Thin Copper Foil Heater for Measuring the Thermal Conductivity of Polymers

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ABSTRACT: A new and rather simple apparatus is described for measuring the thermal conductivity of insulating materials. The technique employs a double-sided, copper-coated plastic sheet, known as a printed circuit board, to generate a nearly uniform wall heat flux. Heating is achieved by passing an electrical current through the copper coating. Identical sample slabs are placed against opposite sides of the heater, and the combination is placed in a bath having constant and uniform temperature. When thermal equilibrium is reached, the temperature drops across the central portions of the sample slabs are measured with thermocouples. The one-dimensional form of Fourier heat transfer equation is used to compute thermal conductivity from the observed quantities. In preliminary tests with polymer materials, equilibrium is reached within half an hour. It is estimated that the apparatus is capable of giving measurements accurate to within 5%, and experimental results are consistent with this estimate. Thermal conductivity values are reported for pure polyethylene (PE) and PE mixed with aluminum powder and carbon black. Also reported is the thermal conductivity of pure polycarbonate (PC) and PC mixed with carbon black. The results obtained with the present apparatus are consistent with previous findings. The characteristics of the apparatus make it especially suitable for academic laboratory instruction and for low temperature thermal conductivity measurements. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 88: 2823–2827, 2003

Key words: conducting polymers; polycarbonate; polyethylene; thermal properties

INTRODUCTION

If identical infinite-plane slabs of thermal insulating material are placed on opposite sides of an infinite-plane heater in which heat is generated at a fixed rate per unit area, and if the two outer surfaces of the slabs are kept at the same fixed temperature, the assembly will eventually arrive at thermal equilibrium. The thermal conductivity of the material can be computed by dividing the heat flux through one of the samples by the thermal gradient in that sample. The computation is especially simple because of the one-dimensional character of the heat flow pattern.

In the case of the guarded hot-plate apparatus, usually regarded as the principal device for measuring the thermal conductivity of insulating materials,[1] heat is forced to pass through the samples in approximately the required manner by means of a coplanar guard ring kept at the same temperature as the hot plate. The main difficulties experienced with this method are that the most satisfactory systems for controlling the guard temperature are complicated and expensive, and the heavy copper plates generally employed have considerable thermal inertia and do not reach thermal equilibrium as promptly as is desired.

It is recognized that these objections could be avoided by using the present method. In this case, the known energy is passed through the samples in the required manner, at least in the central region where measurements are made. The heater is made out of a double-sided printed circuit board (PCB). Because there is no separate guard plate, there is no need for a special control system. In addition, because the heater has little thermal inertia, equilibrium is obtained relatively quickly. Furthermore, if the rate at which heat flux is generated in the central region of the heater is to be calculated from external electrical measurements, then the thickness of the metal must be uniform and the heater should transmit negligible heat in a direction parallel to its surface at a rate greatly exceeding that transmitted through its thickness. Constructing a heater simultaneously fulfilling the requirements for low heat transmission and uniform heat generation is the key to developing a device capable of competing with conventional thermal conductivity apparatus.

In order to assess the viability of the present technique, the thermal conductivity of two types of polymer—polyethylene (PE) and polycarbonate (PC)—with different conductive fillers—aluminum powder (AL) and carbon black (CB)—were measured. Where possible, the results were compared with those avail-

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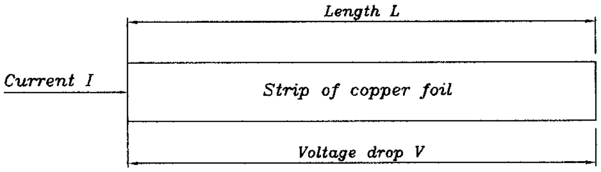

Figure 1 A typical PCB strip.

able in the literature and good agreements were observed. Compared with the existing methods, the present technique proved viable for the measurement of low thermal conductivity materials with good accuracy.

THEORY

If a current, I, passes through the copper strip of a PCB as shown in Figure 1, and the voltage drop across the strip is V, then the power dissipated is given by $P = VI$ and the voltage difference across the strip is given by Ohm's law as $V = IR$. Then, q'', the rate of heat generation per unit area, A, is given by

$$q'' = VI/A \tag{1}$$

Under conditions of thermal equilibrium it is assumed, similar to Plane Source Method[1] (PSM), that all of the heat generated in the central region of the heater flows outward through the samples in a direction normal to the heater. According to the one-dimensional form of the Fourier heat flow equation, the rate of heat flux through one sample is given by

$$q'' = k\Delta T/D \tag{2}$$

where k is the thermal conductivity of the sample, D, is its thickness, and ΔT is the temperature difference across the sample ($T_1 - T_2$), where T_1 and T_2 are the hot and cold plate temperatures respectively.

If two samples are identical, half of the energy generated in the heater passes through each sample so that

$$k = DVI/2A\Delta T \tag{3}$$

Two type K thermocouples were used to measure the temperature on both sides of the sample and then the difference was calculated. Alternatively, a differential thermocouple can be used to measure the temperature drop across the sample.

CONSTRUCTION OF THE MODEL

The PCB used consists of an epoxy fiber substrate of 2 mm thickness, which is copper coated on both sides with a thin and uniform layer of 0.01 mm thickness. The present development has been made possible by commercial production of PCB possessing the required characteristics. For the present investigation, a fine zigzag circuit was found to be adequate. It was first produced using computer graphics to give an accurate and uniform strip width along the board (Fig. 2). The board, 14 cm square, was divided into 46 uniformly spaced strips each 2.5 mm wide, separated by 0.5 mm spacing. The spacing was used to electrically insulate the strips from each other. A transparency of the artwork was produced and then the required gaps in the copper foil were made using a standard etching technique. The use of computer graphic software and the etching technique allows one to produce different board layout and finer strip width or gap spacing, if required. This method of grill layout and construction overcomes most of the difficulties encountered by the previous investigators.[2,3] A fine groove (2 mm width, 70 mm length) was machined in the middle of the heater to allow a fine thermocouple to be imbedded for temperature measurement. The total resistance of the PCB was about 3.84 Ω and the voltage and current needed for heating it to 50°C was about 5 V and 1.3 A respectively.

AUXILIARY APPARATUS

The power leads capable of carrying about 10 A were fastened to the input of PCB. A 30 V regulated dc power supply used as a current source for the heater was capable of delivering five amps regulated to within 0.1%. Both the current and voltage were read from the power supply. Two identical type K thermocouples were used to measure the temperatures on both sides of the samples. The interface temperatures were recorded using a type KM43 Comark temperature indicator to within 0.1°C.

EXPERIMENTAL

Similar to PSM, four identical samples of 2 mm thick and 14 cm square each were placed in position on opposite sides (two on each side) of the heater, and they were held firmly against the heater with a U-shape clamp as shown in Figure 3. The test samples were already compression molded in the form of plates in a Collin press to the required size, thickness, and surface finish. Therefore, the samples' area was equivalent to the area of the central heater. Thermocouples data taken after the assembly (with the power supply turned off) indicated zero temperature difference across the samples, as expected. When the power supply was turned on, the thermocouples reading the hot and cold plate temperatures increased steadily, and within half an hour they reached a new equilibrium value. There were no further changes except those that could be attributed to changes in the heater

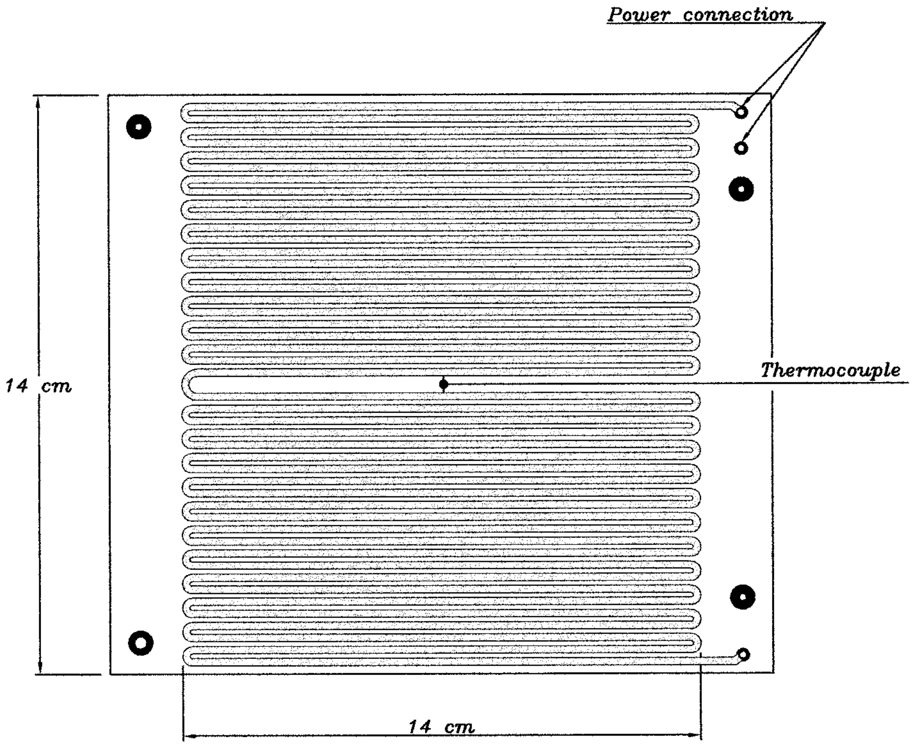

Figure 2 Configuration of the PCB heater.

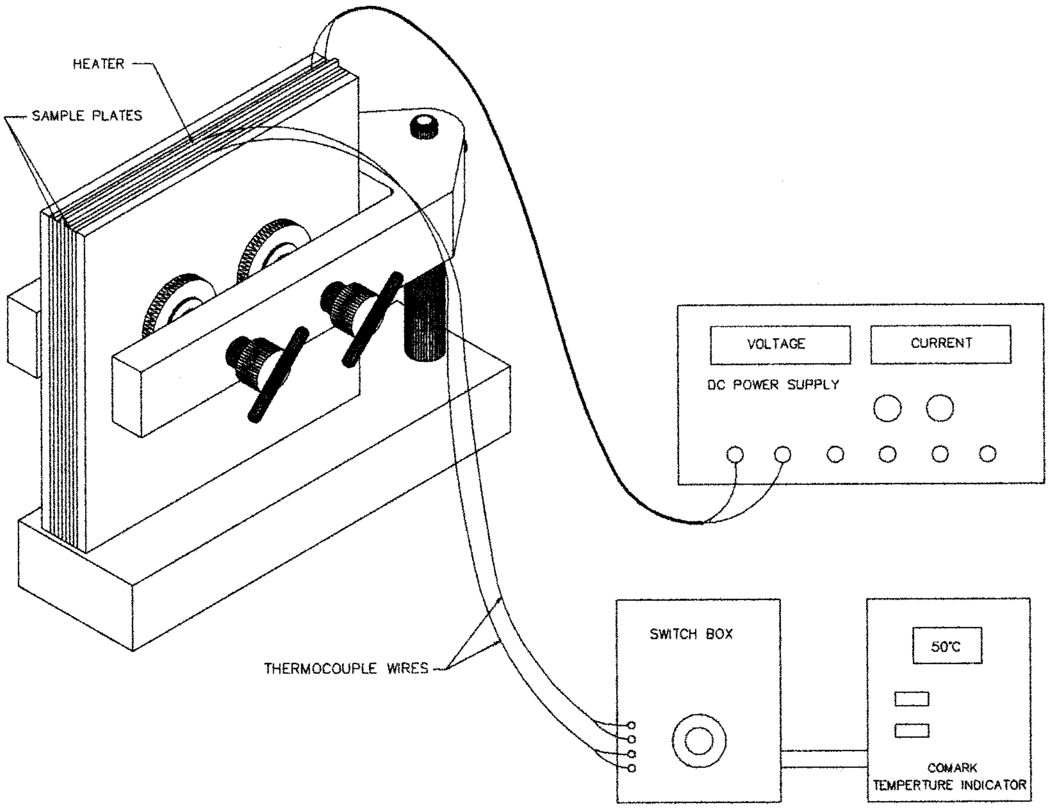

Figure 3 Experimental apparatus.

TABLE I
Tabulation of Measured Data and Thermal Conductivity Values

Material	Voltage, V (V)	Current, I (A)	ΔT (°C)	Thermal conductivity, k (W/m°C)
PE, Pure	5.0	1.31	1.9	0.351
PE, 5% AL	5.0	1.32	1.8	0.374
PE, 20% AL	5.0	1.32	1.5	0.441
PE, 35% AL	5.0	1.31	1.3	0.514
PE, 35% CB	5.0	1.32	1.5	0.448
PC, Pure	5.0	1.31	2.8	0.238
PC, 35% CB	5.0	1.31	2.3	0.290

current caused by heating in the power circuit. The change in the current were less than 0.02 A. When four successive readings did not differ by more than 1%, the measured values of V, ΔT, and I were used in the calculation of k via eq. (3). Of course, the necessary dimensions of sample thickness and area were also needed.

RESULTS

The results of thermal conductivity values computed from eq. (3) are presented in Table I. As was expected, the increase in thermal conductivity of PE with the addition of CB and AL powder and PC with the addition of CB is evident from the result obtained in the present investigation, with AL powder composite having the highest value of thermal conductivity. The thermal conductivity values obtained using the present technique (0.351 W/m °C, for pure PE and 0.238 W/m °C for pure PC) were compared with those reported in the literature (0.335 W/m °C for pure PE and 0.2 W/m °C for pure PC[4]) and good agreement was observed, less than 4.5% deviation for pure PE and higher than 5% deviation for pure PC. The deviation between measured and reported values of thermal conductivity could be attributed to the molding process of the samples and sample grades that might be different from that used by other investigators, especially for pure PC. Furthermore, it could also be due to the heat lost by natural convection through the periphery of the test samples that were difficult to measure and quantify accurately, and were therefore neglected.

The present method is almost similar to the PSM, except for the central heating unit, which is based on a special printed circuit board. The samples used in PSM are four or eight slabs of the order of 20 cm square and a total thickness not exceeding 2.5 cm. However, in PSM for stack sample approximately 1.25 cm thick with a total volume of 10^3 cm^3, Steere[5] reports that for polymers, an accuracy of 3% can be obtained in the measured value of thermal conductivity. Therefore, by reducing the periphery to sample surface area ratio or carefully insulating the periphery of samples, two-dimensional effects are minimized and also better accuracy can be obtained in the measured value of thermal conductivity.

UNCERTAINTY ANALYSIS

A precise method of estimating uncertainty in experimental results has been presented by Moffat.[6] The estimate in uncertainty in the computed thermal conductivity is based on the uncertainties in the primary measurements. The result, R, is a given function of the independent variables $x_1, x_2, \ldots, x_N$. Thus

$$R = x_1^a x_2^b x_3^c x \ldots x_N^N \tag{4}$$

where a, b, c, etc., are uncertainties in the independent variables. Then the uncertainty in the dependent variable R is given by

$$\frac{\delta R}{R} = \left\{ \left(a\frac{\delta x_1}{x_1}\right)^2 + \left(b\frac{\delta x_2}{x_2}\right)^2 + \ldots \left(N\frac{\delta x_N}{x_N}\right)^2 \right\}^{1/2} \tag{5}$$

The following are the possible uncertainties for the measured values:

1. Temperatures on both sides of the sample were measured with two type K thermocouples connected to a Comark type KM43 temperature indicator with an accuracy of ±0.1°C.
2. Voltage was measured with a digital voltmeter with an accuracy of ±0.1 V.
3. Current was measured with a digital ammeter with an accuracy of ±0.01 A.
4. Sample dimensions were measured with a vernier caliper with an accuracy of ±0.1 mm.

Using eqs. (3) and (5) and inserting the numerical values of uncertainty for the independent variables, the uncertainty in the value of dependent variable, i.e., thermal conductivity, was determined to be less than 5%, which is well within the range of experimental uncertainty.

CONCLUSIONS

Since the main object of the present investigation was to assess the copper foil technique, the actual thermal conductivity values obtained are of secondary importance and at this stage cannot be treated as definitive date, since no other means of measuring and comparing the thermal conductivity of the present samples were available to the author. Nevertheless, the few results obtained with the present apparatus are consistent with those available in the literature, obtained by other means. In addition, it was demonstrated that the present method proved viable for the measurement of thermal conductivity of polymers or composites and nonmetallic materials. It is easy to implement and cheap to construct.

The results obtained also show that binary composite systems, comprised of conductive filler (e.g., CB, AL powder, etc.) in a polymer matrix, create a material that is thermally conductive. These conductive polymer composites may find use in a variety of thermal applications.

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