Designation: C 335 – 05a$^{\epsilon 1}$

Standard Test Method for Steady-State Heat Transfer Properties of Pipe Insulation[1]

This standard is issued under the fixed designation C 335; 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.

This standard has been approved for use by agencies of the Department of Defense.

ϵ^1 NOTE—Adjunct references were corrected editorially in April 2006.

1. Scope

1.1 This test method covers the measurement of the steady-state heat transfer properties of pipe insulations. Specimen types include rigid, flexible, and loose fill; homogeneous and nonhomogeneous; isotropic and nonisotropic; circular or non-circular cross section. Measurement of metallic reflective insulation and mass insulations with metal jackets or other elements of high axial conductance is included; however, additional precautions must be taken and specified special procedures must be followed.

1.2 The test apparatus for this purpose is a guarded-end or calibrated-end pipe apparatus. The guarded-end apparatus is a primary (or absolute) method. The guarded-end method is comparable, but not identical to ISO 8497.

1.3 When appropriate, or as required by specifications or other test methods, the following thermal transfer properties for the specimen can be calculated from the measured data (see 3.2):

1.3.1 The pipe insulation lineal thermal resistance and conductance,

1.3.2 The pipe insulation lineal thermal transference,

1.3.3 The surface areal resistance and heat transfer coefficient,

1.3.4 The thermal resistivity and conductivity,

1.3.5 The areal thermal resistance and conductance, and

1.3.6 The areal thermal transference.

NOTE 1—In this test method the preferred resistance, conductance, and transference are the lineal values computed for a unit length of pipe. These must not be confused with the corresponding areal properties computed on a unit area basis which are more applicable to flat slab geometry. If these areal properties are computed, the area used in their computation must be reported.

NOTE 2—Discussions of the appropriateness of these properties to particular specimens or materials may be found in Test Method C 177, Test Method C 518, and in the literature (**1**).[2]

1.4 This test method allows for operation over a wide range of temperatures. The upper and lower limit of the pipe surface temperature is determined by the maximum and minimum service temperature of the specimen or of the materials used in constructing the apparatus. In any case, the apparatus must be operated such that the temperature difference between the exposed surface and the ambient is sufficiently large enough to provide the precision of measurement desired. Normally the apparatus is operated in closely controlled still air ambient from 15 to 30°C, but other temperatures, other gases, and other velocities are acceptable. It is also acceptable to control the outer specimen surface temperature by the use of a heated or cooled outer sheath or blanket or by the use of an additional uniform layer of insulation.

1.5 The use any size or shape of test pipe is allowable provided that it matches the specimens to be tested. Normally the test method is used with circular pipes; however, its use is permitted with pipes or ducts of noncircular cross section (square, rectangular, hexagonal, etc.). One common size used for interlaboratory comparison is a pipe with a circular cross section of 88.9-mm diameter (standard nominal 80-mm (3-in.) pipe size), although several other sizes are reported in the literature (**2-4**).

1.6 The test method applies only to test pipes with a horizontal or vertical axis. For the horizontal axis, the literature includes using the guarded-end, the calibrated, and the calibrated-end cap methods. For the vertical axis, no experience has been found to support the use of the calibrated or calibrated-end methods. Therefore the method is restricted to using the guarded-end pipe apparatus for vertical axis measurements.

1.7 This test method covers two distinctly different types of pipe apparatus, the guarded-end and the calibrated or calculated-end types, which differ in the treatment of axial heat transfer at the end of the test section.

1.7.1 The guarded-end apparatus utilizes separately heated guard sections at each end, which are controlled at the same

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[1] This test method 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 references at the end of this test method.

TABLE 1 Conversion Factors (International Table)

NOTE—For thermal conductance per unit length or thermal transference per unit length, use the inverse of the table for thermal resistance per unit length. For thermal resistivity, use the inverse of the table for thermal conductivity. For thermal conductance (per unit area) or thermal transference (per unit area), use the inverse of the table for thermal resistance (per unit area).

Thermal Resistance per Unit Length[A]

	K·m·W^{-1}(B)	K·cm·W^{-1}	K·cm·s·cal^{-1}	K·m·h·kg-cal^{-1}	°F·ft·h·Btu^{-1}
1 K·m·W^{-1} =	1.000	100.0	418.7	1.163	1.731
1 K·cm·W^{-1} =	1.000×10^{-2}	1.000	4.187	1.163×10^{-2}	1.731×10^{-2}
1 K·cm·s·cal^{-1} =	2.388×10^{-3}	0.2388	1.000	2.778×10^{-3}	4.134×10^{-3}
1 K·m·h·kg-cal^{-1} =	0.8598	85.98	360.0	1.000	1.488
1°F·ft·h·Btu^{-1} =	0.5778	57.78	241.9	0.6720	1.000

Thermal Conductivity[A]

	W·m^{-1}·K^{-1}(B)	W·cm^{-1}·K^{-1}	cal·s^{-1}·cm^{-1}·K^{-1}	kg-cal·h^{-1}·m^{-1}·K^{-1}	Btu·h^{-1}·ft^{-1}·°F^{-1}	Btu·in.·h^{-1}·ft^{-2}°F^{-1}
1 W·m^{-1}·K^{-1} =	1.000	1.000×10^{-2}	2.388×10^{-3}	0.8598	0.5778	6.933
1 W·cm^{-1}·K^{-1} =	100.0	1.000	0.2388	85.98	57.78	693.3
1 cal·s^{-1}·cm^{-1}·K^{-1} =	418.7	4.187	1.000	360.0	241.9	2903.
1 kg-cal·h^{-1}·m^{-1}·K^{-1} =	1.163	1.163×10^{-2}	2.778×10^{-3}	1.000	0.6720	8.064
1 Btu·h^{-1}·ft^{-1}·°F^{-1} =	1.731	1.731×10^{-2}	4.134×10^{-3}	1.488	1.000	12.00
1 Btu·in.·h^{-1}·ft^{-2}·°F^{-1} =	0.1442	1.442×10^{-3}	3.445×10^{-4}	0.1240	8.333×10^{-2}	1.000

Thermal Resistance per Unit Area[A]

	K·m^{2}·W^{-1}(B)	K·cm^{2}·W^{-1}	K·cm^{2}·s·cal^{-1}	K·m^{2}·h·kg-cal^{-1}	°F·ft^{2}·h·Btu^{-1}
1 K·m^{2}·W^{-1} =	1.000	1.000×10^{4}	4.187×10^{4}	1.163	5.678
1 K·cm^{2}·W^{-1} =	1.000×10^{-4}	1.000	4.187	1.163×10^{-4}	5.678×10^{-4}
1 K·cm^{2}·s·cal^{-1} =	2.388×10^{-5}	0.2388	1.000	2.778×10^{-5}	1.356×10^{-4}
1 K·m^{2}·h·kg-cal^{-1} =	0.8598	8.594×10^{3}	3.600×10^{4}	1.000	4.882
1°F·ft^{2}·h·Btu^{-1} =	0.1761	1.761×10^{3}	7.373×10^{3}	0.2048	1.000

[A] Units are given in terms of (*1*) the absolute joule per second or watt, (*2*) the calorie (International Table) = 4.1868 J, or the British thermal unit (International Table) = 1055.06 J.

[B] This is the SI (International System of Units) unit.

temperature as the test section to limit axial heat transfer. This type of apparatus is preferred for all types of specimens within the scope of this test method and must be used for specimens incorporating elements of high axial conductance.

1.7.2 The calibrated or calculated-end apparatus utilizes insulated end caps at each end of the test section to minimize axial heat transfer. Corrections based either on the calibration of the end caps under the conditions of test or on calculations using known material properties, are applied to the measured test section heat transfer. These apparatuses are not applicable for tests on specimens with elements of high axial conductance such as reflective insulations or metallic jackets. There is no known experience on using these apparatuses for measurements using a vertical axis.

1.8 SI units are standard for this test method. Conversion factors to other units are given in Table 1. The units used must accompany all numerical values.

1.9 *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.*

2. Referenced Documents

2.1 *ASTM Standards:* [3]

C 168 Terminology Relating to Thermal Insulation

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C 302 Test Method for Density and Dimensions of Preformed Pipe-Covering-Type Thermal Insulation

C 518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C 680 Practice for Estimate of Heat Gain or Loss, and Surface Temperature of Insulated Flat, Cylindrical, and Spherical Systems by the Use of a Computer Program

C 870 Practice for Conditioning of Thermal Insulating Materials

C 1045 Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions

E 230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

2.2 *ISO Standards:*

ISO 8497 Thermal Insulation-Dermination of Steady State Thermal Transmission Properties of Thermal Insulation for Circular Pipes

2.3 *ASTM Adjuncts:*[4]

Guarded-end Apparatus

Calibrated-end Apparatus

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[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.

[4] Documents showing details of both guarded-end and calibrated-end apparatus complying with the requirements of this method are available from ASTM for a nominal fee. Order Adjunct: ADJC033501 for the Guarded-End Apparatus and Adjunct: ADJC033502 for the Calibrated-End Cap Apparatus.

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology C 168.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *areal thermal conductance, C*—the steady-state time rate of heat flow per unit area of a specified surface (Note 3) divided by the difference between the average pipe surface temperature and the average insulation outer surface temperature. It is the reciprocal of the areal thermal resistance, *R*.

$$C = \frac{Q}{A(t_o - t_2)} = \frac{1}{R} \qquad (1)$$

where the surface of the area, *A*, must be specified (usually the pipe surface or sometimes the insulation outer surface).

NOTE 3—The value of *C*, the areal thermal conductance, is arbitrary since it depends upon an arbitrary choice of the area, *A*. For a homogeneous material for which the thermal conductivity is defined as in 3.2.7 (Eq 8), the areal conductance, *C*, is given as follows:

$$C = \frac{2\pi L\lambda_p}{A\ \ln\,(r_2/r_o)} \qquad (2)$$

If the area is specially chosen to be the "log mean area," equal to $2\pi L\ (r_2 - r_o)/\mathrm{l}\ n\ (r_2/r_o)$, then $C = \lambda_p/(r_2 - r_o)$. Since ($r_2 - r_o$) is equal to the insulation thickness measured from the pipe surface, this is analogous to the relation between conductance and conductivity for flat slab geometry. Similar relations exist for the areal thermal resistance defined in 3.2.2. Since these areal coefficients are arbitrary, and since the area used is often not stated, thus leading to possible confusion, it is recommended that these areal coefficients not be used unless specifically requested.

3.2.2 *areal thermal resistance, R*—the average temperature difference between the pipe surface and the insulation outer surface required to produce a steady-state unit rate of heat flow per unit area of a specified surface (Note 3). It is the reciprocal of the areal thermal conductance, *C*.

$$R = \frac{A(t_o - t_2)}{Q} = \frac{1}{C} \qquad (3)$$

where the surface of the area, *A*, must be specified (usually the pipe surface or sometimes the insulation outer surface).

3.2.3 *areal thermal transference,* T_r—the time rate of heat flow per unit surface area of the insulation divided by the difference between the average pipe surface temperature and the average air ambient temperature.

$$T_r = \frac{Q}{2\pi r^2 L\ (t_o - t_a)} \qquad (4)$$

3.2.4 *pipe insulation lineal thermal conductance,* C_L—the steady-state time rate of heat flow per unit pipe insulation length divided by the difference between the average pipe surface temperature and the average insulation outer surface temperature. It is the reciprocal of the pipe insulation lineal thermal resistance, R_L.

$$C_L = \frac{Q}{L(t_o - t_2)} = \frac{1}{R_L} \qquad (5)$$

3.2.5 *pipe insulation lineal thermal resistance,* R_L—the average temperature difference between the pipe surface and the insulation outer surface required to produce a steady-state unit time rate of heat flow per unit of pipe insulation length. It is the reciprocal of the pipe insulation lineal thermal conductance, C_L.

$$R_L = \frac{L(t_o - t_2)}{Q} = \frac{1}{C_L} \qquad (6)$$

3.2.6 *pipe insulation lineal thermal transference,* T_{r_p}—the steady-state time rate of heat flow per unit pipe insulation length divided by the difference between the average pipe surface temperature and the average air ambient temperature. It is a measure of the heat transferred through the insulation to the ambient environment.

$$T_{r_p} = \frac{Q}{L(t_o - t_a)} \qquad (7)$$

3.2.7 *pipe insulation thermal conductivity,* λ_p—of homogeneous material, the ratio of the steady-state time rate of heat flow per unit area to the average temperature gradient (temperature difference per unit distance of heat flow path). It includes the effect of the fit upon the test pipe and is the reciprocal of the pipe insulation thermal resistivity, r_L. For pipe insulation of circular cross section, the pipe insulation thermal conductivity is:

$$\lambda_p = \frac{Q\ 1n\ (r_2/r_o)}{L2\pi(t_o - t_2)} = \frac{1}{r_L} \qquad (8)$$

3.2.8 *pipe insulation thermal resistivity,* r_L—of homogeneous material, the ratio of the average temperature gradient (temperature difference per unit distance of heat flow path) to the steady-state time rate of heat flow per unit area. It includes the effect of the fit upon the test pipe and is the reciprocal of the pipe insulation thermal conductivity, λ_p. For pipe insulation of circular cross section, the pipe insulation thermal resistivity is calculated as follows:

$$r_L = \frac{2\pi L(t_o - t_2)}{Q\ 1n\ (r_2/r_o)} = \frac{1}{\lambda_p} \qquad (9)$$

3.2.9 *surface areal heat transfer coefficient,* h_2—the ratio of the steady-state time rate of heat flow per unit surface area to the average temperature difference between the surface and the ambient surroundings. The inverse of the surface heat transfer coefficient is the surface resistance. For circular cross sections:

$$h_2 = \frac{Q}{2\pi r^2 L(t_2 - t_a)} \qquad (10)$$

3.3 *Symbols:* see 1.8:

C_L = pipe insulation lineal thermal conductance, W/m·K,
R_L = pipe insulation lineal thermal resistance, K·m/W,
T_{r_p} = pipe insulation lineal thermal transference, W/m·K,
λ_p = pipe insulation thermal conductivity, W/m·K,
r_L = pipe insulation thermal resistivity, K·m/W,
h_2 = surface areal heat transfer coefficient of insulation outer surface, W/m^2·K,
C = areal thermal conductance, W/m^2·K,
R = areal thermal resistance, K·m ^{2}/W,
T_r = areal thermal transference, W/m^2·K,
Q = time rate of heat flow to the test section of length *L*, W,
t_o = temperature of pipe surface, K,

t_1 = temperature of insulation inside surface, K,

t_2 = temperature of insulation outside surface, K,

t_a = temperature of ambient air or gas, K,

r_o = outer radius of circular pipe, m,

r_1 = inner radius of circular insulation, m,

r_2 = outer radius of circular insulation, m,

L = length of test section (see 8.1.1), m, and

A = area of specified surface, m^2.

4. Significance and Use

4.1 As determined by this test method, the pipe insulation lineal thermal resistance or conductance (and, when applicable, the thermal resistivity or conductivity) are means of comparing insulations which include the effects of the insulation and its fit upon the pipe, circumferential and longitudinal jointing, and variations in construction, but do not include the effects of the outer surface resistance or heat transfer coefficient. They are thus appropriate when the insulation outer-surface temperature and the pipe temperature are known or specified. However, since the thermal properties determined by this test method include the effects of fit and jointing, they are not true material properties. Therefore, properties determined by this test method are somewhat different from those obtained on apparently similar material in flat form using the guarded hot plate, Test Method C 177, or the heat flow meter apparatus, Test Method C 518.

4.2 The pipe insulation lineal thermal transference incorporates both the effect of the insulation and its fit upon the pipe and also the effect of the surface heat-transfer coefficient. It is appropriate when the ambient conditions and the pipe temperature are known or specified and the thermal effects of the surface are to be included.

4.3 Because of the test condition requirements prescribed in this test method, recognize that the thermal transfer properties obtained will not necessarily be the value pertaining under all service conditions. As an example, this test method provides that the thermal properties shall be obtained by tests on dry or conditioned specimens, while such conditions are not necessarily realized in service. The results obtained are strictly applicable only for the conditions of test and for the product construction tested, and must not be applied without proper adjustment when the material is used at other conditions, such as mean temperatures that differ appreciably from those of the test. With these qualifications in mind, the following apply:

4.3.1 For horizontal or vertical pipes of the same size and temperature, operating in the same ambient environment, values obtained by this test method can be used for the direct comparison of several specimens, for comparison to specification values, and for engineering data for estimating heat loss of actual applications of specimens identical to those tested (including any jackets or surface treatments). When appropriate, correct for the effect of end joints and other recurring irregularities (4.4).

4.3.2 When applying the results to insulation sizes different from those used in the test, an appropriate mathematical analysis is required. For homogeneous materials, this consists of the use of the thermal conductivity or resistivity values (corrected for any changes in mean temperature) plus the use of the surface heat transfer coefficient when the ambient temperature is considered (for example, see Practice C 680). For nonhomogeneous and reflective insulation materials, a more detailed mathematical model is required which properly accounts for the individual modes of heat transfer (conduction, convection, radiation) and the variation of each mode with changing pipe size, insulation thickness, and temperature.

4.4 It is difficult to measure the thermal performance of reflective insulation that incorporate air cavities, since the geometry and orientation of the air cavities can affect convective heat transfer. While it is always desirable to test full-length pipe sections, this is not always possible due to size limitations of existing pipe insulation testers. If insulation sections are tested less than full length, internal convective heat transfer are usually altered, which would affect the measured performance. Therefore, it must be recognized that the measured thermal performance of less than full-length insulation sections is not necessarily representative of full-length sections.

4.5 The design of the guarded-end pipe apparatus is based upon negligible axial heat flow in the specimen, the test pipe, heaters, and other thermal conductive paths between the metering and guard sections. Some nonhomogeneous and reflective insulation are usually modified at the end over the guard gap in order to prevent axial heat flow. While these modifications are not desirable and should be avoided, for some nonhomogeneous insulation designs, they provide the only means to satisfy the negligible heat flow assumption across the guard gaps. Therefore, thermal performance measured on insulation specimens with modified ends are not necessarily representative of the performance of standard insulation sections.

4.6 It is acceptable to use this test method to determine the effect of end joints or other isolated irregularities by comparing tests of two specimens, one of which is uniform throughout its length and the other which contains the joint or other irregularity within the test section. The difference in heat loss between these two tests, corrected for the uniform area covered by the joint or other irregularity, is the extra heat loss introduced. Care must be taken that the tests are performed under the same conditions of pipe and ambient temperature and that sufficient length exists between the joint or irregularity and the test section ends to prevent appreciable end loss.

4.7 For satisfactory results in conformance with this test method, the principles governing construction and use of apparatus described in this test method should be followed. If the results are to be reported as having been obtained by this test method, then all the pertinent requirements prescribed in this test method shall be met or any exceptions shall be described in the report.

4.8 It is not practical in a test method of this type to establish details of construction and procedure to cover all contingencies that might offer difficulties to a person without technical knowledge concerning the theory of heat flow, temperature measurements, and general testing practices. Standardization of this test method does not reduce the need for such technical knowledge. It is recognized also that it would be unwise to restrict the further development of improved or new methods or procedures by research workers because of standardization of this test method.

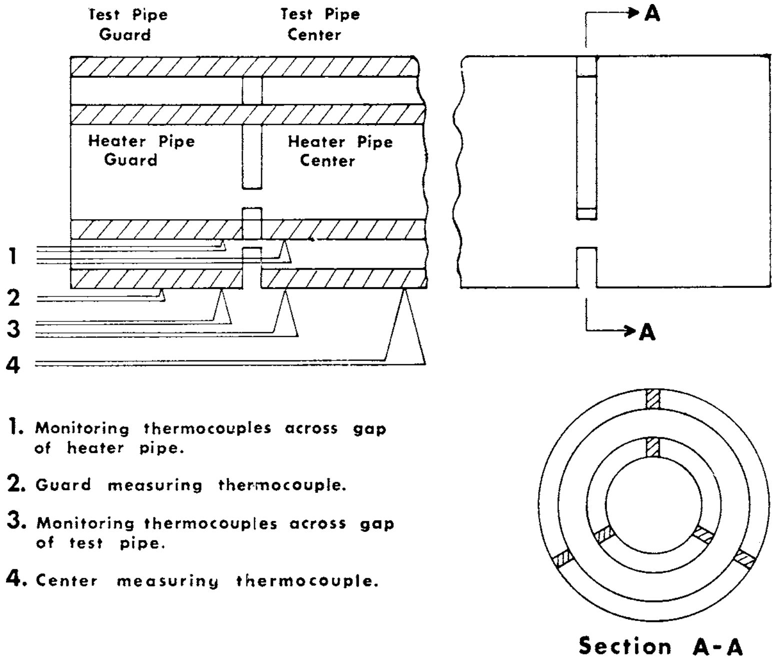


FIG. 1 Guarded-End Apparatus

NOTE 4—When testing at ambient temperatures below normal room temperatures, theoretical analysis shows that the experimental heat flow direction is unimportant for a perfectly homogenous material. However, if the properties of the insulation vary in the radical direction, the experimental heat flow direction will significantly affect the measured thermal conductivity. Exercise great care when using data from a radial heat flow outward experiment for a radial heat flow inward application.

5. Apparatus

5.1 The apparatus shall consist of the heated test pipe and instrumentation for measuring the pipe and insulation surface temperatures, the average ambient air temperature, and the average power dissipated in the test section heater. The pipe shall be uniformly heated by an internal electric heater (Notes 5 and 6). In large apparatus, give some consideration on providing internal circulating fans or to filling the pipe with a heat transfer fluid to achieve uniform temperatures. The guarded end design also requires, a short section of pipe at each end of the test section, with its own separately controlled heater (see 5.3 and Fig. 1). The calibrated or calculated-end design requires suitable insulated caps at each end (see 5.4 and Fig. 2). An essential requirement of the test is an enclosure or room equipped to control the temperature of the air surrounding the apparatus. The apparatus shall conform to the principles and limitations prescribed in the following sections, but it is not intended in this test method to include detailed requirements for the construction or operation of any particular apparatus.[4]

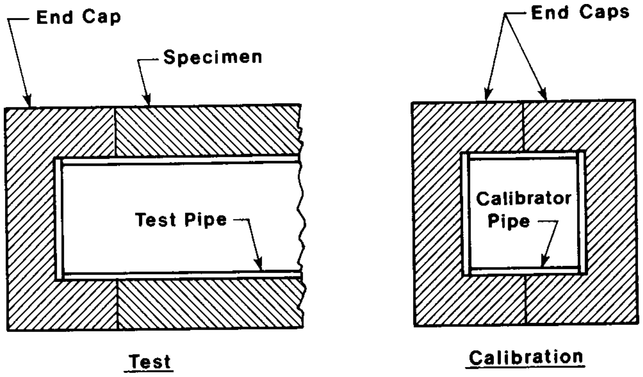
NOTE 5—Experiments have been reported that use an electrically heated cylindrical screen rather than an internally heated pipe (5). An extension of the heated screen technique has been reported (6) for testing below normal temperatures using the radial heat flow inward, similar to some insulation system applications. While these designs and the accompanying analysis are not included in this test method, their findings are pertinent to this standard.

NOTE 6—The most commonly used heater consists of electrical resistance wire or ribbon on the surface or in the grooves of a tubular ceramic core that is internal to the test pipe. If the heater fits snugly inside the test pipe, the contact must be uniform to achieve uniform test pipe temperatures. If the heater core is smaller than the inside diameter of the pipe, then fill the gap with a material such as sand to provide uniform heat transfer. In this standard the combination of heater winding and heater pipe will be called either a "heater" or a "heater pipe."

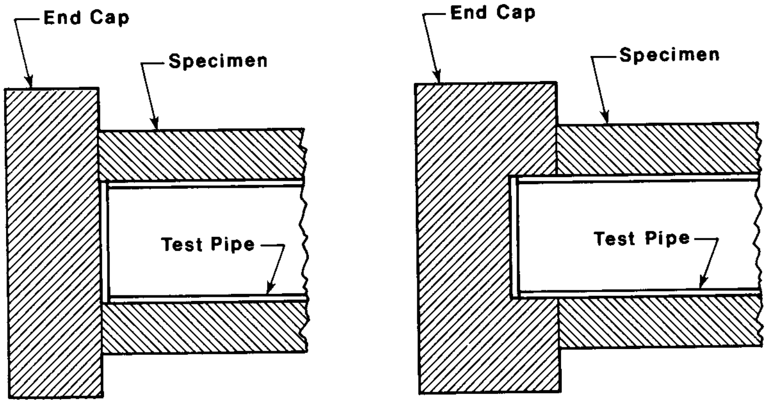
5.2 *Apparatus Pipe*, no restriction is placed on the cross section size or shape, but the length of the test section must be sufficient to ensure that the total measured heat flow is large enough, when compared to end losses and to the accuracy of the power measurement, to achieve the desired test accuracy (see 5.3 and 8.4). A test section length of approximately 0.5 m has proven satisfactory for an apparatus with a circular cross-section of 88.9 mm (standard 80-mm, (3-in.) pipe size) that is often used for inter-laboratory comparisons. Do not assume that this length is satisfactory for all sizes of apparatus and for all test conditions. Estimates of the required length must be made from an appropriate error analysis. As a convenience, it is recommended that the apparatus be constructed to accept an integral number of standard lengths of insulation.

5.3 *Guarded-End Apparatus* (Fig. 1), uses separately heated pipe sections at each end of the test section to accomplish the purposes of minimizing axial heat flow in the apparatus, of aiding in achieving uniform temperatures in the test section, and of extending these temperatures beyond the test section length so that all heat flow in the test section is in the radial direction. Both test and guard section heaters shall be designed to achieve uniform temperatures over the length of each section. This typically requires the use of auxiliary heaters at the outside ends of single guards or the use of double guards.

5.3.1 The length of the guard section (or the combined length of double guards) shall be sufficient to limit at each end of the test section the combined axial heat flow in both



CALIBRATED END APPARATUS



ALTERNATE CONFIGURATIONS
CALCULATED END APPARATUS

FIG. 2 Calibrated or Calculated-End Apparatus

apparatus and specimen to less than 1% of the test section measured heat flow. A guard section length of approximately 200 mm has been found satisfactory for apparatus of 88.9 mm (standard nominal 80-mm (3-in.) pipe size) when testing specimens that are essentially homogeneous, are only moderately nonisotropic, and are of a thickness not greater than the pipe diameter. Longer guard sections are usually required when testing thicker specimens or when the specimen possesses a high axial conductance.

5.3.2 A gap shall be provided between the guards and the test section, and between each guard section if double-guarded, in both the heater pipe and the test pipe (except for small bridges necessary for structural support). It is highly desirable that all support bridges of high conductance be limited to the test pipe since any bridges in heater pipes or internal support members make it difficult or impossible to achieve uniform surface temperatures while at the same time minimizing end losses in the apparatus. Internal barriers shall be installed at each gap to minimize convection and radiation heat transfer between sections.

5.3.3 Thermocouples of wire as small as possible but not larger than 0.64 mm (22 Awg) and meeting the requirements of 5.11, shall be installed in the test pipe surface on both sides of each gap, and not more than 25 mm from the gap, for the purpose of monitoring the temperature difference across each gap. It is acceptable to connect the thermocouples in series and use as a differential thermopile. Similar thermocouples shall also be installed on any heater pipes or support members that provide a highly conductive path from test section to guard sections.

5.4 *Calibrated or Calculated-End Apparatus* (Fig. 2), uses insulated caps at each end of the test section to minimize axial heat flow. The measured test section heat loss is then corrected for the end cap loss, that has been determined either by direct calibration under the conditions of test (the calibrated-end apparatus) or by calculation, using known material properties (the calculated-end apparatus). Internal electric heaters shall be provided to heat the test section uniformly over its length. It is usually necessary to provide supplementary internal heaters at each end to compensate for the end heat loss. The power to such heaters must be included in the measured test section power.

5.4.1 For the calibrated-end apparatus, the end caps shall be of the same cross-section as the test specimen and have approximately the same thermal transfer properties. Each end cap shall have a cavity of minimum depth equal to one half the test pipe diameter (or one half the major cross-section diagonal of noncircular pipes) and of a size and shape to accept the end of the test pipe. The calibrator pipe shall consist of a short section of the same pipe used to construct the test pipe of a length equal to the combined cavity depth of the two end caps. It shall be fitted with internal heaters similar to those used in the end sections of the test pipe including any supplementary end heaters. A minimum of four thermocouples spaced 90° apart shall be provided in the surface of the calibrator pipe to measure its temperature. They shall meet the requirements of 5.5.1 and be of a wire size as small as possible but in no case larger than 0.64 mm diameter (22 Awg).

5.4.2 For the calculated-end apparatus, the end caps shall be as large or larger than the test specimen. They shall be made of homogeneous insulation material of low conductivity and may or may not have a cavity for the test pipe end. The thermal conductivity of the end cap material shall be determined by Test Method C 177 or Test Method C 518 over the temperature range of contemplated use. If the material is not isotropic, the thermal conductivity must be determined in different directions as needed.

5.5 *Thermocouples*, for measuring the surface temperature of the test pipe shall meet the requirements of 5.5.1 and be of a wire size as small as possible, but in no case larger than 0.64 mm (22 Awg) in diameter.[5] At least four thermocouples, or one for each 150 mm of length of the test section, whichever is greater, shall be located to sense equally the temperature of all areas of the test section surface. They shall be applied either by peening the individual wires into small holes drilled into the pipe surface not more than 3 mm apart or by joining the wires by a welded bead and cementing them into grooves so that the bead is tangent to the outer surface of the pipe, but does not project above the surface. For direct averaging, it is acceptable to connect the thermocouples in parallel, provided their junctions are electrically isolated and the total resistances are essentially equal.

5.5.1 Thermocouples used for this method shall be made of special grade wire as specified in Tables E 230 or shall be individually calibrated to the same tolerance. Generally, thermocouples made from wire taken from the same spool will be found to agree with each other within the required tolerance and thus only one calibration will be required for each spool of wire.

5.6 *Temperature-Measuring System*, excluding the sensor, with an accuracy equivalent to ±0.1 K. A d-c potentiometer or digital microvoltmeter is normally used for thermocouple readout.

5.7 *Power Supplies*, use a closely regulated a-c or d-c supply for operating the test section heater. Power supplies for guard heaters, if used, need not be regulated if automatic controllers are used.

5.8 *Power-Measuring System*, capable of measuring the average power to the test section heater with an accuracy of ± 0.5% shall be provided. If power input is steady, this is typically a calibrated wattmeter or a voltage-measuring system for voltage and amperage (using a standard resistance). If power input is variable or fluctuating, an integrating type of power measurement, using an integrating period long enough to assure a reliable determination of average power, is required. In all cases, care must be taken that the measured power is only that dissipated in the test section. This requires that corrections be applied for power dissipated in leads, dropping resistors, or uncompensated wattmeters.

5.9 For a given set of observations as defined in 8.4 the ambient air temperature shall be maintained within ± 1% of the smallest temperature difference between the test pipe and the ambient or to ± 1°C, whichever is greater. The apparatus shall be located in a region of essentially still air and shall not be close to other objects that would alter the pattern of natural convection around the heated specimen. All surfaces or objects that could exchange radiation with the specimen shall have a total hemispherical emittance of at least 0.85 and shall be at approximately the same temperature as the ambient air. Additional optional equipment is required to use gases other than air and to simulate wind effects by establishing forced air velocities of the direction and magnitude desired.

5.10 An optional temperature-controlled jacket is an acceptable procedure to control the outer surface of the specimen to a temperature different than that of the ambient air. An alternative procedure for raising the outer surface temperature of a specimen is to surround it with an additional layer of thermal insulation. In either case the thermocouples specified in 6.5 for the measurement of the specimen outer surface temperature must be installed prior to placement of the jacket or additional insulation layer. Moreover, the emittance of the inner surface of the jacket or added insulation (facing the specimen) must be greater than 0.8 in order not to reduce any radiation transfer within the specimen. In such cases it is not possible to measure directly the thermal transference for the specimen.

6. Test Specimen

6.1 Specimens types include rigid, semi-rigid, or flexible (blanket-type), or loose-fill, suitably contained. Specimens shall be uniform in size and shape throughout their length (except for any intentional irregularities that occur well within the test section) and shall be designed for use on pipes of the same size and shape as the available test apparatus.

6.2 If test results are to be considered as representative of a type of product or of a particular production lot, etc., or of a material (in the case of homogeneous materials), then appropriate sampling plans must be followed. In the absence of such plans, the test results can be considered to represent only the specimens tested.

6.3 The intended purpose of the test must be considered in determining details of the specimen and its applications to the test pipe (Note 7). Some considerations are:

6.3.1 The means of securing the specimen to the test pipe.

6.3.2 The use of sealants or other materials in the joints.

6.3.3 Whether jackets, covers, bands, reflective sheaths, etc., are included.

6.3.4 For the testing of reflective insulation, there are additional considerations. It is recommended that at least two insulation sections be mounted within the central test section. While the use of full length specimens within the central test section is preferred, this may not be practical within the limits of existing apparatus. Air exchange must not occur between the test and guard sections. Install a fibrous or other airtight, low

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[5] Any temperature-measuring sensor can be used, but thermocouples are used predominantly.

conductivity, nonmetallic insulation seal, not more than 25 mm wide, between the hot pipe and specimen inner casing to prevent air exchange within this annular space. This seal must be installed in the guard region adjacent to the guard gap and not in the central test section.

NOTE 7—Unless another purpose is intended, secure the specimen to the test pipe in accordance with normal application practice. Include jackets and other features when desired.

6.4 After the specimen is mounted on the test pipe, measurements of the outside dimensions needed to describe the shape shall be made to within ± 0.5% (both before and after testing). For circular shapes, measurements an acceptable procedure is to use a flexible steel tape to obtain the circumference which is divided by 2π to obtain the radius r_2. The test section length shall be divided into at least four equal parts, and dimension measurements shall be taken at the center of each, except that any irregularity being investigated shall be avoided. Additional measurements shall be taken to describe the irregularities. For guarded-end apparatuses, additional measurements at the center of each guard section are also required. Specimens intended to be of uniform cross section dimensions throughout their length should be rejected if any individual dimension measurement (test section or guard) differs from the average of the test section measurements by more than 5%.

6.5 Thermocouples for the measurement of the average outside surface temperature, t_2, shall be attached to the insulation surface in accordance with the following:

6.5.1 The test section length shall be divided into at least four equal parts and surface thermocouples shall be longitudinally located at the center of each. Large apparatuses will require a greater number of thermocouples. For circular shapes, the thermocouples shall also be circumferentially equally spaced to form helical patterns with an integral number of complete revolutions and with the angular spacing between adjacent locations from 45 to 90°. For non-circular shapes, the thermocouples shall be spaced around in much the same manner but located to obtain an area-weighted average. Any of the above specified locations shall, whenever possible, be offset a distance equal to the specimen thickness from any joint or other irregularity, and additional thermocouples shall be used as necessary to record the surface temperature. In such situations the individual temperatures and locations shall be reported (see 11.1.6).

6.5.2 Thermocouples shall be made of wire not larger than 0.40 mm (26 Awg) and shall meet the requirements of 5.5.1. They shall be fastened to the surface by any means that will hold the junction and the required length of adjacent wire in intimate thermal contact with the surface but does not alter the radiation emittance characteristics of the adjacent surface.

6.5.2.1 For nonmetallic surfaces, a minimum of 100 mm of adjacent wire shall be held in contact with the surface. One satisfactory method of fastening is to use masking tape either adhered to the specimen surface or wrapped around the specimen and adhered to itself.

6.5.2.2 For metallic surfaces, a minimum of 10 mm of adjacent lead wire shall be held in contact with the surface. Acceptable means of fastening thermocouple junctions are by peening, welding, soldering or brazing, or by use of metallic tape of the same emittance as the surface. Capacitive discharge welding is especially recommended. Small thin strips of metal similar to the surface metal shall be welded to the surface to hold the lead wire in contact with the surface.

6.5.3 The average surface temperature is calculated by averaging the individual readings of the surface thermocouples. If desired, measure the average by directly connecting the thermocouples in parallel, provided that the junctions are electrically isolated and the total electrical resistances are essentially equal.

6.6 Thermocouples meeting the requirements of 5.5.1 shall be installed on elements of high axial heat conductance such as metallic jackets or accessible liners (specimens with such elements must be tested on a guarded-end apparatus) in order to measure axial temperature gradients needed to compute axial heat transfer. These thermocouples shall be installed at both top and bottom locations, and shall be located an equal distance of approximately 45 mm on each side of the gap between the test section and each guard.

7. Conditioning

7.1 In general, specimens shall be dried or otherwise conditioned to stable conditions immediately prior to test unless it has been shown that such procedures are unnecessary to achieve reproducible results for the material being tested. When applicable, follow the conditioning procedures of the materials specification; otherwise, the normal procedure is to dry to constant weight at a temperature of 102 to 120°C, unless the specimen is adversely affected, in which case drying in a desiccator from 55 to 60°C is recommended (see Practice C 870). When desired, report any weight changes due to conditioning. Determine specimen density by Test Method C 302.

7.2 During the experimentation, operate the apparatus in a controlled room or enclosure so that the ambient temperature does not vary during a test by more than ± 1°C or ± 1% of the difference between the test pipe and the ambient ($t_o - t_a$), whichever is greater. Run the test in essentially still air (or other desired gas) unless appreciable velocity is needed to attain uniform temperatures or when the effect of air velocity is to be included as part of the test conditions. Measure any forced velocity and report its magnitude and direction.

8. Procedure

8.1 Measure the test section length, L, and the specimen outside circumference or other dimensions needed to describe the shape. Normally dimensions used in this method shall be those measured at ambient temperatures of 10 to 35°C. If properties based upon actual dimensions at operating temperature are desired, determine the dimensions by calculation from those measured at ambient temperature using previously measured or known coefficients of thermal expansion, or directly measure the dimensions at operating temperature. Any properties based upon dimensions at operating temperature must be so identified.

8.1.1 For guarded-end pipes, the test length, L, is the distance between the centerlines of the gaps at the ends of the test section. For calibrated or calculated-end pipes, the test length, L, is the distance between the end caps.

8.1.2 Take outside dimensions of the specimen at locations described in 6.4.

8.2 Adjust the temperature of the test pipe (or the test section of a guarded-end apparatus) to the desired temperature.

8.3 When using the guarded-end method, adjust the temperature of each guard so that the temperature difference across the gap between the test section and the guard (measured on the surface of the test pipe) is zero or not greater than the amount that will introduce an error of 1% in the measured heat flow. Ideally, the axial temperature gradient across the gaps between the test and guard sections of both the outer test pipe and the internal heater pipe and along any internal support members is zero to eliminate all axial heat flow within the pipe. In some designs, it is impossible to balance both surface and internal elements at the same time, and it will be necessary to correct for internal apparatus axial losses. When the only support bridges are in the outer test pipe, it is sufficient to bring the test pipe surface gap balance (between test section and guards) to zero and no corrections are needed. When the apparatus uses internal support bridges, it is necessary to use the readings of the internal thermocouples specified in 5.3, along with the known dimensions and properties of the support bridges, to estimate the internal axial losses that must be added to (or subtracted from) the measured power input to the test section. In either case it is often desirable to run two tests, one with the temperature of the guards slightly higher than the test section and one with it slightly lower. Interpolation between these gives an accurate value for the zero balance heat flow along the internal bridges and for the test section power input and provides information on the maximum allowable imbalance that still meets the 1% criterion. One criterion which has often been used is that the allowable imbalance is no greater than 0.5% of the temperature drop through the specimen, $(t_2 - t_1)$. This must be verified using the above procedure at the conditions of the test.

8.3.1 When evaluating reflective insulation, measure the temperature gradients along the interior and exterior casings with thermocouples detailed in 6.6. Compute the axial heat conduction along the inner and outer casings from the average gradients for that casing. Using the average of the four gradients, compute the total axial heat conduction for all internal liners. The total axial heat flow for each end of the test section should not exceed ±1% of the heat input to the heater in the test section.

8.4 Conduct the test as follows:

8.4.1 Thermal steady state must be achieved for this test method to be valid. To determine if steady state is achieved, the operator must document steady state by time averaging the data, computing the variation and performing the following tests on the data taken.

8.4.2 Thermal steady state for the purpose of this test method is defined analytically as:

8.4.2.1 The temperature of the hot surface is stable within the capability of the equipment at the test conditions. Ideally, an error analysis will determine the magnitude of the allowable variation, however the variation is usually less than 1 % of the expected hot surface temperature.

8.4.2.2 The power to the metering area is stable within the capability of the equipment at the test conditions. Ideally, an error analysis will determine the magnitude of the allowable variation. However the variation is usually less than 0.2 % of the average result expected.

8.5 After steady-state conditions have been attained, determine:

8.5.1 The average temperature of the pipe test section, t_o,

8.5.2 The test section to guard balances (for guarded-end apparatuses),

8.5.3 The average temperature of the specimen outer surface, t_2,

8.5.4 The average ambient air temperature, t_a, and, if forced air is used, the air velocity, and

8.5.5 The average electrical power to the test section heater measured over a minimum 30-min period.

8.6 Continue the observations until at least three successive sets of observations of minimum 30-min duration give thermal transfer properties not changing monotonically and not differing by more than 0.5 %. Use more stringent requirements when required.

9. End Cap Corrections

9.1 Corrections are required for the heat loss through the end caps of calibrated or calculated-end apparatuses, but are not required for the guarded-end apparatus. These corrections, in watts, are obtained either by calibration or calculation of the end cap heat loss and are to be subtracted from the power measured during specimen tests under the same conditions.

9.2 Calibrated-end apparatuses require calibration of the end caps over a range of temperatures that cover the conditions of intended use. It is convenient to run at least three or four calibrations at approximately equally spaced pipe temperatures and to plot a curve of electrical power versus temperature difference between the pipe and the ambient air. Obtain separate calibration curves for each ambient temperature. If the test apparatus is to be used at only one set of conditions, then it is acceptable to interpolate between two tests run in the same ambient but with the calibrator pipe slightly above and slightly below the desired temperature. The procedure for end cap calibration is as follows:

9.2.1 Assemble the end caps to the calibrator pipe and seal the crack with glass fiber or other suitable sealant. Connect the power and thermocouple leads.

9.2.2 Adjust the power input to the heater to achieve the desired temperature. After steady-state conditions are attained, make the necessary observations to determine the following:

9.2.2.1 The temperature of the calibrator pipe,

9.2.2.2 The temperature of the ambient air, and

9.2.2.3 The average electrical power over a minimum 30-min period.

9.2.3 Continue the observations until at least three successive sets of measurements of minimum 30-min duration give heat transfer properties not changing monotonically or more than 0.5%. In some cases, more stringent requirements are necessary.

9.3 Calculated-end apparatuses require detailed mathematical calculation (such as a finite element analysis) of the heat loss under the conditions of test using known thermal properties of the end cap materials. Determine the material thermal properties on flat specimens taken from the same lot of material used to construct the end caps, data obtained on other similar material if estimates show that the expected error in corrected test heat loss due to any uncertainty in materials properties is well within the allowable test uncertainty. Measurements of material thermal properties shall be made either by the guarded hot plate, Test Method C 177, or by the heat flow meter, Test Method C 518, and must be taken in all pertinent directions if the material is not isotropic.

10. Calculation

10.1 Calculate the corrected test section power input, Q, from the measured power input as follows:

10.1.1 For guarded-end apparatus with no internal support bridges—no correction needed.

10.1.2 For guarded-end apparatus with internal support bridges, follow the procedure described in 8.3 using measured support gradients, dimensions, and material properties.

10.1.3 For calibrated-end apparatus, use the calibration corrections developed in 9.2.

10.1.4 For calculated-end apparatus, use the corrections developed in 9.3.

10.2 Calculate the heat transfer properties for each of the three or more observations required in 8.5.2 or in 9.2.2 and average the values of those differing by no more than 1% for reporting in 11.1.8. For pipes of circular cross section, make calculations for those properties desired as follows:

10.2.1 Calculate the pipe insulation lineal thermal conductance, C_L, by means of Eq 5 (see 3.2.4).

10.2.2 Calculate the pipe insulation lineal thermal resistance, R_L, by means of Eq 6 (see 3.2.5).

10.2.3 Calculate the pipe insulation lineal thermal transference, T_{rp}, by means of Eq 7 (see 3.2.6).

10.2.4 Calculate the surface areal heat transfer coefficient, h_2, by means of Eq 10 (see 3.2.9).

10.2.5 When applicable, calculate the pipe insulation thermal conductivity, λ_p, from Eq 8 (see 3.2.7). The thermal conductivity for a large temperature difference is not, in general, the same as that for a small temperature difference at the same mean temperature. When conductivities are measured at three or more mean temperatures, a correction can be made to account for the large temperature difference. Use the guidelines in Practice C 1045 to make the correction.

10.2.6 When applicable, calculate the pipe insulation thermal resistivity, r_p, from Eq 9 (see 3.2.8).

10.2.7 When applicable, calculate the areal thermal resistance, conductance and transference from Eq 2-4 (see 3.2.1-3.2.3).

11. Report

11.1 The report shall describe the test specimens, the sampling and test procedures, the test apparatus, and the results. Whenever numerical values are reported, both SI and inch-pound units shall be stated. The appropriate items of those listed below shall be included:

11.1.1 Sample description and other identification including the trade and manufacturer's name, the generic type of material, the date of manufacture, the procurement date and source, the nominal size and shape, and when desired, the nominal weight and density. Also include observations of specimen condition including any unusual details both before and after test.

11.1.2 Measured dimensions and, when obtained, the measured weight and density both before and after test. If dimensions are at temperatures other than ambient, the temperature and the means of obtaining the dimensions must be reported.

11.1.3 Description of the application and means of securing the sample to the test pipe including the number, type, and location of any bands or fasteners, the type of jacket or cover if used, and the type and location of any sealants used.

11.1.4 Description of any conditioning or drying procedures followed and, when obtained, the weight, density, or dimensional changes due to conditioning or drying.

11.1.5 Average temperature of the pipe test section, t_o.

11.1.6 Average temperature of the specimen outside surface, t_2, and for irregular specimens, the readings and positions of thermocouples used to describe uneven surface temperatures (see 6.5.1).

11.1.7 The type of ambient gas, its average temperature, t_a, and when forced, the velocity (both magnitude and direction) or details of other means of controlling outer temperature such as extra insulation or temperature-controlled sheath or blankets.

11.1.8 The corrected test section power input, Q.

11.1.9 The desired thermal transfer properties, including any or all of the following when applicable and the corresponding mean temperature, $(t_o + t_2)/2$. These shall be the averages calculated in 8.4:

11.1.9.1 Pipe insulation lineal thermal conductance, C_L,

11.1.9.2 Pipe insulation lineal thermal resistance, R_L,

11.1.9.3 Pipe insulation lineal thermal transference, T_{r_p},

11.1.9.4 Pipe insulation thermal conductivity, λ_p, or the corrected pipe insulation thermal conductivity when available,

11.1.9.5 Pipe insulation thermal resistivity, r_L,

11.1.9.6 Insulation surface areal heat transfer coefficient, h_2,

11.1.9.7 Areal thermal conductance, C, with the surface referenced,

11.1.9.8 Areal thermal resistance, R, with the surface referenced,

11.1.9.9 Areal thermal transference T_r, with the surface referenced, and

11.1.10 When more than one measurement is made, report if measurements started at the lowest mean temperature and progressed to the maximum test temperature, or started at the highest reported temperature and progressed to the lowest temperature.

11.1.11 Estimates of error of the test results.

11.1.12 Any exceptions made in the test method.

11.1.13 Outlines of, or references to, any special calculations used.

11.2 Graphical representations of results obtained over a temperature range are useful and should be included when applicable. Recommended plots are:

11.2.1 Pipe insulation lineal thermal conductance or resistance, and when applicable, thermal conductivity or resistivity versus mean temperature, $(t_o + t_2)/2$.

11.2.2 Pipe insulation lineal thermal transference versus overall temperature difference, $(t_o - t_a)$.

12. Precision and Bias [6]

12.1 Three interlaboratory round-robin comparison programs have been conducted by ASTM Subcommittee C16.30 to determine the reproducibility of this test method.

12.1.1 Tests performed at several laboratories on a single sample of glass fiber insulation in the range, of mean temperatures from 60 to 160°C and reported in Hollingsworth (**7**), shows that the measured heat transfer properties should not vary by more than ± 3% of the average.

12.1.2 Tests performed at three laboratories on similar samples of reflective insulation over the hot surface temperature range of 149 to 482°C shows that the heat-transfer properties of reflective insulation materials should not vary by more than ± 7 % of the average.

12.1.3 Tests were performed at seven different laboratories using guarded-end horizontal pipe test apparatus on similar samples of preformed mineral fiber pipe insulation. The hot surface temperature range was 46 to 670°C. The maximum deviation from the average was + 10 % and – 9 % (**8**).

12.1.4 Tests performed at seven different laboratories using the horizontal guarded-end apparatus and at one laboratory using an unguarded cylindrical screen test apparatus on two samples of calcium silicate insulation in the range of mean temperatures from 35 to 390°C did not vary by more than 6.3 % of the average (**9**).

12.2 The behavior of this test method outside the reported conditions is unproven, and additional comparisons at higher temperatures are recommended when suitable high-temperature standards are developed. For nonhomogeneous and reflective insulations, the precision of measurements in the vertical orientation is expected to be comparable to the horizontal orientation. The bias in the vertical orientation is expected to be somewhat poorer than the horizontal orientation due to the difficulty in maintaining proper guarding of the central test specimens in the vertical orientation.

12.3 The task group will continue to address the issues of using this method for testing at temperatures below ambient as information becomes available.

13. Keywords

13.1 apparent thermal conductivity; experimental design; radial heat transfer; steady state heat transfer; thermal resistance

ANNEX

(Mandatory Information)

A1. MEASUREMENT UNCERTAINTY

NOTE A1.1—The uncertainty of the apparatus is based upon consideration of the random and systematic components of the following measurement uncertainties: uncertainty in heat flow, Q; uncertainty in temperature difference, $T = (TH - TC)$; uncertainty in metered area, A; and, uncertainty in specimen thickness, L.

A1.1 Other specimen characterization and test condition data may need to be reported. The precision and bias of these data are to be reported to the extent they have a direct bearing on the accuracy of the results. Prescribed precision and bias of the primary data are not mandated by this test method. However, it is required that the operator assess and report the precision and bias of the data. The discussion below provides guidelines to assist the user in performing this uncertainty assessment. A variety of helpful performance checks are included in this discussion. In the following discussion both random and systematic errors are considered. The subscript sis used to denote systematic, and the subscript r is used for the random components.

A1.1.1 *Systematic Error, s*—Systematic error, *s*, is any component of error that remains fixed during the runs that constitute a successful test. To simplify the discussion, this does not include any components of error that are known both in magnitude and sign. Under such circumstances, the user should make appropriate corrections to the conductivity measurements and supply the justification for them. The user may check for the presence of unexpected errors by participating in an interlaboratory comparison or using a transfer standard available from appropriate sources. If errors are discovered, their source should be identified and corrected. A guarded end pipe apparatus cannot be calibrated. The task of estimating the remaining systematic errors is based on judgment and experience, including an awareness of the results of interlaboratory comparisons and statistical techniques such as using control charts. The implications of such estimates is often that they are the maximum possible systematic errors. In this event the total maximum systematic error is the sum of the errors. It is, however, more likely that these estimates are probabilistic in nature and do not, in fact, represent the worst possible case. The total probable systematic errors are summed in the same manner as random errors, that is, the square root of the sum of squares. In the following discussion the latter approach is taken. However, the operator must decide if the bias estimates are worst cases or probabilistic in nature, and sum them accordingly.

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[6] Supporting data for these round robins have been filed at ASTM Headquarters. Request RR: C16–1003, RR: C16–1004, and RR: C16–1019.

A1.1.2 *Random Error, r*—Random error, *r*, is that component of error that may vary both in sign or magnitude during the runs that constitute a successful test. For simplicity, it is assumed that the variations are normally distributed and conventional statistical techniques are applicable. An estimate of random error components can be obtained by repeat measurements of each variable.

A1.1.3 It is important to distinguish between random and systematic errors for the following reason. The results reported in the test method are mean values derived from more than a single run. The uncertainties reported generally apply to these mean values. The uncertainty of a mean value due to the random error component decreases approximately as $1/n$ where n is the number of repeat runs. In contrast to this, the uncertainty of the mean value due to the systematic error component does not decrease with repeat runs. Thus, it is recommended that the error components be treated separately. The total uncertainty is expressed by reporting both components separately.

A1.2 *Error Components*—In the following sections, the error components of each reported variable are discussed. The total random or systematic uncertainty for each variable is taken to be the square root of the sum of squares.

A1.2.1 *Heat Flow, Q*—The objective of the test method is to establish and measure radial heat flow through the metered area of the specimen. Any deviation from this objective represents error in the reported heat flow. The following sources of error should be considered:

A1.2.2 *Edge Heat Loss, sQse*—Edge heat loss, *sQse*, is a systematic error as the conditions surrounding the pipe, specimen, and pipe supports remain constant throughout the test procedure. The optimum environmental temperature to minimize this error is a small fraction of *T* above the mean test temperature. To determine the sensitivity of this error to test conditions, the user should determine the heat flux as a function of ambient temperature. This dependence may change appreciably with specimen and apparatus characteristics and, therefore, should be done under typical test conditions. Usually this is a small value considering the total heat flow produced by the heater in the metered section is very large and the proportion of the surface area of the exposed end of the pipe and the area of the metered section is very small.

A1.2.3 *Gap Heat Loss*—Gap heat loss is considered to be composed of both systematic, *sQgp*, and random, *rQgp*, components. The systematic component can be, in part, due to the fact that there may be a finite number of locations along the gap at which the imbalance is measured; reducing the temperature difference between a finite number of points on opposite sides of the gap to zero may not necessarily ensure that there is zero net flow of heat across the gap. Improper position of the sensors will lead to systematic error. Spurious emfs within the circuitry will result in a systematic imbalance. The random component is due to short-term control fluctuations. After estimating the probable imbalance across the gap in terms of temperature (or sensor voltage), the operator needs to determine the effect of this imbalance on the measured heat flow through the metered area. This can be done by measuring the dependence of metered area power on intentionally introduced gap imbalance. A typical way of addressing this is to run three tests, one with the guard balanced and one each biased positive and negative. The results are plotted, lambda versus gap balance, and the zero intercept is determined. The imbalance introduced should be large enough to yield an easily measured change in *Q*, but small enough to remain in the region where the dependence of *Q* upon imbalance is approximately linear.

A1.3 *Effect of Drift of the Metered Area Heater*—A quasi-heat loss exists due to the changing heat content of the metered area heater as its temperature changes. Typical pipes have a relatively high heat capacity and even for small drift rates can produce significant errors in measured heat flow. If the drift is monotonic, the error is systematic, *sQd*; if not, the error is exhibited as random error, *rQd*. Normally, the experiment is conducted so that there is no observable drift. Under this circumstance, the possible drift is determined by the detectability or control limit, *dT/dt*, of the system. The operator can compute the magnitude of this error, *Qd* in watts, from a knowledge of the maximum possible *dT/dt* and the specific heats and masses of the various components of the metered section of the pipe as follows:

$$Qd\ 5\ dT/dt\ CiMi \qquad \text{(A1.1)}$$

A1.3.1 The specimen heat capacity also contributes to the drift error, but for most pie insulation materials, the heat capacity of the specimen is small compared to the pipe. This error also can be determined by measuring the dependence of drift rate on measured heater power. Comparison of the calculated and measured results is advised to increase confidence in the reported result.

A1.4 *Power Determination Error*, composed of both systematic, *sQp* and random, *rQp*, components. With high quality instrumentation these errors can be reduced to an insignificant level. The manufacturers' specifications on bias and precision will normally suffice to define these errors.

A1.5 *Temperature and Temperature Difference*—Temperature error is composed of systematic, *sT*, and random, *rT*, components. In addition, these errors are further subdivided according to the source of the error:

A1.5.1 *Calibration Error, sTc*, is entirely systematic as long as the same calibration is used. It is, however, not necessarily the same for each temperature sensor. In the case of thermocouples, calibration is frequently performed for each spool of wire, not for each piece of wire from that spool. Therefore, systematic differences can occur as one progresses through the spool. The calibration is frequently represented by an equation which approximates the experimental calibration data taken at selected temperatures. If a digital read-out device is used that yields temperature directly, the calibration formulation is built into the device and the same basis for error exists.

A1.5.2 *Instrumentation Measurement Error, Tm*, occurs when the sensor output is measured. This error contains both systematic and random components. Each component should be estimated from equipment manufacturer's specifications and from estimated spurious circuit effects. In addition, temperature errors are introduced by long and short-term control fluctuations.

A1.5.3 *Sensor Positioning*, a potentially significant source of error in temperature measurement, can be caused by improper positioning of the sensor or the disturbance caused by the presence of or finite size of the sensor itself. It is intended that the average temperature of each specimen surface be measured. If the sensor is mounted in the pipe surface, thermal contact resistance between the pipe and specimen is a source of error. If the sensor is mounted in the specimen surface, sensor separation (specimen thickness) is a source of error. If the specimen is inhomogeneous across the metered area, surface temperature variations exist and the indicated temperature will depend on its location on the surface. If heat flows along the sensor leads from the external environment, the measured temperature will be in error because of the presence of the sensor. For a single test on a given specimen, this source of error, sTp, is systematic. A performance check that is helpful to determine the potential temperature error due to temperature nonuniformity is as follows: Assemble a multijunction thermocouple and place it between the specimen and pipe in question. Establish steady-state at the desired test condition. Determine the variation in temperature across the pipe from the multijunction thermocouple outputs.

A1.5.4 A helpful technique to estimate interface temperature errors is to mount sensors both within the pipe and within the specimen surface. Then perform a test and calculate the difference between the two sets of data.

A1.5.5 *Temperature Difference Error* is also composed of systematic, sT, and random components, tT. Care must be exercised in estimating these components compared to the error components for temperature itself. The results can depend strongly on whether a differential measurement or two absolute measurements are performed. Because T is frequently small, large percentage errors can occur if care is not observed. For example, at a mean specimen temperature of 300 K, an error of 1 K in the mean temperature, that corresponds to an error of about 0.2 % in thermal resistance for typical insulations. However, this same error of 1 K in measurement of a specimen temperature difference of 25 K corresponds to a 4 % error in both T and in the value of the thermal resistance, independent of the mean temperature.

A1.5.6 *Specimen Thickness Error, sL, and Meter Area Error, sA*, are both systematic errors. The specimen thickness error is determined by the ability to measure the pipe insulation diameters (including variations of this thickness over the metered area) or, in the case of rigid specimens, the specimen thickness and the changes due to thermal expansion. The effect of bowing or warping at operating temperatures should be given attention.

REFERENCES

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