Principal Methods of Thermal Conductivity Measurement

Thermal conductivity is defined as

$$K = \frac{Q/A}{\Delta T/\Delta L}$$

(See Figure 1)

where Q is the amount of heat passing through a cross section (A) and causing a temperature difference (ΔT)over a distance of ΔL. (Q/A) is therefore the heat flux which is causing the thermal gradient (ΔT/ΔL).

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.

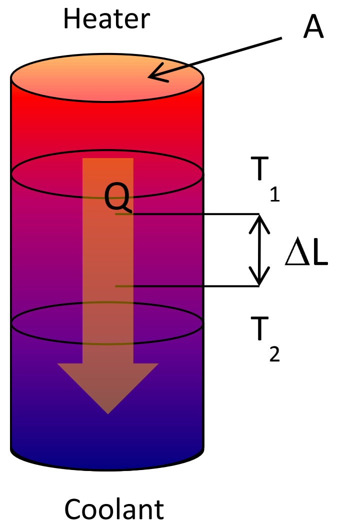

Figure 1

In addition to these two main methods, other secondary methods usually transient in nature, can also yield thermal conductivity.

In all cases, the entire heat flux must be uniaxial, that is it has to flow through the sample (and the references, in the comparative case). Thus, the heat losses or heat gains must be minimized in the radial direction. To some degree, this can be accomplished with packing insulation around the sample, or, at higher temperatures, where such simple solutions become inefficient, with installation of a “guard”. If the guard is controlled to have the identical temperature gradient as the sample, then the radial heat flow will be minimized.

The configuration of a given measurement system and of the specimen itself is influenced most prominently by the magnitude of the thermal conductivity. When the thermal conductivity is high, the specimens are usually “long” (for example, in the form of cylinders). When the conductivity is low, the specimens are usually “flat” (for example, in the form of plates or disks). Simple thermal considerations indicate why this is so. When the specimen conductivity is high, the heat flux is usually fairly high so that, relatively speaking, heat losses from the large lateral surface area of the specimen are small; a long specimen in the direction of flow helps establish a reasonably high temperature gradient which can then be accurately measured. When the specimen conductivity is low and the heat flux correspondingly low, only a relatively small thickness is required to generate a large, accurately measurable gradient. With this low specimen heat flux, lateral losses are of concern, thus a plate-type specimen itself tends to minimize these spurious flows since the lateral surface area is small. As a matter of fact, in some cases the lateral surfaces of the specimen are surrounded by pieces of the same specimen material to provide self-guarding.

Another independent parameter of fundamental importance is the magnitude of specimen conductivity relative to the surroundings. It is generally desired that the specimen effective conductance be as high as possible relative to that of the surrounding insulation. This generally becomes more of a problem as the temperature of the measurement system rises. With some measurement techniques used at very high temperatures, which will be discussed, the lateral losses are allowed to be high, but they are accounted for quantitatively in the conductivity measurement.

The following section covers the principal methods of measuring this property from subambient temperatures up to 1500^{o}C on solid materials exhibiting a very wide range of conductivity. These techniques are axial flow, radial flow, guarded hot plate, and hot-wire method.

Axial Flow Methods

Axial flow methods have been long established and have produced some of the most consistent, highest accuracy results reported in the literature. It is the method of choice at cryogenic temperatures. Key measurement issues center mainly on reduction of radial heat losses in the axial heat flow developed through the specimen from the electrical heater mounted at one end (the power dissipation of this heater is used in calculating column heat flux). These losses are minimal at low temperatures. As the specimen temperature moves above room temperature, control of heat losses becomes more and more difficult. Thus a great deal of attention centers on important experimental parameters such as the ratio of effective specimen conductance to lateral insulation conductance (the higher the better) and to the quality of guarding (that is the match of the axial gradient in the specimen to that of the surrounding insulation). In practice only, cylindrical symmetry heat transfer is used.

In addition to guarded and unguarded solutions, other categories are separated:

Absolute axial heat flow, which is mostly used in subambient environments. Systems of this nature require very precise knowledge of the electrical power feeding the heater. Consequently, the losses from the hot heater surfaces also play a major role.

Comparative cut bar (ASTM E1225 Test Method)

This is perhaps the most widely used method for axial thermal conductivity testing. In this, the principle of the measurement lies with passing the heat flux through a known sample and an unknown sample and comparing the respective thermal gradients, which will be inversely proportional to their thermal conductivities. Most commonly, the unknown is sandwiched between two known samples, “the references”, to further account for minor heat losses that are very difficult to eliminate (Figure 2).

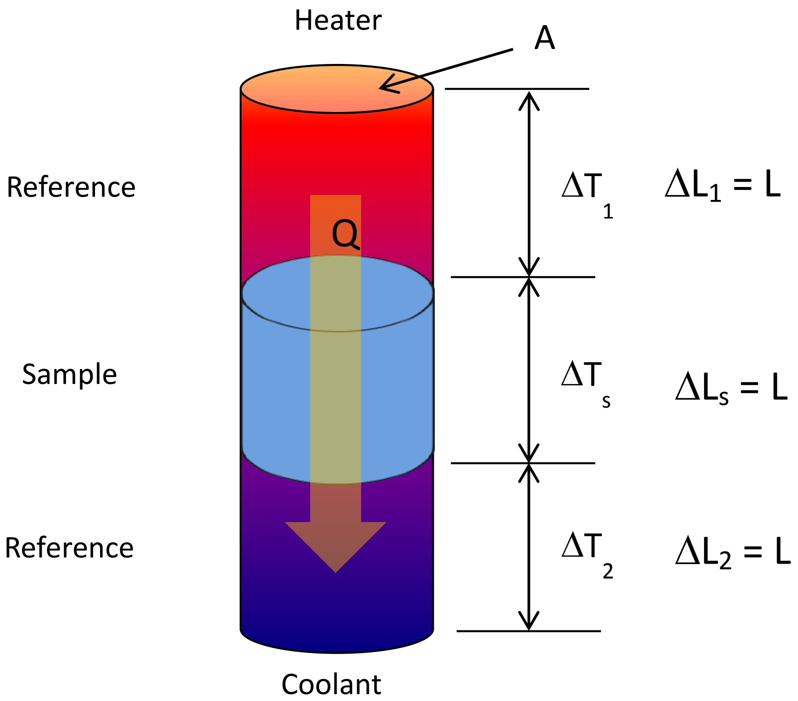

Figure 2

Where K_R is the thermal conductivity of the references. From this, the thermal conductivity of the unknown sample (K_S) can be derived from the following equation:

$$\frac{Q}{A} = K_S \frac{\Delta T_S}{L} = K_R \frac{\Delta T_1 + \Delta T_2}{2} \frac{1}{L}$$

Guarded or unguarded heat flow meter method (ASTM C518, E1530 Test Methods)

These techniques involves the use of a flux gauge. The flux gauge is very similar, in its purpose, to the references in the comparative cut bar method. In practice, the reference material has a very low thermal conductivity and, therefore, it can be made very thin. Usually, a large number of thermocouple pairs are located on both sides of the reference plate, connected differentially to yield directly an electrical signal proportional to the differential temperature across it.

$$K_S = K_R \frac{\frac{\Delta T_1 + \Delta T_2}{2}}{\Delta T_S}$$

The assembly is cast into a protective coating for durability. This type of flux gauge is mostly used with instruments testing very low thermal conductivity samples, such as building insulations.

In a similar fashion, flux gauges can be constructed from just about any material, thick or thin, depending on the material's thermal conductivity. Common requirements for all flux gauges are that the material used for the measuring section be stable, not affected by the thermal cycling, and the gauge be calibrated by some method independently. A very large variety of testing instruments use this method.

Guarded Hot Plate Method (ASTM C 177 Test Method)

Guarded hot plate is a widely used and versatile method for measuring the thermal conductivity of insulations. Although the specimens are often rather large, this usually presents no difficulty. A flat, electrically heated metering section surrounded on all lateral sides by a guard heater section controlled through differential thermocouples, supplies the planar heat source introduced over the hot face of the specimens. The most common measurement configuration is the conventional, symmetrically arranged guarded hot plate where the heater assembly is sandwiched between two specimens (Figure 3). In the single sided configuration, the heat flow is passing through one specimen and the back of the main heater acts as a guard plane creating an adiabatic environment.

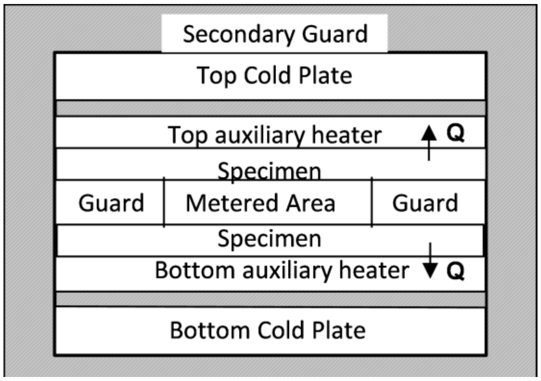

Figure 3

This is an absolute method of measurement and its applicability requires: (a) the establishment of steady-state conditions, and (b) the measurement of the unidirectional heat flux in the metered region, the temperatures of the hot and cold surfaces, the thickness of the specimens and other parameters which may affect the unidirectional heat flux through the metered area of the specimen.

Three different categories of measurement systems can be distinguished: apparatus working around room temperatures, apparatus working below room temperatures (down to about -180^{o}C), and apparatus working at high temperature (600^{o}C or above). A given apparatus is most often best adopted for measurement in one of these temperature ranges.

Hot Wire Method (ASTM C1113 Test Method)

Hot wire methods are most commonly used to measure the thermal conductivity of “refractories” such as insulating bricks and powder or fibrous materials. Because it is basically a transient radial flow technique, isotropic specimens are required. The technique has been used in a more limited way to measure properties of liquids and plastics materials of relatively low thermal conductivity.

Relatively recent modification of this long-established technique is the “probe“ method. This configuration is particularly practical where the specimen conductivity is determined from the response of a “hypodermic needle” probe inserted in the test specimen. Thus the method is conveniently applied to low-conductivity materials in powder or other semirigid form. A probe device can be used to measure the thermal properties of soils in situ, but most commonly a closely controlled furnace is used to contain the sample and produce the base temperatures for the tests. The probe contains a heater and a thermocouple attached to it. When a certain amount of current is passed through the heater for a short period of time, the temperature history of the heater’s surface will take on a characteristic form. In the initial phase, the temperature will rapidly rise, and as the heat begins to soak in, the rate of rise becomes constant. When the thermal front reaches the outer boundary of the sample, the rise will slow down or stop altogether due to losses into the environment. From the straight portion of the rate curve (temperature vs. time) the thermal conductivity can be calculated.

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