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Thermal insulation — Determination of steady-state thermal transmission properties of thermal insulation for circular pipes

Isolation thermique — Détermination des propriétés relatives au transfert de chaleur en régime stationnaire dans les isolants thermiques pour conduites

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 8497 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*, Subcommittee SC 1, *Test and measurement methods*.

Annex A of this International Standard is for information only.

Introduction

The thermal transmission properties of pipe insulation generally have to be determined using pipe test apparatus rather than flat specimen apparatus such as the guarded hot plate or the heat flow meter apparatus, if results are to be representative of end-use performance. Insulation material formed into flat sheets often has different internal geometry from that of the same material formed into cylindrical shapes. Furthermore, properties often depend significantly upon the direction of heat flow in relation to inherent characteristics such as fibre planes or elongated cells: thus flat specimen one-dimensional heat flow measurements may not necessarily be representative of the two-dimensional radial heat flow encountered in pipe insulation.

Another consideration is that commercial insulations for pipes are often made with the inside diameter slightly larger than the outside diameter of the pipe, otherwise manufacturing tolerances may result in an imperfect fit on the pipe, thus creating an air gap of variable thickness. In those cases where end-use performance data rather than material properties are to be determined, the insulation is mounted on the test pipe in the same loose manner so that the effect of the air gap will be included in the measurements. This would not be the case if properties were determined in a flat plate apparatus where good plate contact is required.

Still another consideration is that natural convection currents around insulation installed on a pipe will cause non-uniform surface temperatures. Such conditions will not be duplicated in a flat plate apparatus with uniform plate temperatures.

NOTE 1 Comparison tests on apparently similar material using both pipe apparatus and flat plate apparatus have shown varying degrees of agreement of measured thermal transmission properties. It appears that better agreement is often obtained for heavier density products which tend to be more uniform, homogeneous and sometimes more isotropic. For those materials which have repeatedly shown acceptable agreement in such comparisons, the use of data from flat plate apparatus to characterize pipe insulation may be justified. As a general rule, when such agreement has not been shown, the pipe test apparatus shall be used to obtain thermal transmission data for pipe insulations.

Thermal insulation — Determination of steady-state thermal transmission properties of thermal insulation for circular pipes

1 Scope

This International Standard specifies a method for the determination of steady-state thermal transmission properties of thermal insulations for circular pipes generally operating at temperatures above ambient. It specifies apparatus performance requirements, but it does not specify apparatus design.

The type of specimen, temperatures and test conditions to which this International Standard applies are specified in clauses 5 and 6.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7345:1987, *Thermal insulation — Physical quantities and definitions.*

ISO 8301:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus.*

ISO 8302:1991, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus.*

3 Definitions

NOTE 2 The geometry of pipe insulation requires special terms not applicable to flat specimens. The word "linear" is used to denote properties based upon a unit length (in the pipe axis direction) of a specified insulation size. These linear properties, identified by the subscript "l", are convenient since the total heat loss can then be calculated knowing the pipe length and the applicable temperature.

"Linear" does not denote heat flow in the axial direction. In this International Standard, the direction of heat flow is predominantly radial.

For the purposes of this International Standard, the following definitions apply. The definitions and symbols given in the following clauses are based upon those in ISO 7345 except for the linear thermal transference (3.1).

3.1 linear thermal transference, K_l: Linear density of heat flow rate divided by the temperature difference between the pipe surface and the ambient air in the steady-state condition. It relates to a specific insulation size and is a measure of the heat transferred through the insulation to the ambient atmosphere.

$$K_l = \frac{\Phi/L}{T_0 - T_a} \qquad \ldots (1)$$

3.2 linear thermal resistance, R_l: Temperature difference between the pipe surface and the insulation outer surface divided by the linear density of heat flow rate in the steady-state condition. It relates to a specific insulation size and is the reciprocal of the pipe linear thermal conductance, Λ_l.

$$R_l = \frac{T_0 - T_2}{\Phi/L} = \frac{1}{\Lambda_l} \qquad \ldots (2)$$

3.3 linear thermal conductance, Λ_l: Reciprocal of the linear thermal resistance, R_l, from the pipe surface to the insulation outer surface. It relates to a specific insulation size.

$$\Lambda_l = \frac{1}{R_l} = \frac{\Phi/L}{T_0 - T_2} \qquad \ldots (3)$$

3.4 surface coefficient of heat transfer, h_2: Areal density of heat flow rate at the surface in the steady-state condition divided by the temperature difference between the surface and the surrounding ambient air. For pipe insulation geometry the following relation applies.

$$h_2 = \frac{\Phi}{\pi D_2 L (T_2 - T_a)} \qquad \ldots (4)$$

3.5 thermal conductivity, λ: Defined by the following relation specifically applicable to the pipe insulation geometry. It applies to homogeneous material in the steady-state condition and is the reciprocal of the thermal resistivity, r.

$$\lambda = \frac{\Phi \ln(D_2/D_0)}{2\pi L (T_0 - T_2)} = \frac{1}{r} \qquad \ldots (5)$$

NOTES

3 In ISO 7345, the thermal conductivity is also defined by the more general relation $q = -\lambda \operatorname{grad} T$.

4 Since the pipe surface temperature, T_0, is used, the thermal conductivity will include the effect of any gap that exists between the insulation and the pipe (see 6.1).

3.6 thermal resistivity, r: Reciprocal of the thermal conductivity, λ, for a homogeneous material in the steady-state condition.

$$r = \frac{2\pi L (T_0 - T_2)}{\Phi \ln(D_2/D_0)} = \frac{1}{\lambda} \qquad \ldots (6)$$

3.7 areal thermal resistance, R: Temperature difference between the pipe surface and the insulation outer surface divided by the areal density of heat flow rate in the steady-state condition. It is the reciprocal of the areal thermal conductance, Λ.

$$R = \frac{T_0 - T_2}{\Phi/A} = \frac{1}{\Lambda} \qquad \ldots (7)$$

where the surface of area A must be specified (usually the pipe surface, sometimes the insulation outer surface, or other as chosen; see note 6 in 3.8).

NOTE 5 The more common "areal" properties, based upon unit area, are often confusing when applied to pipe insulation since the area must be chosen arbitrarily and may range from that of the pipe surface to that of the insulation outer surface. If these areal properties are computed, the area and its location used in the computation must be reported.

3.8 areal thermal conductance, Λ: Reciprocal of the areal thermal resistance, R.

$$\Lambda = \frac{1}{R} = \frac{\Phi/A}{T_0 - T_2} \qquad \ldots (8)$$

where the location of the surface of area A must be specified (usually the pipe surface, sometimes the insulation outer surface, or other as chosen).

NOTE 6 The value of Λ, 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 3.5, the areal conductance, Λ, is given by

$$\Lambda = \frac{2\pi L \lambda}{A \ln(D_2/D_0)} \qquad \ldots (9)$$

If the area is specially chosen to be the "log mean area", equal to $\pi L(D_2 - D_0)/\ln(D_2/D_0)$ then $\Lambda = 2\lambda/(D_2 - D_0)$. Since $(D_2 - D_0)/2$ 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, R, defined in 3.7. Since these areal coefficients are arbitrary and since the area used is often not stated, thus leading to possible confusion, it is recommended that they be used only if specified.

4 Symbols and units

For the purposes of this International Standard, the following symbols and units apply. (See clause 3.)

	Symbol	Unit
heat flow rate	Φ	W
linear density of heat flow rate (heat flow rate per axial length)	Φ/L	W/m
areal density of heat flow rate (heat flow rate per area of a surface)	Φ/A	W/m^2
temperature of pipe surface	T_0	K
temperature of insulation outside surface	T_2	K
temperature of ambient air or gas	T_a	K
outer diameter of circular pipe	D_0	m
outer diameter of circular insulation	D_2	m
length of test section (in the axial direction)	L	m
area of specified surface	A	m^2
linear thermal conductance	Λ_l	W/(m·K)
linear thermal resistance	R_l	(m·K)/W
linear thermal transference	K_l	W/(m·K)
thermal conductivity	λ	W/(m·K)
thermal resistivity	r	(m·K)/W
surface coefficient of heat transfer of insulation outer surface	h_2	W/(m^2·K)
areal thermal conductance	Λ	W/(m^2·K)
areal thermal resistance	R	(m^2·K)/W
thickness of end cap beyond test pipe (in axial direction)	S	m
factor for Nukiyama calculation	n	

NOTES

7 The subscript "l" is used to denote linear properties (per unit axial length).

8 The subscript "cyl" is added to the symbols listed when it is important to indicate that the properties were derived from measurements on a pipe apparatus.

9 When both "l" and "cyl" subscripts are used together, they are written "l, cyl".

10 In ISO 7345, the linear density of heat flow rate and the areal density of heat flow rate are given the symbols q_l and q respectively. The more descriptive ratio symbols given here are used throughout this International Standard.

5 Requirements

5.1 Test specimens

Specimens may be rigid, semirigid or flexible (blanket-type), or may be loose-fill, suitably contained. They may be homogeneous or nonhomogeneous, isotropic or anisotropic, may include slits, joints or metallic elements and may include jackets or other coverings. Specimens shall be uniform in size and shape throughout their length (except for any intentional irregularities which occur well within the metered test section) and shall be designed for use on pipes of the same size as the test apparatus available. Generally, specimens will have a circular outside shape concentric with the bore; other outside shapes are allowed but only thermal transference may then be determined.

5.2 Operating temperature

The pipe may be operated at temperatures up to the maximum service temperature of the specimen or of the materials used in constructing the apparatus. The lower limit of the pipe temperature is determined by the restriction that it be sufficiently greater than the temperature of the specimen outer surface to provide the precision of measurement desired. Normally, the apparatus is operated in still air maintained at an ambient temperature of 15 °C to 35 °C, but this may be extended to other temperatures, other gases and other velocities. The outer specimen surface temperature may also be fixed by the use of a heated or cooled outer sheath or blanket or by the use of an additional layer of insulation. If a cold outer sheath or jacket is used, operation at low temperatures is possible provided that the pipe is maintained at a higher temperature.

5.3 Pipe size and shape

The test pipe shall have a circular cross-section.

5.4 Orientation

The test pipe normally has a horizontal orientation. Other orientations may be used but require special considerations because of possible convection effects both within and around the test pipe and the specimen.

5.5 Types of apparatus

Two distinctly different types of pipe apparatus are covered: the guarded end and the calibrated or calculated end types, which differ in the treatment of axial heat transfer at the ends of the test section. Specimens incorporating elements of high axial conductance, such as metallic jackets, shall be tested only on the guarded end type of apparatus.

5.6 Relevant properties

The linear thermal transference (defined in 3.1) can be calculated for all specimens and is the property most useful in quantifying pipe insulation performance. Knowing its value and the mean temperatures of the pipe and of the surrounding ambient air, the heat loss for a given length of insulated pipe can be directly calculated provided that the conditions in use are comparable with those of testing.

The thermal conductivity (see 3.5) is often used in specifications. In theory, it can be calculated only for homogeneous specimens of concentric circular shape which fit the test pipe tightly with no air gaps. In practice, it is often necessary to deviate from ideal conditions if errors introduced are judged to be acceptable. The thermal conductivity is useful in deriving the linear transference or other properties for insulation sizes different than that used for the measurement (see 6.2). The other properties defined in clause 3 may be used when specified and appropriate.

6 General considerations

6.1 Objectives

Two distinctly different objectives may be addressed as specified in 6.1.1 and 6.1.2. The specimen preparation and mounting depend on the choice of objective made by the user. Procedures aimed at either objective may be used and shall be fully reported.

6.1.1 End-use performance

If end-use performance data are desired, the specimen shall remain unaltered and be mounted in the same manner as would occur in normal application. In this case, the measured properties include the effects of any joints or slits, and of the resistance of any air gaps created by a loose fit on the pipe.

6.1.2 Material properties

If values of material properties are desired, the specimen shall be chosen or altered so that all pieces fit tightly together without open joints or slits and so that the specimen fits the test pipe tightly without an air space.

6.2 Application to other sizes

It is impractical to provide test apparatus to match the size of all pipe insulations manufactured. Thus it is necessary to calculate the properties for other sizes from data measured on a limited number of sizes of similar insulation. Procedures may differ depending on whether the specimen material and the test conditions are ideal or non-ideal.

Where end-use performance is measured including any air gap and/or imperfect fit, it is not permissible to calculate the properties for other sizes.

6.2.1 Ideal materials and conditions

For materials that are homogeneous with thermal conductivity either constant or a linear function of temperature and which are tested under uniform temperature conditions, it is possible to determine the thermal conductivity from a single test at a specific mean temperature using the relationship given in 3.5. This thermal conductivity may then be used to calculate the heat flow rate and other thermal transmission properties for other sizes of pipes, other thicknesses of insulation, and other temperature differences for the same material operating at the same mean temperature.

6.2.2 Non-ideal materials and conditions

In practice, many materials are not strictly homogeneous because

- their thermal conductivity is a complex function of temperature;
- during measurements the outer surface of the specimen is not at a uniform temperature due to heat transfer by convection and radiation; and/or
- an air gap can exist between the apparatus and the specimen.

A critical evaluation of the practical impact of these factors shall be made whenever data is to be extended to sizes and conditions other than those of the measurement.

Generally, measurements shall be made for a particular product or material on a minimum of two pipe sizes approximating to the range of interest. If the values of thermal conductivity from those measurements agree among themselves within acceptable limits, then their average may be used for calculation of other thermal transmission properties for other sizes in the range and for other conditions, for the products and mean temperature of the tests. If the measured thermal conductivities do not agree within acceptable limits, then suitable trend analyses shall be employed to determine the appropriate values of thermal conductivity pertinent to the sizes for which thermal transmission properties are to be obtained. If the measured thermal conductivities differ widely, then tests on additional sizes should be conducted. An alternative procedure is to interpolate between values of a measured transmission property (for example, thermal transference) from measurements taken on different pipe sizes but on the same thickness of insulation and at the same temperatures.

6.3 Required knowledge

Since it is impractical to include all details relating to the wide range of types of apparatus and procedures covered by this International Standard, users shall have appropriate prior knowledge and experience in thermal measurements.

6.4 Detailed instructions

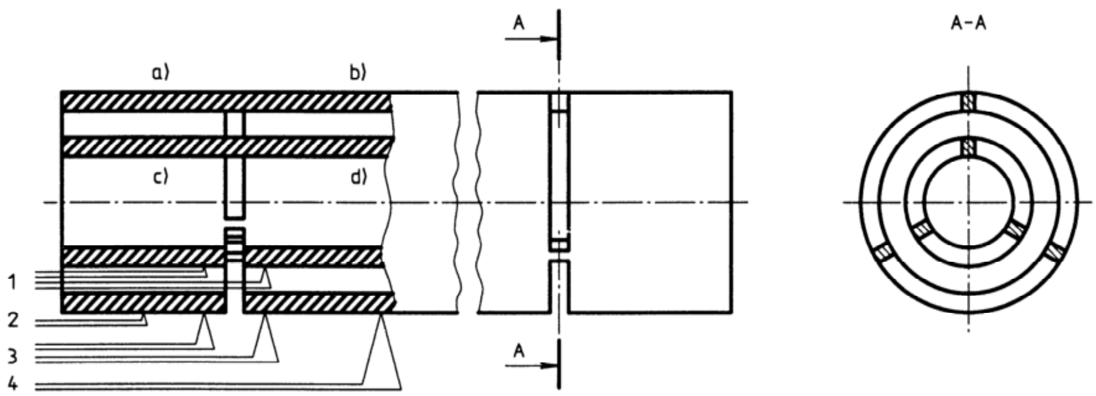
Users shall prepare detailed construction and operating instructions to aid builders and operators of specific apparatus to meet general requirements and objectives.

7 Apparatus

7.1 General requirements

The apparatus shall consist of the heated test pipe and instrumentation for controlling and measuring the pipe and ambient air temperatures, and the mean power dissipated in the test section heater. Instrumentation for the measurement of the insulation outer surface temperature shall also be included, unless only thermal transference is to be determined. The pipe shall be uniformly heated by an internal electric heater such as an electrical resistance winding on a separate internal pipe. In large apparatus it can be necessary to provide internal circulating fans or to fill the pipe with a heat transfer liquid to achieve uniform temperatures. Axial heat flow at the ends of the test section shall either be minimized by the use of separately heated guard sections (see 7.3 and figure 1) or by the use of insulated end caps and corrections applied to the measured quantity of heat (see 7.4 and figure 2). An enclosure or room equipped to control the temperature of the air surrounding the apparatus shall also be provided.

The apparatus shall conform to the principles and limitations set in this International Standard, but it is not intended in this method to include detailed requirements for the construction or operation of any particular apparatus. Such detailed instructions shall be prepared specifically for each apparatus.



Key
1 Monitoring thermocouples across gap of heater pipe
2 Guard measuring thermocouple
3 Monitoring thermocouples across gap of test pipe
4 Centre measuring thermocouple

a) Test pipe guard
b) Test pipe centre
c) Heater pipe guard
c) Heater pipe centre

Figure 1 — Guarded end apparatus

7.2 Dimensions

No restriction is placed on the apparatus pipe diameter, but the length of the test section shall be sufficient to ensure that the total measured heat flow is large enough, compared to end losses and to the accuracy of the power measurement, to achieve the desired test accuracy.

NOTE 11 For a guarded end apparatus (see 7.3) of 88,9 mm outside diameter, a test section length of 0,6 m, with a total specimen length of approximately 1 m has proven satisfactory. Calibrated or calculated end apparatus (see 7.4) of similar diameter usually suit specimen lengths of 2 m or more. These lengths can be unsatisfactory for some sizes of apparatus and for some test conditions, and estimates of the required length need to be made from appropriate error analysis.

As a convenience, the apparatus should be constructed to accept an integral number of standard lengths of insulation.

7.3 Guarded end apparatus

The guarded end apparatus (see figure 1) uses separately heated pipe sections, called "guards", located at each end of the metered test section which are maintained at the test section temperature to eliminate axial heat flow in the apparatus, and to aid in achieving uniform temperatures so that all heat flow in the specimen test section will be in the radial direction. Both test and guard section heaters shall be designed to achieve uniform temperatures over their lengths unless it has been shown that the expected deviation from temperature uniformity does not cause unacceptable errors in test results. Auxiliary heaters at the outside ends of single guards or a second guard, at each end, shall be used if required. The length of each 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 apparatus and specimen to an acceptably small amount compared to the test section measured heat transfer rate.

NOTES

12 No known analysis exists for predicting the exact length of the guard sections or the degree of temperature uniformity necessary to achieve a desired accuracy of test results. It is hoped that such analysis will be forthcoming; in the meantime, apparatus should be designed with the same approximate geometrical ratios as those of existing proven apparatus and attempts should be made to achieve uniform temperatures over the guard lengths.

13 A guard section length of approximately 200 mm has been found satisfactory for apparatus of 88,9 mm outside diameter when testing specimens that are essentially homogeneous, are only moderately anisotropic and are of a thickness not greater than the pipe diameter. Longer guard sections may be required when testing thicker specimens or with specimens of high axial conductance.

A gap, normally not more than 4 mm in width, 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 if needed for structural support). These gaps may be filled with material the thermal conductivity of which is much lower than that of the pipe.

Internal barriers shall be installed at each gap to minimize convection and radiation heat transfer between sections. Thermocouples, connected as differential thermopiles, shall be installed in the test pipe on both sides of each gap, and not more than 25 mm from the gap, for the purpose of monitoring the temperature differential across each gap. Thermocouples shall also be installed on any heater pipes or support members which provide a highly conductive path from test section to guard sections.

7.4 Calibrated or calculated end apparatus

The calibrated or calculated end apparatus (see figure 2) uses insulated caps at each end of the test section to minimize axial heat flow. Corrections for the end cap loss shall be determined either by direct calibration under the test conditions (the calibrated end apparatus) or by calculation using material properties (the calculated end apparatus). Internal electric heaters shall be designed to heat the test section uniformly over its length. If supplementary end heaters are used within the test section length, the power to such heaters shall be included in the measured test section power.

7.4.1 Calibrated end caps and calibrator pipe

For the calibrated end apparatus, the end caps shall have the same cross-sectional area as the test specimen and shall 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 and of a size to accept the end of the test pipe. The calibrator pipe shall consist of a short section of the same 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 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 be of a wire size as small as practical but in no case larger than 0,64 mm diameter.

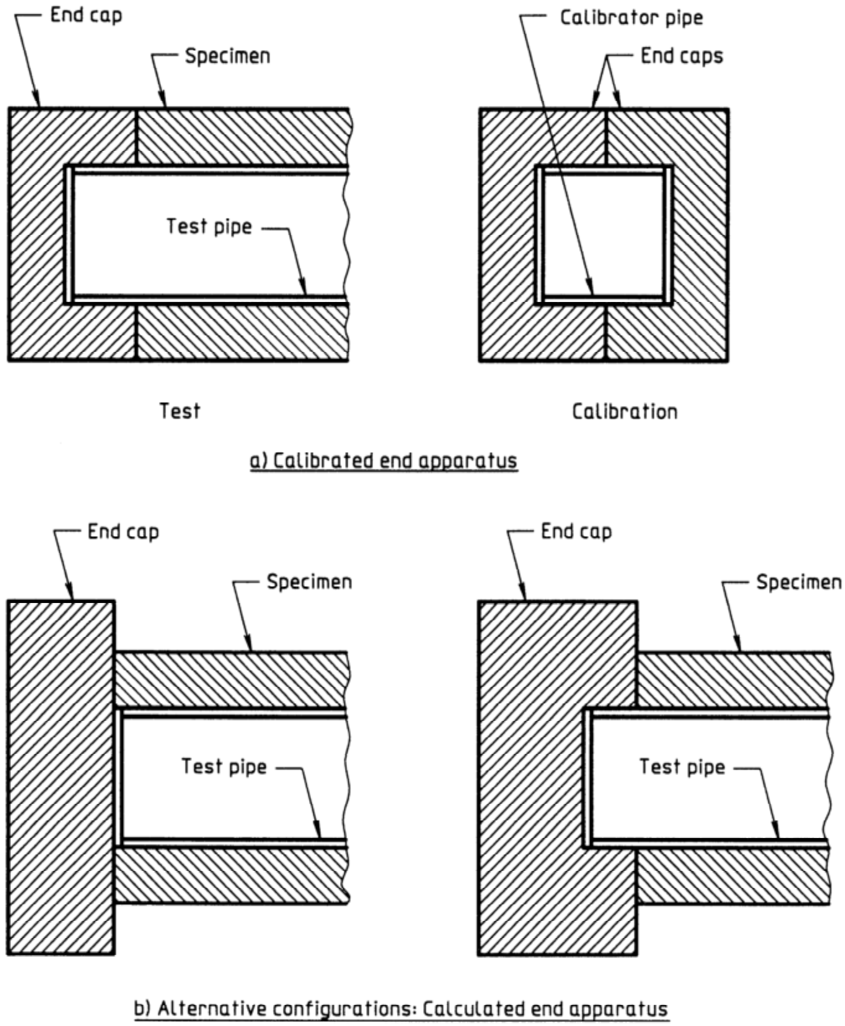


Figure 2 — Calibrated or calculated end apparatus

7.4.2 Calculated end caps

For the calculated end apparatus, the outside diameter of the end caps shall be as large or larger than that of the test specimen (see figure 2). The end caps shall be made of low conductivity homogeneous insulation material and may optionally have a cavity for the test pipe end [but see 10.2.3.1 d) for one restriction]. The thermal conductivity of the end cap material shall be determined by guarded hot plate or heat flow meter apparatus tests over the temperature range of contemplated use. If the material is not isotropic, the thermal conductivity shall be determined in different directions as required by the calculation procedure used (see 10.2.3).

7.5 Pipe surface temperature measurement

The surface temperature of the metered pipe test section shall be measured by a minimum number of four thermocouples, or one thermocouple for each 150 mm of length of the pipe, whichever is greater. They shall be located longitudinally at the centre of equal lengths of the test section and shall be equally spaced circumferentially in a helical pattern.

7.6 Temperature sensors

Bare bead insulated wire thermocouples should generally be used for sensing temperature and are specified throughout this International Standard. Such thermocouples shall be individually calibrated or taken from the same spool of premium grade wire which has been calibrated. Generally, the wire diameter should be as small as is practical and in no case shall it be larger than 0,63 mm when measuring metallic surfaces or 0,4 mm for non-metallic surfaces. Metal sheathed mineral insulated thermocouples, resistance thermometers, or other temperature sensors may also be used if the indicated temperatures can be shown to equal that indicated by a bare bead thermocouple. Mean temperatures may be calculated by taking the mean of the individual readings of several thermocouples or may be read directly by connecting the thermocouples in parallel providing that the junctions are electrically isolated and the total electrical resistances are equal. For the measurement of the gap differential between guards and test section, the thermocouples shall be connected in series to form a thermopile.

7.7 Temperature measuring system

The temperature measuring system, usually a d.c. potentiometer or digital microvoltmeter, shall have an accuracy sufficient to limit the error in the determination of temperature difference to an acceptable amount.

NOTE 14 A percentage error in the measurement of temperature difference will produce an equal percentage error in the thermal transmission properties calculated by the relationships in clause 3. Thus for a specified temperature difference and a chosen acceptable limit of error, the requirements of the temperature measurement may be established using standard error analysis (see 12.1). As an extreme example, consider tests with a temperature difference as low as 20 K. If an error of 1 % is judged acceptable for the error introduced by the temperature difference measurement, then the difference must be measured to within 0,2 K. If the temperatures are measured individually and the errors are random, the individual measurements must then be within 0,14 K (fixed bias errors in individual measurements will cancel in the determination of temperature difference). Obviously the requirements for absolute measurement accuracy are much less stringent for larger temperature differences.

7.8 Power supplies

Power supplies for the test section heater shall be closely regulated and may be either a.c. or d.c. Power supplies for guard heaters, if used, shall be regulated unless automatic controllers are used.

7.9 Power measuring system

A 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 may consist of 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 (energy) instrument such as a joule (watthour) meter shall be used.

In all cases care shall be taken that the measured power is only that dissipated in the test section. Correction shall be applied for power dissipated in leads, dropping resistors or uncompensated wattmeters.

7.10 Ambient control and measurement

A temperature-controlled enclosure or room shall be provided; it shall be capable of maintaining the desired ambient air temperature to within ± 1 K for temperature differences between the test pipe and the ambient air of 200 K or less, and to within ± 2 K for temperature differences above 200 K. The enclosure or room may be designed to maintain the ambient temperature at any desired value, above or below the normal value. The apparatus shall be located in a region of essentially still air and shall not be close to other objects which would alter the pattern of natural convection around the heated specimen. All surfaces or objects which could exchange radiation with the specimen shall have a total hemispherical emissivity of at least 0,85 and shall be at approximately the same temperature as the ambient air. Optional equipment may be provided to use gases other than air and to simulate wind effects by establishing forced air velocities of the direction and magnitude desired.

Air temperature sensors shall be designed and located so they are not directly affected by the pipe or other heat sources. Suitable locations may be determined by experiment and radiation shielding shall be used if necessary. Locations directly above the apparatus shall not be used.

7.11 Jacket or added insulation

An optional temperature-controlled jacket may be provided to modify the outer surface of the specimen to a desired temperature other than ambient. 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 8.6 for the measurement of the specimen outer surface temperature shall be installed prior to placement of the jacket or additional insulation layer. The emissivity of the inner surface of the jacket of added insulation (facing the specimen) shall be greater than 0,8 in order not to reduce any radiation transfer within the specimen. In such cases it is not possible to determine the thermal transference.

8 Test specimens

8.1 General requirements

For general requirements, see 5.1 and 6.1.

8.2 Sampling

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 shall be followed. In the absence of such plans, the test results shall be considered to represent only the specimens tested.

8.3 Installation

The intended objective of the test shall be considered in determining details of the specimen and its application to the test pipe. Some considerations are the means of securing the specimen to the test pipe, the use of sealants or other materials in the joints, and whether jackets, covers, bands, reflective sheaths, etc. are included. Unless other objectives are intended or specified, the specimen shall be secured to the test pipe in accordance with normal application practice and shall include jackets and other features normally used in application (see 6.1.1).

8.4 Conditioning

Specimens shall be dried or otherwise brought 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. Conditioning procedures specified for the material should be followed when applicable; otherwise the normal procedure is to dry to constant mass at a temperature of 102 °C to 120 °C, unless the specimen would be adversely affected. For example, maximum drying temperatures of 40 °C for gypsum and 55 °C to 60 °C for cellular plastics are usually recommended. In some cases, lower temperatures can be desirable.

Mass changes due to conditioning may be determined when desired, and mass and density after conditioning shall be determined.

8.5 Dimension measurement

After the specimen is mounted on the test pipe, measurements of the outside dimensions needed to describe the shape shall be made to within $\pm$ 0,5 % (both before and after testing). For circular shapes, measurements shall be made using a flexible steel tape to obtain the circumference which is divided by π to obtain the diameter D_2. The alternative procedure of measuring the outside diameter using calipers may be used only if a sufficient number of measurements are taken and averaged to include the effects of deviations from a true circular shape.

The test section length shall be divided into at least four equal parts and dimension measurements shall be taken at the middle of each, except that any irregularity being investigated shall be avoided. Additional measurements shall be taken to describe the irregularities. For guarded end apparatus, additional measurements at the centre of each guard section shall also be made.

Specimens intended to have a uniform cross-section throughout their length shall be rejected if any individual dimension measurement (test section or guard) differs from the mean of the test section measurements by more than 5 %.

NOTE 15 Additional dimension measurements, such as inner diameter or thickness, can be required by applicable product specifications. These measurements should be made as directed in those specifications.

8.6 Specimen surface temperature measurement

Thermocouples for the measurement of the mean outside surface temperature, T_2, shall be attached to the insulation surface in accordance with the following.

8.6.1 Location of thermocouples

The test section length shall be divided into at least four equal parts and surface thermocouples shall be longitudinally located at the centre of each. Large apparatus 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°. 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 13.6).

8.6.2 Fastening of thermocouples

Thermocouples shall be fastened to the surface so that the junction and the required length of adjacent wire is held in close thermal contact with the surface but does not alter the radiation emissivity characteristics of the adjacent surface.

8.6.2.1 Nonmetallic surfaces

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 tape either stuck to the specimen surface or wrapped around the specimen and adhering to itself. Small (approximately 20 mm × 20 mm or smaller, corresponding to the curvature of the specimen surface) sheets of metal foil with the thermocouples fastened to them should be used when the specimen surface is smooth but nonuniform in temperature. The surface of such metal foils shall be painted or otherwise covered to achieve an emissivity approximately equal to that of the specimen surface.

8.6.2.2 Metallic surfaces

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 emissivity as the surface. Capacitive discharge welding is specially recommended. Small thin straps of metal similar to the surface metal may be welded to the surface to hold the lead wire in contact with the surface.

8.7 High heat conductance elements

Thermocouples shall be installed on elements of high axial heat conductance such as metallic jackets and liners (specimens with such elements shall 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.

9 Procedure

9.1 Dimension measurement

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

9.1.1 Test length

For guarded end pipes, the test length, L, is the distance between the centrelines 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.

9.1.2 Diameter

Outside dimensions of the specimen shall be measured as specified in 8.5.

9.2 Ambient requirements

Operate the apparatus in a room or enclosure controlled to the desired ambient temperature so that it does not vary during a test by more than ± 1 K or ± 1 % of the difference between the test pipe temperature and the ambient temperature, $(T_0 - T_a)$, whichever is greater. The test shall be run in essentially still air (or other desired gas) unless appreciable velocity is needed to attain uniform temperatures or when the effects of air velocity is to be included as part of the test conditions. Any forced velocity shall be measured and its magnitude and direction reported.

9.3 Test pipe temperature

Adjust the temperature of the test pipe (the test section of a guarded end apparatus) to the desired temperature. When tests are to be run over a range of pipe temperatures to characterize a material, a minimum of three or four test temperatures should be chosen, approximately equally spaced over the range. If data is required at only one temperature as, for example, for quality control or acceptance testing, the test may be run at that temperature, or the desired value may be interpolated from tests at temperatures slightly above and below the desired temperature.

NOTE 16 Tests are usually run with the outer surface of the insulation exposed to normal ambient temperatures. These conditions will duplicate the majority of applications where the temperature difference increases as the pipe temperature and the corresponding mean temperature increase. If desired to duplicate other applications or to maintain a small temperature difference, the outer surface temperature may be raised or lowered by changing the ambient air temperature or by a temperature-controlled outer jacket, or raised by the use of an additional insulation layer. A description of such test conditions should be included in the report.

9.4 Guard balance

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 which will introduce an error of 1 % in the measured heat flow. 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 which meets the 1 % criterion. One criterion which has often been used is that the imbalance shall be no greater than 0,5 % of the temperature drop through the specimen, $(T_2 - T_0)$. This does not necessarily hold under all conditions.

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 should be 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 7.3, along with the dimensions and properties of the support bridges, to estimate the internal axial losses which must be added to (or subtracted from) the measured power input to the test section.

9.5 Thermal test measurements

9.5.1 Required data

After steady-state conditions have been attained, determine:

a) the average temperature of the pipe test section, T_0;

b) the test section to guard balances (for guarded end apparatus);

c) the mean temperature of the specimen outer surface, T_2 (this may be omitted if only the thermal transference is desired);

d) the mean ambient air temperature, T_a, and, if forced air is used, the air velocity;

e) the mean electrical power to the test section heater (the instantaneous value if the power is steady or the total energy divided by the measurement period if not).

9.5.2 Axial heat flow

9.5.2.1 In the apparatus

Measure the axial temperature gradients at the boundaries between the test section and the guards for any internal heater pipes or support bridges (see 7.3 and 9.4).

9.5.2.2 In the specimen

For specimens with elements of high axial conductance, measure the thermocouples specified in 8.7 to determine axial gradients. Using the mean of the gradients and known dimensions and thermal conductance properties of the highly conductive elements, calculate the estimated total axial heat conduction. Reject any tests where the specimen axial heat flow at either end is estimated to be more than 1 % of the mean heat input to the test section.

9.5.3 Test period and stability

Continue the observations until at least three successive sets of observations (made with a minimum time interval of 0,5 h between each set) differ by no more than 1 % from the mean value of the three sets, and do not exhibit unidirectional trends. Where the power measurement is made with an integrating instrument, each observation shall be of minimum 0,5 h duration. More stringent requirements can be necessary in some cases.

10 End cap corrections

Corrections are required for the heat loss through the end caps of calibrated or calculated end apparatus but are not required for the guarded end apparatus.

10.1 Calibrated end caps

10.1.1 Temperature range

Calibrated end apparatus requires 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 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. Separate calibration curves shall be obtained for each ambient temperature. If the test apparatus is to be used at only one set of conditions then it may be convenient to interpolate between two tests carried out at the same ambient temperature but with the calibrator pipe slightly above and slightly below the desired temperature.

10.1.2 Assembly

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

10.1.3 Calibration procedure

Adjust the power input to the heater to achieve the desired temperature. After steady-state conditions have been attained, make the necessary observations to determine the temperature of the calibrator pipe and of the ambient air and the mean electrical power to the heater over a minimum 0,5 h period.

Continue the observations until at least three successive sets of observations (made with a minimum time interval of 0,5 h between each set) differ by no more than 1 % from the mean value of the three sets, and do not exhibit unidirectional trends. Where the power measurement is made with an integrating instrument, each observation shall be of minimum 0,5 h duration. More stringent requirements can be necessary in some cases.

10.2 Calculated end caps

10.2.1 Calculation procedures

For calculated end apparatus, a correction for the axial heat loss at the ends is required. Any of several procedures that have proven satisfactory may be used.

10.2.2 Method of van Rinsum

10.2.2.1 Summary of method

Axial heat loss will cause a drop in temperature toward the ends of the test pipe surface which is a function of the thermal conductivities of the pipe (and internal heater) and of the specimen. If this temperature drop is measured and the pipe and heater thermal conductivities are known, it is possible to calculate the specimen thermal conductivity from the measured heat transfer rate. The method of van Rinsum (see[5]) calculates a temperature to be added to the temperature measured on the pipe surface at its midpoint. The corrected pipe surface temperature is then used in the standard thermal conductivity equation (see 3.5). The method is as follows.

10.2.2.2 Measurements

Four thermocouples, evenly spaced around the circumference of the test pipe at the top, bottom and two sides shall be located at the middle of the test pipe. Similar sets of four thermocouples shall be installed at a distance X from the middle toward one end and toward the other. The distance X shall be 200 mm or greater. These thermocouples shall be set in grooves and fastened as described in 7.5. Mean readings for each set of four thermocouples shall be obtained.

10.2.2.3 Calculations

Calculate an approximate value of thermal conductivity, λ', from the equation:

$$\lambda' = \frac{\Phi \ln(D_2/D_0)}{2\pi L(T_{0m} - T_2)} \qquad \ldots (10)$$

where all terms are as previously defined in clause 4 except T_{0m} which is the temperature of the pipe surface at its middle (average of four thermocouples).

Calculate a correction factor, c, from the equation:

$$c = \frac{2\pi\lambda'}{(A_1\lambda_1 + A_2\lambda_2)\ln(D_2/D_0)} \qquad \ldots (11)$$

where

A_1 and λ_1 are the cross-sectional area and the thermal conductivity of the test pipe respectively;

A_2 and λ_2 are the same properties of the internal heater pipe.

Calculate a correction to be applied to the pipe surface temperature at its middle, ΔT_{0m}, by the equation:

$$\Delta T_{0m} = \frac{T_{0m} - T_{0X}}{\cosh(X\sqrt{c})} \quad \ldots (12)$$

where T_{0X} is the mean temperature of the pipe surface at a distance X from the middle (average of eight thermocouples, four toward each end).

Calculate the corrected thermal conductivity, λ, from the equation:

$$\lambda = \frac{\Phi \ln(D_2/D_0)}{2\pi L(T_{0m} + \Delta T_{0m} - T_2)} \quad \ldots (13)$$

10.2.3 Method of Nukiyama

10.2.3.1 Summary of method

Heat loss through insulated end caps has the same effect on the total measured power as lengthening the test section. The method of Nukiyama (see[4]) calculates a length correction to be added to the measured test section length. The corrected length is then used in the thermal conductivity equation of 3.5. In order to apply the method the following conditions shall be met:

a) the end cap material and the specimen material shall be homogeneous and isotropic;

b) the thermal conductivity of the end cap material shall be the same as that of the specimen;

c) the outside diameter of the end caps shall be the same as that of the specimen;

d) the test pipe shall be of the same length as the specimen and shall be uniformly heated over that length.

10.2.3.2 Calculations

The thermal conductivity shall be calculated by the equation:

$$\lambda = \frac{\Phi \ln(D_2/D_0)}{2\pi(L + nD_0)(T_0 - T_2)} \quad \ldots (14)$$

The factor n shall be taken from figure 3, using the appropriate diameter ratio, (D_2/D_0), and the end cap thickness to pipe diameter ratio, (S/D_0).

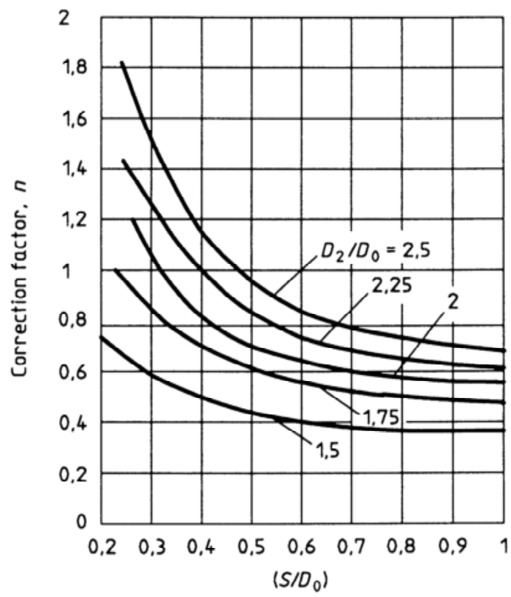


Figure 3 — Nukiyama correction

10.2.4 Method of finite differences

Another procedure is to employ a finite difference analysis using thermal properties determined on flat specimens taken from the same lot of material used to construct the end caps or from data obtained on other similar material if estimates show the expected error to be within the allowable test uncertainty. Measurements of material thermal properties may be made either by the guarded hot plate method (see ISO 8302) or the heat flow meter method (see ISO 8301) and shall be taken in all appropriate directions if the material is not isotropic (usually the axial and radial directions).

11 Calculations

The desired thermal transmission properties shall be calculated for each of the three or more observations required in 9.5.3 and the mean of these values reported in 13.9. The calculation shall be made using the equations in clause 3 or, for calculated end caps, the appropriate equations in 10.2. When appropriate, correction shall be applied to the measured power loss for axial heat loss through internal support bridges using measured gradients, dimensions and material properties (see 9.4). For calibrated end apparatus apply the calibration correction determined in 10.1.

12 Test precision and accuracy

12.1 Estimates

The precision and accuracy of the test depend upon the apparatus and its operation and upon specimen properties and test conditions chosen, thus no simple quantitative statement can be made that will apply to all tests. For each set of test conditions, it is possible to estimate the errors in the individual items entering into the calculation of the thermal transmission properties and then to combine the individual errors, using statistical propagation of error theory, to obtain an estimate of the uncertainty of the final result.

12.2 Interlaboratory comparisons

Interlaboratory comparison test programmes may be used to obtain an estimate of the precision of the method.

NOTE 17 One interlaboratory comparison programme involving nine laboratories (see[6]) showed that tests on the same specimen did not vary by more than ± 3 % of the mean value. This programme involved glass fibre insulation tested in a controlled ambient temperature of approximately 20 °C to 25 °C and covered the range of mean temperatures from 60 °C to 160 °C. The precision of the method outside the reported conditions in unproven and additional comparisons under the auspices of ISO/TC 163 are planned.

13 Test report

The test report shall contain the information specified in the following subclauses.

13.1 General requirements

Descriptions of the test specimens, the sampling and test procedures, the test apparatus and the results, and, when appropriate, a graphical representation of the measured properties versus temperature for the range of application. Whenever numerical values are reported, the units shall also be stated. The appropriate items, of those listed in 13.2 to 13.12, shall be included.

13.2 Specimen description

The specimen 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 mass and density. Any unusual specimen conditions observed both before and after the test shall also be reported.

13.3 Dimensions and density

The measured dimensions and, when obtained, the measured mass and density both before and after the test. If dimensions are measured at temperatures other than ambient, the temperature and the means of obtaining the dimensions shall be reported.

13.4 Installation

A description of the application and means of securing to the test pipe including the number, type and location of any bands or fasteners, the type of jacket or cover if used, the type and location of any sealants used, and whether the specimen fitted the pipe tightly or whether an air gap existed between the specimen and the pipe. If possible, the thickness of the air gap should be reported.

13.5 Conditioning

A description of any conditioning or drying procedures followed and, when obtained, the mass, density or dimensional changes due to conditioning or drying.

13.6 Temperatures

The following temperatures shall be indicated:

a) the mean temperature of the pipe test section, T_0;

b) the mean 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 8.6.1).

13.7 Ambient conditions

The type of ambient gas, its mean 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 sheaths or blankets.

13.8 Power

The test section average power input and any corrections used.

13.9 Thermal transmission properties

The desired thermal transmission properties including any or all of the following when applicable and the corresponding mean temperature $(T_0 + T_2)/2$. These shall be the mean values calculated in clause 11.

a) the linear thermal transference, K_l, the corresponding ambient temperature, T_a, and the surface coefficient of heat transfer, h_2;

b) the linear thermal conductance, Λ_l;

c) the linear thermal resistance, R_l;

d) the thermal conductivity, λ;

e) the thermal resistivity, r;

f) the insulation surface coefficient of heat transfer, h_2;

g) the areal thermal conductance, Λ, and the surface referenced;

h) the areal thermal resistance, R, and the surface referenced.

13.10 Error estimates

Estimates of error of the test results.

13.11 Exceptions to this International Standard

Reference to this International Standard and any exceptions made.

13.12 Special calculations

Outlines of, or references to any special calculations used.

Annex A
(informative)

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