



Limitations Encountered in Thermal Conductivity & Thermal Diffusivity Testing

It is often desirable to identify a single instrument that can test widely differing materials as glass, metal, ceramics, polymers, insulation, thin films, diamond, and a variety of composites, to obtain thermal conductivity data directly. The answer is that no such device exists.

The parametric requirements for testing these materials are often diametrically opposite and, when an instrument is being set up for one, it nearly precludes the other. Below is a short review of the principles that prevent the construction of such a universal machine.

Direct Measurement of Thermal Conductivity

Thermal conductivity is defined:

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

where (Q/A) is the heat flux (Q is the amount of heat passing through a cross section A of a sample), and ($\Delta T/\Delta L$) is the resultant thermal gradient (ΔT temperature difference over ΔL length along the heat flow). This is of course only true for uniaxial heat flow, so means of guarding must be provided to cut heat flow in other directions to minimum. Since one must know the quantity of heat that produces the measured temperature difference, all such methods are quantitative. As long as the components of this quantitative relationship are measured, the method is somewhat independent of the nature of the sample.

Steady State Thermal Conductivity Testers

For insulators, one uses a squatty disk sample (like a hockey puck) with a thickness-to-diameter ratio typically $\frac{1}{2}$ or less. Due to the low conductivity of the material, it is easy to build up an appreciable temperature gradient across even a thin sample without asking too much from the heater. On the other hand, if such a sample is made of a metal, the gradient would become very small. To make it larger, and therefore more measurable, one either increases the power, or has to use a thicker or more slender sample. So, for a good conductor sample, the above ratio would be 2 or higher. Just increasing power will rapidly run into trouble with increased losses, shunting paths, etc., so at the end it is a combination of the two that is used. The above is true for any steady state thermal conductivity tester, by any method. Simply increasing thickness on a given sample is not proper as radical changing of sizes will upset the guarding geometry and the machine will likely work well only with one type of material, but not with another. This is true for the product of any manufacturer (So far no manufacturer has been able to counter the laws of Physics, regardless of what their brochures claim!)

Transient Mode Testers

Even though they are transient mode instruments, these instruments operate in the steady state portion of transient phenomena.

Most of these instruments, like the hot-wire types, can not handle conductivities above 4-5 W/(m·K), and definitely run into trouble around 10. These are ideal for insulators, such as firebrick shapes, and are easy to use, and work well with porous and large aggregate containing samples.

Indirect Measurement of Thermal Conductivity

The most frequently used indirect measurement is by the Flash Method.

The Flash Method does not measure thermal conductivity, but it measures thermal diffusivity, from which under certain circumstances thermal conductivity may be calculated.

This is based on the relationship:

$$\lambda = \alpha \cdot C_p \cdot \rho$$

where α is thermal diffusivity, C_p is specific heat capacity and ρ is density. Thus, one may derive thermal conductivity from thermal diffusivity data. While this is quite useful in many cases, it can also be disastrous in others. The above relationship is true for homogeneous, pure, and anisotropic materials. As long as the intended samples fall into this category the elegance and speed of this method is very attractive. Nevertheless, one still must know the proper values for C_p and ρ , otherwise the resultant λ value will be inaccurate. It is easy to see that any error in those two properties will directly affect λ . Estimating either or both of those properties will be just as bad as estimating λ itself.

Problems arise when the material does not fit into the above category. The more severe the deviation from the above criteria, the more suspect the computed value of λ becomes.

The discussion below pertains to the most frequently encountered deviations and their implications on calculated thermal conductivity.

The Flash Method is based on measuring the characteristic temperature rise of the rear surface of the sample, when the front is irradiated with a high energy pulse usually from a laser or flash lamp. In essence, the temperature rise follows the propagation pattern of pulse. It is therefore a qualitative and not quantitative heat transfer measurement. The mathematical solutions all assume homogeneous materials. Composites have not been universally analyzed and very often yield erroneous data especially when converted into conductivity. Also as a general rule, highly porous insulators should not be tested by this method.

For example, a copper matrix having 90% sand in it will give a diffusivity value better than half of pure copper. This is a true result for diffusivity, as the heat pulse will propagate through the matrix just like if it were pure copper, qualitatively. Since the flash method deals with the shape of the curve of rear temperature excursion qualitatively, not with the amplitude (quantitative), the

difference between the 10% matrix or a solid slug is not obvious. When such results are converted into conductivity, the results become useless. The 10% matrix will show half the conductivity of a solid slug, something that is completely wrong. For this reason, using diffusivity data obtained on inhomogeneous or composite mixtures for the purpose of deriving thermal conductivity values, is a very questionable matter.

Samples' dimensions should be, typically 12.5mm in diameter and 1-2mm thick (up to 5mm for very high conductors), although larger samples are sometimes used in special cases.

This small sample size makes this method very attractive for many applications. The same, however, makes it unattractive when individual pores or particles are a large fraction of the sample thickness.

This discussion is provided to alert the investigator to pitfalls in trying to select or specify a machine that is universal and covers an unreasonably broad range of temperatures and materials. The closest one approaches the proverbial "flying submarine" the less utility it will have in any specific application. The Flash Method, perhaps the fastest growing segment of testing in the thermophysical properties measurement field, is also not a panacea, and its applicability is very strictly limited. We strive to match the best instrument to each application. This discussion is intended to alert the potential user to factors that may severely affect the usefulness of a device for the intended application.

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