaces that can be easily accessed, 24 gauge or smaller, bare bead thermocouples or equivalent shall be used.

6.4 *Attachment Materials*—Pressure-sensitive adhesive tape, elastic bands, straps, mastic, grease, or other means may be used to hold the HFT in place on the test surface.

6.5 *Thermal Contact Materials*—Patching cement, silicone grease, heat sink grease, silicone sealant, room temperature vulcanizing elastomer, thermally conducting epoxy, or conformable pads may be used to provide maximum contact between the test surface and the HFT where applicable. The thermal coupler should not add to or reduce the resistance of the system such that the temperature patterns of heat flows are significantly changed. This could be measured by surface temperature probes or infrared measurement devices.

6.6 *Surfacing Materials*—Coating, films, or foils to adjust the surface emittance of the HFT to match the radiant characteristics of the test surface.

7. Calibrations

7.1 HFT must be calibrated under the conditions of use; for example, a calibration under aluminum jacketing on a test setup in accordance with Test Method C335, would be proper for calibration of an HFT for subsequent testing under similar conditions.

7.2 Calibrate HFT to national reference standards in accordance with Test Methods C177, C335, or C518. A calibration

curve showing q/V versus insulation surface temperature (expected to be the HFT temperature) shall be developed covering the intended range of operating temperatures and heat fluxes.

7.2.1 The following is an example of calibration under use conditions (pipe insulated with preformed insulation and jacketed with aluminum):

7.2.1.1 Set up the apparatus in accordance with Test Method C335 with preformed insulation, jacketed with aluminum jacket in the same condition as that to be tested.

7.2.1.2 Establish steady-state at test temperature (3.1.2).

7.2.1.3 Insert flexible HFT under jacket, near the center of the insulation section. The jacket should be lifted enough to provide guidance in placing the HFT away from all joints in the insulation section. (When a belt HFT is being calibrated, it must be wrapped in a tight helix around the center of the insulation section with the appropriate side, foil or gray to match emittance, exposed. Attach the strap to the belt, pulling and rubbing the belt into close contact with the insulation section, making sure that the lap of the belt is on the side of the pipe.)

7.2.1.4 Insert a bare temperature sensor about 50 mm away from the HFT. After calibrating the belt HFT, place the sensor between the belt and the insulation surface to measure surface temperature.

7.2.1.5 Read pseudo steady-state electrical output of HFT and temperature at both surfaces of the insulation. Since the output of the HFT will fluctuate under most conditions, a graphical or integrated average of the output of the HFT must be made.

7.2.1.6 Utilizing q , as may be calculated from Test Method C335 data, determine the calibration value for the HFT in q/V for at least 3 insulation surface temperatures.

7.2.1.7 Plot calibration value (q/V) versus insulation surface temperature (7.2.1.6).

7.3 Calibrate the thermocouple in accordance with Test Method E220.

8. Test Section and HFT and Temperature Sensor Placement Guidelines

8.1 Test Section:

8.1.1 Selection of the test sections must be appropriate and consistent with the test objectives. Several test sections may be needed.

8.1.2 Infrared scanning is an appropriate way to identify relative surface uniformity conditions so that the HFT may be placed to measure the thermal transport properties of a representative area.

8.1.3 Test sections must be amenable to attachment of the HFT with good thermal coupling and with minimal disturbance of normal heat transfer.

8.2 HFT Placement:

8.2.1 Where block or pipe insulation is being tested, place a spot HFT preferably under the jacketing material near the center of a formed section of material. Avoid placement on joints in insulation or laps in jacketing unless joint loss is being evaluated.

8.2.2 When a spot HFT is surface-mounted, it may be attached by using an adhesive two-sided tape, heat transfer

grease, or other appropriate means. The emittance of the HFT must match the surface as closely as possible. With one transducer an error of 0.01 at the 0.05 emittance level displaces the reading by 3.5 %. An error of 0.1 at the 0.5 emittance level displaces the reading by 3.5 %.

8.2.3 Use a belt HFT for obtaining system thermal performance data of block or pipe insulation, including heat loss from large joints. When the belt HFT is mounted on reflective insulation jacketing, it should have the foil side exposed; when it is mounted on a surface with high emittance, the gray side must be exposed. Wrap the belt HFT around the insulation test section in a tight helix with no overlap, with the belt pulled and rubbed to achieve close contact with the test surface. For full circumferential integration, a minimum of one complete wrap must be made. If the HFT is not long enough to wrap completely around the test section, connect additional belts in series until a full wrap is made. Any helical lap of the belt past full circle should be on the side of the test section, not at the top or bottom. Do not overwrap a flexible HFT because compression may cause a change in calibration.

8.3 Thermocouple Placement:

8.3.1 Measure the process surface temperature by inserting a thermocouple probe as described in 6.3.1 such that the probe lies against the process surface for 150 mm (6 in.) or more. For purposes of inserting the probe, pierce the insulation with an ice pick or other means at an angle of 30° or less to the plane of the surface to be measured. The correct insertion of the probe should show the maximum ΔT across the insulation.

8.3.1.1 If the process system has built-in temperature-measuring capabilities in good repair and calibration the output from such devices may be usable in place of a temperature probe.

8.3.2 A bare bead thermocouple should be inserted under the jacket to measure the surface temperature of the insulation near the HFT (see 7.2.1.4).

8.3.3 When the HFT is installed on a surface rather than under a jacket (or other cover), measure the surface temperature of the insulation near the HFT by taping a bare bead thermocouple to the insulation surface (6.3.2) such that at least 100 mm of the thermocouple is in contact with the surface. The emittance of the tape should match that of the insulation surface within ± 0.2 (see 8.2.2).

9. HFT and Temperature Data Points

9.1 The output from the HFT shall be recorded with a suitable recorder such that pseudo steady-state (3.1.2) may be observed when attained. Depending on exact environmental conditions, the recorder usually traces a “band” of data which must be averaged graphically.

9.2 As an alternative to recording the output of the HFT, an integrating voltmeter may be used. While the exact conditions to be utilized will depend upon the capabilities of the voltmeter at hand, it is suggested that short integration periods be averaged over sequential 5-min intervals to determine when pseudo steady-state (3.1.2) is achieved.

9.3 Temperature readings shall be taken when the HFT reading comes to pseudo steady-state as defined in 3.1.2.

9.4 Multiple location data points must be taken and averaged.

10. Procedure

10.1 Select an appropriate test area and install HFT and temperature sensors in accordance with Section 8.

10.2 Shield the HFT from direct solar radiation unless solar gain is intended as a factor in the study.

10.3 Connect the HFT to the recorder or integrating voltmeter and take readings until pseudo steady-state is achieved in accordance with Section 9.

10.4 Measure the surface temperature of the insulation near the HFT in accordance with 8.3.2, 8.3.3, and 9.3.

10.5 Measure the temperature of the process surface in accordance with 8.3.1 and 9.3.

10.6 If appropriate, measure ambient weather conditions near the HFT. Measurements of air movement, humidity, precipitation, insolation, etc. may be important in the interpretation of results.

10.7 Measure the physical dimensions of the insulation.

10.7.1 *Pipe Cover:*

10.7.1.1 Measure the circumference to the nearest millimetre ($1/16$ in.) and divide by 2π to determine the outer radius of insulation plus jacket or finish as applicable.

10.7.1.2 Determine the insulation thickness to the nearest millimetre ($1/16$ in.) by perpendicular penetration to the pipe with a sharp instrument such as an ice pick. Avoid locations where the insulation is damaged. With rigid insulation such as calcium silicate a single measurement at the top of a horizontal pipe will suffice. With compressible materials such as fibrous insulation, measurements must be made at top, bottom, and sides, and averaged.

10.7.1.3 Subtract thickness from outer radius to determine inner radius.

10.7.2 *Flat Sections:*

10.7.2.1 Measure the thickness to the nearest millimetre ($1/16$ in.) by perpendicular penetration with a sharp instrument such as an ice pick. Avoid locations where the insulation is damaged.

11. Calculation

11.1 The following calculations are applicable to steady state conditions as defined in 3.1.2.

11.2 Heat flux, q (Q/A), is calculated by multiplying the voltage reading by the calibration constant for the HFT (unless the transducer/meter reads directly in energy units). Where the HFT is operating at other than its calibration temperature, an adjustment for operating temperature must be applied, as indicated by the calibration data.

11.3 Calculate the overall conductance and resistance of a test specimen as follows:

$$C = q/(t_1 - t_2) \quad (2)$$

$$R = 1/C$$

11.4 Calculate the apparent thermal conductivity of the insulation section as follows:

11.4.1 For pipe covers:

$$\lambda_p = [q \cdot r_2 \cdot \ln(r_2/r_0)/(t_1 - t_2)] \quad (3)$$

11.4.2 For flat sections:

$$\lambda = (q \cdot D)/(t_1 - t_2) \quad (4)$$

12. Interpretation of Results

12.1 Since the HFT measures heat flux over a relatively small, discrete portion of an insulation section, care must be exercised to ensure that the measured test section is typical. As previously mentioned in 8.1.2, an infrared scan may be used to determine where the representative area is for the measurement of heat flux by means of the HFT. Lacking infrared observation or other means, however, the site must be selected to avoid joints, hot spots, or other discontinuities that might be obvious from the construction of the system.

12.2 Environmental factors must be taken into account in the interpretation of data. Direct sunshine adds heat to the system and causes the HFT to show lower heat loss for heated systems (higher for cooled systems). Wind can affect the system by heating or cooling the surface.

12.3 With insulated cold systems, the effects of environmental factors are similar. Direct insolation causes greater heat gain that is indicated by the HFT. Wind causes greater heat gain that is also correctly indicated by the HFT.

13. Report

13.1 The report shall include the following information:

13.1.1 Description of equipment used.

13.1.2 Description of test procedure used.

13.1.3 Description of the test section.

13.1.4 Method of choosing a representative area for measurement.

13.1.5 Duration of the test.

13.1.6 Ambient conditions during the test, including temperature, insolation, precipitation, and wind.

13.1.7 Calibration information for HFT.

13.1.8 Data and calculations.

14. Precision and Bias

14.1 *Heat Flux Transducers* come in a variety of sizes, shapes, sensitivities, and materials of construction. The exact HFT to be used for a particular application must be chosen carefully, using past experience, recommendations from the manufacturer, and other information as available. The precision and bias attained with any particular setup is also highly dependent on the proper choice of HFT, HFT calibration, instrumentation, installation techniques, and data acquisition techniques. Estimates of the precision and accuracy which can be expected are given here along with some real examples. This analysis is done for 95 % confidence limits, (that is, 2σ or $2S$).

14.2 *Precision:*

14.2.1 An outside limit or worst case estimate of the precision for a flat section is just the sum of the relative uncertainties of each of the calculation components for λ , the thermal conductivity.

$$\begin{aligned}\delta\lambda/\lambda &= [(\delta q/q) + (\delta D/D) + (\delta\Delta T/\Delta T)] \\ &= 2S_v/V + [(0.001 \text{ m}/D) + (1^\circ\text{C}/\Delta T)]\end{aligned}\quad (5)$$

where S_v represents the standard deviation of the output voltage V , of the HFT, with time. The ΔT and D uncertainties are taken from 6.3 and 10.7.

14.2.2 The largest single addition to the uncertainty in making precise determinations of λ is that due to finding the average output of the HFT over a pseudo steady-state time period.

14.2.3 An example of the typical uncertainties expected is shown here, using the formula in 14.2.1 with $\Delta T = 300^\circ\text{C}$, $D = 10 \text{ cm}$, and a high output HFT.

$$\text{Precision of } \lambda = 14.0\% + 1.0\% + 0.3\% = 15.3\% \quad (6)$$

14.2.4 A more probable estimate of the precision than the “worst case” given in 14.2.1, can be calculated by using:

$$2S_\lambda/\lambda = 2\sqrt{[S_v/V]^2 + [S_D/D]^2 + [S_{\Delta T}/\Delta T]^2} \quad (7)$$

where $S_a^2 = [(2\delta a)^2/12]$, $a = D$ or $a = \Delta T$ is used to express the variances of both the thickness measurement and temperature measurement, since their probability distributions are assumed to be rectangular instead of normal.

14.2.5 A more probable estimate of the precision is obtained using the equation in 14.2.4 and the same example as used in 14.2.3 is the following:

$$\text{Precision of } \lambda = 2\sqrt{4.9 \times 10^{-3} + 3.3 \times 10^{-5} + 3.7 \times 10^{-6}} = 14\% \quad (8)$$

14.3 Bias:

14.3.1 The bias that can be attained using this test method depends upon two main items. First, the test method cannot be any more accurate than the method used to calibrate the HFT (for example, Test Methods C177, C335, or C518). In addition, any changes from the conditions under which the HFT was originally calibrated will result in a further inaccuracy.

14.3.2 Some areas where the measurement situation can vary from the calibration conditions are the following:

14.3.2.1 Determining a representative spot for the HFT.

14.3.2.2 A change in temperature with no or inadequate calibration coefficient compensation.

14.3.2.3 Use of HFT on top of pipe jacketing if it was calibrated under jacketing, or use in a different position or curvature than when calibrated.

14.3.2.4 Use of HFT on a surface with a different emittance than the surface used during calibration.

14.3.2.5 Inaccuracies resulting from the above have been shown to be significant.

14.3.3 An estimate of the bias includes an uncertainty from each 14.3.1 and 14.3.2, in addition to the uncertainties previously discussed under precision in 14.2.1 and 14.2.4.

14.3.4 Following the example in 14.2.3 a “worst case” estimate of the bias would be:

$$\begin{aligned}\text{Bias of } \lambda &= 15.3\% + 3\% + (\text{error of 14.3.2}) \\ &= 18.3\% + (\text{error of 14.3.2})\end{aligned}\quad (9)$$

where 3 % is assumed from a Test Method C335 calibration.

14.3.5 A more probable estimate of the bias would be:

$$\text{Bias of } \lambda = 2\sqrt{4.9 \times 10^{-3} + (0.03)^2 + (\text{error of 14.3.2})} \quad (10)$$

14.4 Examples:

14.4.1 A test was made using two HFTs on a Test Method C335 apparatus (5.1 cm of glass fiber insulation on a 7.6-cm pipe) by re-inserting each HFT 3 times in the same vicinity under the jacket.

	HFT No. 1	HFT No. 2
Precision	±10.6 %	±4.0 %
Bias		
at 150°C	+ 3.0 %	+ 9.3 %
at 200°C	−0.4 %	+ 8.0 %

where HFT No. 2 had a temperature compensating calibration coefficient.

14.4.2 A different type of spot HFT was used on a 193°C 7.6-cm pipe with 3.8 cm of calcium silicate insulation. A long term (one month) and a short term (24 h) test were made.

	Long Term	Short Term
Precision	±4.4 %	±10.3 %
Bias	−7.0 %	−11.1 %

14.4.3 Twenty-one measurements with belt HFTs on un-jacketed Test Method C335 equipment over the temperature range 94 to 191°F (34 to 88°C) gave readings within 5.5 % (at the 95 % 2-σ level) of the heat flux calculated from the calibrations using temperature coefficients. Bias of Test Method C335 is stated to be ± 3 %. Thus indoor measurements with the belt-type HFT tested are expected to be within 9 % of the true value at the 95 % confidence level. Outdoor measurements will be dependent upon weather and duration of the test.

15. Keywords

15.1 heat flux; heat flux transducer; industrial application; in situ measurement

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