Various Methods For Measuring Thermal Conductivity-A Review

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***Abstract*: - The constant want for increasing heat transfer for a range of applications is one of the most complicated challenges faced by thermal engineers. With the innovation of technologies, heat transfer at higher rates and efficiency from small cross section areas or over low temperature difference are causing a rise in demands. As a consequence of the wide range of thermal properties there is no single measure method which can be used for all thermal Conductivity measurements. Consequently, over the past decades a wide variety of techniques for the enhancement of heat transfer has been suggested, where the most well-known and promising methods are briefly described in this paper. The study describes the steady state and transient methods for measuring thermal conductivity for different temperature ranges.**

Keywords—Thermal conductivity, Steady state, transient, analysis.

I.INTRODUCTION

As a definition, thermal conductivity, k, is the property of a material's ability to conduct heat.
To quantify the heat transfer process for heat conduction, the rate equation Fourier's Law is used. [1]

$$Q = -kA\frac{dt}{dx}$$

$$k = -\frac{Q}{A}\frac{dx}{dt}$$

Where, Q = heat transfer rate (in watt)
A = area of heat transfer surface (m^2)
dt/dx = temperature gradient
k = thermal conductivity (W/mK)
Q/A = heat flux (W/m^2)
The minus sign is due to the fact that the heat transfer is in the direction of decreasing temperature. The measurement of thermal conductivity, therefore, always involves the measurement of the heat flux and temperature difference. The difficulty of the measurement is always associated with the heat flux measurement. Where the measurement of the heat flux is done directly (for example, by measuring the electrical power going into the heater), the measurement is called absolute. Where the flux measurement is done indirectly (by comparison), the method is called comparative.

II. METHODS FOR MEASURING THERMAL CONDUCTIVITY

A. Steady-state methods

Steady state conditions refer to steady temperature at every point of the sample, i.e. not a function of time. In practice, the temperature in a steady state system is maintained by an electrical heater. Steady state measuring methods can provide accurate and reliable results; but, the main disadvantage is being time consuming.

1. Guarded hot plate: The guarded hot plate method is practical and generally used method for determining the thermal conductivity of nonmetals such as glass, ceramics, polymers and insulation materials. There are two types of the guarded hot plate equipment: single specimen and two-specimen apparatus as shown in Figure 1. These are capable to work between 80 K to 800 K and there is uncertainty of 2% related to thermal conductivity. This device is made up by one or two cold plates, a hot plate, a system of guard heaters and thermal insulation. The hot plate is enclosed by guard heaters and insulation to make certain that the heat from the hot plate barely passes through the test sample. Steady-state method is an absolute method of measurement and it requires steady-state establishment, and accurate measurements of the relevant parameters which may have an effect on the unidirectional heat flux through the metered region of the test specimen. The benefit of using a two-specimen apparatus is that a successful control of the heat losses is achieved because of the symmetric specimen arrangement. In the single-specimen arrangement apparatus the heat flows through the sample and the back of the main heater acts as a guard plane, ensuing in an adiabatic environment [2]. Even though the guarded hot plate can be effective for many practical conductivity tests, it is complicated to carry out tests of powders because containing the powder within the apparatus is much more challenging as compared to solid materials. A heat leak to mechanical fortifies containing the powder would make the thermal conductivity much harder to determine.
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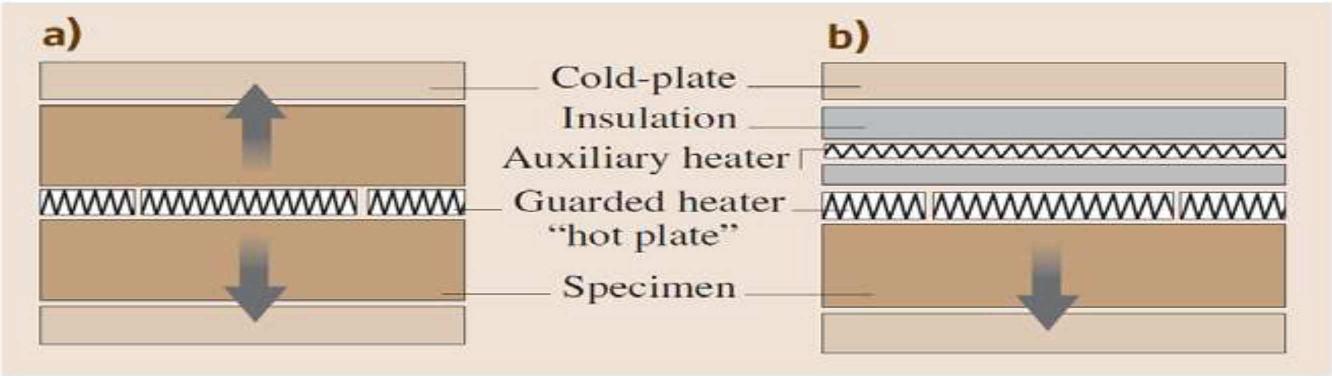

Fig. 1: Principle sketch of guarded hot plate methods, a) two-specimen apparatus. b) Single specimen apparatus [2]

Details for this test method and be found in the following published standards: European Standard EN 12667 [A4], International Standard ISO 8302 [A5] and ASTM C177 [A6].

2. Axial Flow Method: Axial flow methods have been since quite a while ago perceived and have given probably the most dependable and high exactness results reported in writing. The technique is the most widely utilized strategy for warm conductivity estimations for temperatures lower than 100 K because of minimum heat misfortunes at low temperatures for this system. The axial flow method is most appropriate for small specimens with thermal conductivities greater than 1 W/mK and for investigations where simultaneous measurements of other transport properties are required. The key measurement problem for this method is to reduce the radial heat losses in the axial heat flow developed [3]. For this technique, a test specimen of unknown thermal conductivity is sandwiched between two reference specimens of known thermal conductivity, forming the sample column. A heater at one end of the sample column and a heat sink in the other end creates a temperature gradient measured through the test specimen [3]. For an idealized case of perfect axial heat flow (no heat losses), the cross section of the specimen and the useful division of temperature sensors, Δx, is of importance. The cross section can easily be found, however the determination of Δx is more difficult due to the geometrical site of the sensor position. In most cases the heat flow will not merely axial, and corrections for peripheral losses have to be made. The temperature range for the axial heat flow method is 90-1300 K where the accuracy has been determined to be between 0.5-2percent [3]

Details concerning the axial flow method are found in the in printed standards: ASTM E 1225 [A1] and ASTM C335 [A2].

3. Cylinder method: This is also known as heat flow method. This method has verified to be very successful in measurements of thermal conductivity. The idea of the technique is to have heat flowing radially away from a middle heater towards a heat sink, and from this measure the temperature gradient inside the system.

It consists of an electrically heated wire or cylinder located at the central axis within a hollow cylinder. The cylinder is normally liquid cooled. Between the cylinder wall and the heater the sample can be filled and, if desirable, evacuated to a preferred pressure. Thermocouples are mounted in the sample at least two radii near the mid-section of the sample. Determining the specimen's thermal conductivity is done by first passing a constant electric current through the core heater to produce a radial heat flow upwards. This makes a temperature difference between the thermocouples placed in the specimen. When steady state is reached, the temperature measurements at the thermocouples are recorded.

Ideally, a uniform heat flux in the radial direction should be generated in the concentric cylinder apparatus. However, heat losses to the top and bottom will affect temperature gradients in the specimen. These heat losses are challenging to avoid, especially if the conductivity of the specimen is low. Therefore, a key element for a concentric cylinder apparatus design is to make the cylinder long with respect to the cylinder radius. This allows for a fairly uniform temperature profile to be established in the mid-section of the cylinder, where measurements are done. However, heat losses to the top and bottom of the cylinder should still be minimized or one should at least be able to determine the magnitude of the losses. The chief advantages of the cylinder method are that the system can be operated with relatively simple instrumentation as well as the wide range of applicability on specimens with both high and low thermal conductivities. The greatest disadvantage however, is that to be able to get as accurate measurements as possible, large specimen sizes should be used. This can be costly and also requires longer running time to reach steady state conditions. [3] The cylinder method can be used for temperatures in the range of 4 K to 1000 K, and achievable uncertainty for the thermal conductivity measurements of 2% [2].

Figure 2 illustrates the basic components used for the cylinder method. It also shows what the temperature profile would look like for a cross-section of the apparatus

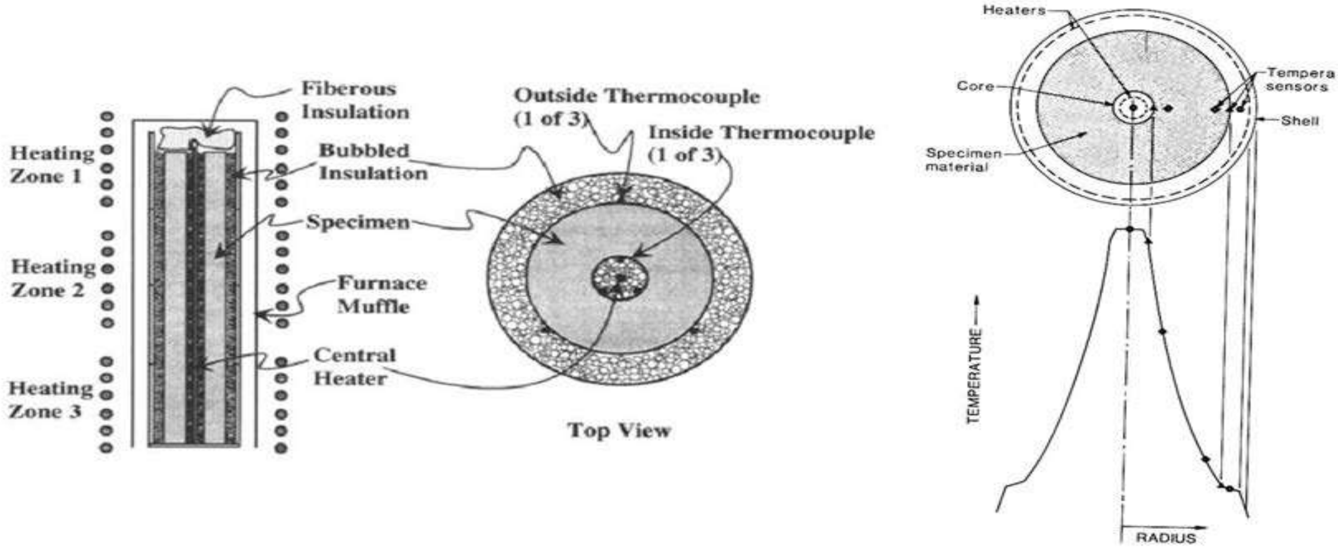

Fig. 2: Basic elements for the cylinder method and the temperature profile of a cross section

No standard for the cylinder method has been found. However, the International Standard ISO 8497 [A3] covers relevant performance requirements and test procedure which can be used for the cylinder method.

4. Heat flow meter method: Heat flow meter method is used to find out the heat flux by measuring the temperature difference across a thermal resistor during steady-state conditions. The design of the heat flow meter method is quite similar to the single-specimen guarded hot plate apparatus, with the difference that the main heater is exchanged with a heat flux sensor. Heat flux sensors are thermal resistors with a series of thermocouples. In some cases a heat flux sensor is placed at the cold plate to determine radial losses and reduce the time duration of measurements. The method is mostly used for polymers and insulation materials where the thermal conductivity is less than 0.3 W/(m*K) and an uncertainty of 3% can be accomplished [2]. However, if losses in radial direction are present the uncertainty increases rapidly. The conventional heat flow meter method assumes one-dimensional conduction for heat transfer, i.e. no convection or radiation present. This assumption is reasonable if the test specimen is thin in the direction of heat flow and has a large cross-section area. The surface area for convection and radiation becomes negligible compared to the conductive heat transfer through the specimen and the method is suited for materials with low thermal conductivity. However, for materials with high thermal conductivity, a thicker test specimen is required to be able to measure the temperature difference. This results in doubt of the 8 accuracy of the measurements since convection and radiation will then be present. Convective heat losses can be minimized by performing the experiments under high vacuum conditions. The technique is ideally suited for testing anisotropic specimens and is very accurate and reliable when measuring thermal conductivity the direction on one-dimensional heat flow [4].

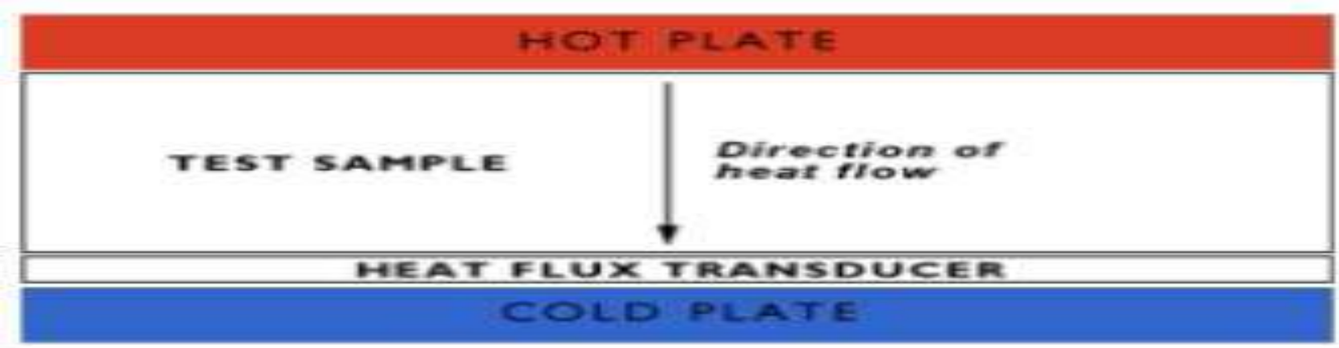

Fig. 3: Typical heat flux transducer heat flow meter apparatus

For detailed description of design and test procedure, see the relevant standards: European Standard EN 12667 [A8], ASTM E 1530 [A9] and ASTM C518 [A7]

B.Transient method: With the accessibility of present computers and data analysis apparatus, transient methods for measuring thermal conductivity have become increasingly popular. The transient methods measures a response as a signal sent out to generate heat in the test specimen. To start with, the specimen is in thermal equilibrium with the surrounding atmosphere. Then, a short heating pulsation is given to the sample. The alter in temperature within the time of measurement is recorded and further used for determining the thermal conductivity of the test specimen [5].
The advantages of the transient techniques are that they generally require much less precise alignment and dimensional and stability knowledge, but most of all the reduced duration needed for the experiments. Typical measurement duration of one hour for a steady-state measurement is reduced to a few minutes with a transient method. The temperature measurement at two opposite surfaces in the specimen needed for steady-state measurements is replaced by a temperature measurement as a function of time at only one position for the transient methods. The design for the transient measurement instruments are therefore quite straight forward and can also improve the accuracy of the results. However, transient conductivity measurements typically involve relatively complicated data analysis tools where advanced equipment is needed.
1. Hot wire method: This is a modification of the steady-state cylinder method geometry with radial heat flux. Hot wire method can measure small, transient resistance changes with high accuracy in duration of less than one second. The hot-wire technique is based on a linear heat source with infinite length (the hotwire) and infinitesimal diameter embedded in a test material. The hot-wire serves as a temperature sensor as well as a heater with a constant output ensured by a power supply (see Figure 4).An electric current of fixed intensity is generated in the wire, and the thermal conductivity is determined from the slope from the linear temperature profile as a function of time established from the measurement [6]. The transient hot-wire technique has the advantages of simplicity, the ability to measure thin material sizes, the short exposure of specimen to a high temperature and the possibility of good accuracy for measurements. In good experimental conditions, an accuracy of less than 5% can be achieved for conductivity measurements [5]. Furthermore, the exact dimensions of the equipment are less important compared to other thermal conductivity measurement techniques. Despite these advantages, the hot-wire method for thermal conductivity measurements is rarely used for commercial tests because of the delicacy of the very thin wire which easily snaps, especially when dealing with fluids and solids [6].

Details of the test method can be found in the standards: ISO 8894–1 [A10] and ISO 8894-2
[A12] and ASTM C 1113 [A11].

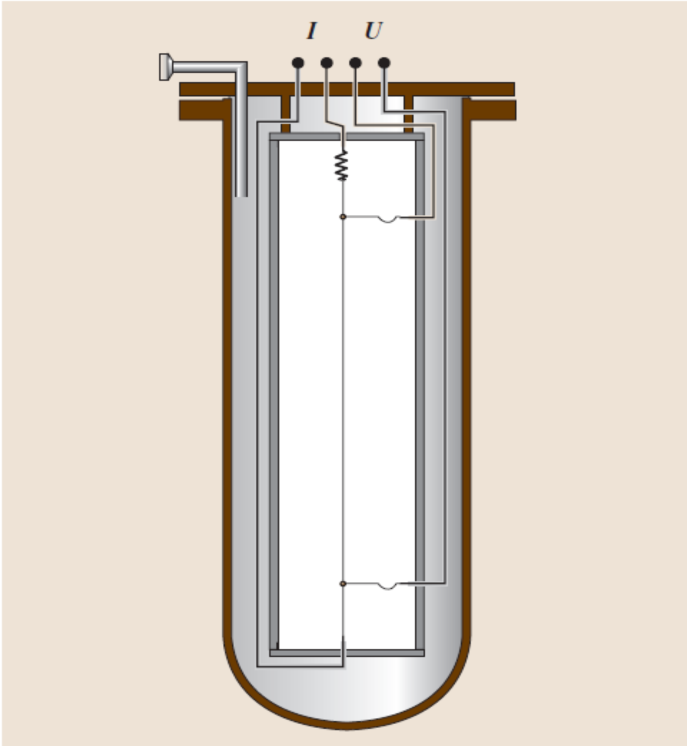

Fig. 4: Principle sketch of the hot-wire method [2]

2. Needle probe: The needle probe method, also referred to as the Line-Source Method, is a variant of the hot wire method and is capable of very fast measurements. It is suitable for both melt and solid state thermal conductivity measurements; however, it is not suited for directional solid-state property measurements in anisotropic materials [7]. A needle probe is located at the center of the test specimen, both kept at constant initial temperature. When running experiments, a known amount of heat is produced in the needle, creating a heat wave which propagates radially in the specimen. The temperature rise in the probe varies linearly with the logarithm of time, and this relationship can be used directly to calculate the thermal conductivity of the test specimen. Small test samples makes it possible to subject the samples to a wide variety of test conditions; the method can cover a temperature range from 233 K to 673 K on materials with thermal conductivity between 0.08 to 2 W/(m*K). However, the standard for this test method, ASTM D 5930 [A14], does not contain numerical precision and bias statement and therefore it should not be used as a reference test method in case of dispute [8].
3. Transient plane source method: The transient plane source method (TPS) is used for thermal conductivity measurements both in fluids and solids with thermal conductivities from 0.01 to 500 W/(m*K) in the temperature range from cryogenic temperatures to 500 K. It is capable of solid-state measurements of sheets of materials and can also be extended to thin films. The technique uses a thin, plane, electrically insulated resistive element, usually in a spiral pattern as shown in Figure 5, as both the temperature sensor and the heat

source. Measurements are performed by placing the heating element between two test samples of the same material. In order to reduce the contact resistance between the sample surface and the sensor the surfaces of the samples need to be as flat and smooth as possible. By recording the increase in resistance as a function of time in the heating element, which is supplied with a constant electrical power, the thermal conductivity can be deduced from one single transient recording [7].

In routine measurements around or below room temperature, accuracy for thermal conductivity measurements is estimated to lie between 2% and 5%. For measurements at higher temperatures this accuracy is estimated at 5% to 7% [9].

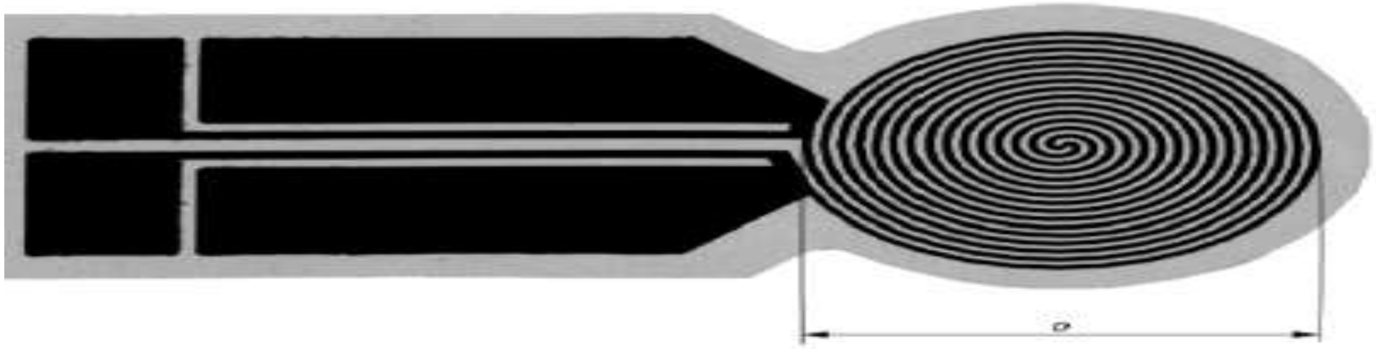

Fig. 5. Heating/sensor element used for TSP [9]

Details regarding the design and test procedure for the TSP method can be found in the International Standard ISO 22007-2 [A13]

III. CONCLUSION

The steady state methods have provided most reliable and precise results reported in writing. Flow of heat in axial direction dominates in steady state methods. Now a day, Guarded Hot Plate method is most versatile and widely used method for nonmetals and insulation materials for temperature range of 80-1500 K. But for porous material radial heat transfer methods also known as cylinder method is used up to temperature 2600 K. But this method require large specimen and this is time consuming also. Steady state methods are quite time consuming and there is uncertainty range from 2-10% in these methods. Time consuming problem is solved by transient methods. The greatest advantage of these methods is the reduced duration required for experiments. Porous materials with very low thermal conductivities can be examined over a wide temperature range and an uncertainty range of 2-15% is expected for these methods. But some of these methods require complicated analysis tool and very delicate measurement instrument especially dealing with fluids and solids.

REFERENCES

[1] Dr. D S Kumar, *Heat and Mass Transfer 8th revised edition,* Katson books, Pg. no. 19

[2] Buck, W. and S. Rudtsch, *"8.thermal properties" Springer Handbook of Materials Measurement Methods*, H. Czichos, T. Saito, and L. Smith, Editors. 2006, Springer Berlin Heidelberg. p. 399-429.

[3] K.D Maglic, A.C., V.E. Peletsky, *Compendium of Thermophysical Property Measurement Methods, Vol.1: Survey of Measurement Techniques* Vol. 1. 1984, New York: Plenum Press. 789pp

[4] Mahanta, N.K. and A.R. Abramson, *The dual-mode heat flow meter technique: A versatile method for characterizing thermal conductivity.* International Journal of Heat and Mass Transfer, 2010. 53(23–24): p. 5581-5586.

[5] Alessandro, F., *An apparatus for the routine measurement of thermal conductivity of materials for building application based on a transient hot-wire method.* Applied Thermal Engineering, 2007. 27(14–15): p. 2495-2504.

[6] William, W. and A. Marc, *Thermal Conductivity Measurement*, in *The Measurement, Instrumentation and Sensors Handbook on CD-ROM*1999, CRC Press.

[7] International_Standard, *ISO 22007-1 Plastics - Determination of thermal conductivity and thermal diffusivity - Part 1: General Prinsiples*, 2009.

[8] American-Society-for-Testing-and-Materials, *ASTM D 5930-01: Standard Test Method for Thermal Conductivity of Plastics my Means of a Transient Line-Source Technique*, 2009.

[9] International_Standard, *ISO 22007-2: Plastics - Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disk) method*, 2008.

APPENDIX A

Relevant standards for thermal conductivity measurement techniques

Axial heat flow method:
[A1] American Society for Testing and Materials, ASTM E1225-09: *Standard Test Method for Thermal conductivity of Solids my Means of the Guarded-Comparative- Longitudinal Heat Flow Technique*
[A2] American Society for Testing and Materials, ASTM C335/C335M: *Standard Test Method for Steady-State Heat Transfer Properties of Pipe Insulation*

Cylinder method:
[A3] European Standard, EN ISO 8497: *Thermal insulation – Determination of steady-state thermal transmission properties of thermal insulation for circular pipes*

Guarded hot plate method:
[A4] European Standard, EN 12667: *Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance*
[A5] International Standard, ISO 8302: *Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus*
[A6] American Society for Testing and Materials, ASTM C177: *Standard Test Method for Steady State Heat Flux Measurements and Thermal Transmission Properties by Mean of the Guarded Hot Plate Apparatus.*

Heat flow meter method:
[A7] American Society for Testing and Materials, ASTM C518: *Standard Test Method for Steady State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*
[A8] European Standard, EN 12667: *Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance*
[A9] American Society for Testing and Materials, ASTM E1530-11: *Standard Test Method for Evaluating the Resistance of Thermal Transmission of Materials by the Guarded Heat Flow Meter Technique*

Hot wire method:
[A10] International Standard, ISO 8894-1: *Refractory materials – Determination of thermal conductivity – Part 1: Hot-wire methods (cross-array and resistance thermometer)*
[A11] American Society for Testing and Materials, ASTM C1113/C1113M – 09: *Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique)*
[A12] International Standard, ISO 8894-2: *Refractory materials – Determination for thermal conductivity – Part 2: Hot-wire method (parallel)*

Transient planar source method:
[A13] International Standard, ISO 22007-2: *Plastics – Determination of thermal conductivity and thermal diffusivity – Part 2: Transient plane heat source (hot disk) method*

Needle probe method:
[A14] American Society for Testing and Materials, ASTM D 5930-01: *Standard Test Method for Thermal Conductivity of Plastics my Means of a Transient Line-Source Technique*