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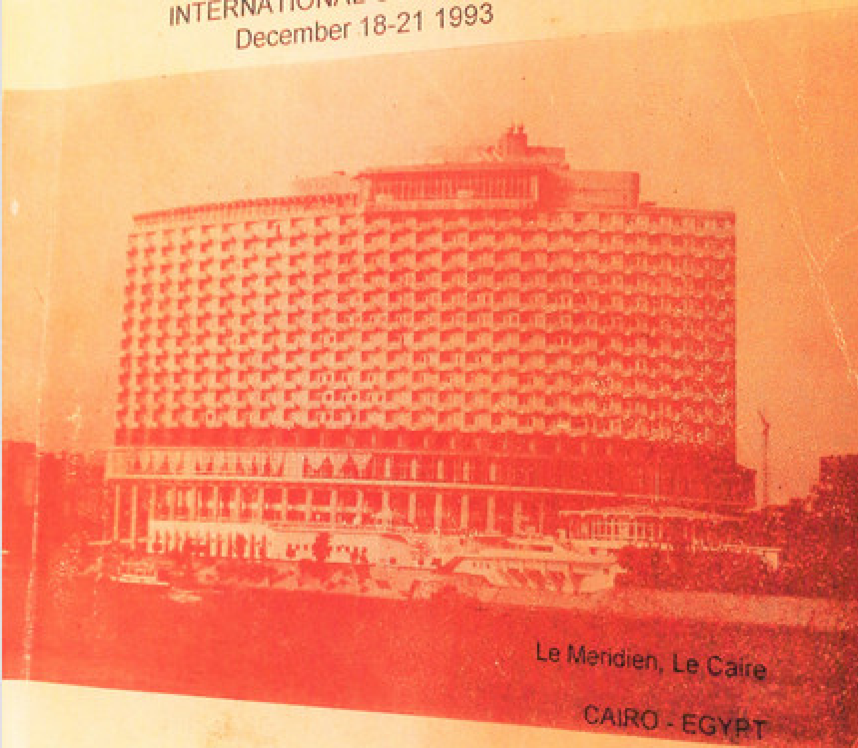

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EXPERIMENTAL AND NUMERICAL EVALUATION OF THERMAL CONDUCTIVITY OF BUILDING & INSULATING MATERIALS

Karem M. EL-SHAZLY & Mohammed F. ABD-RABBO
Mech. Engng. Dept. Faculty of Engng. , Shoubra, Zagazig University

Abstract

Experimental and numerical evaluation of thermal conductivity of building and insulating materials are presented. The method of conductivity measurement using the transient line heat source (thermal conductivity probe) is described. This is due to the fact that the engineering applications may require a spot local and instantaneous thermal conductivity values. The probe was designed so that when embedded in the sample will simulate a one-dimensional unsteady conduction heat transfer system. Experimental and numerical results are presented for five samples; three building materials which are gypsum, red-brick, and concrete and two insulating materials which are styrofoam and glass wool. Temperature-time history was obtained at the midpoint of the probe for different power inputs. A mathematical model is derived based on finite difference technique to solve the transient energy equation. Two equations are derived to obtain experimental and numerical values of thermal conductivity of different materials. Maximum error between experimental and numerical results is 5.9%. The present results are in good agreement with the previously published results

1- Introduction

The thermal conductivity property (k) may very locally with temperature , humidity, material composition, direction ... etc. Knowledge of local thermal conductivity is important in the evaluation of heat transfer rates. The magnitude of thermal conductivity may be very small or very large. This is due to the fact that the thermal conductivity depends on the structure and constituents of the material. Non homogeneous materials are usually treated by evaluation of an effective thermal conductivity. Engineering applications may require a spot local and instantaneous thermal conductivity values, so that the results of field test data may be evaluated accurately. Methods of thermal conductivity measurements can be divided into two categories:

a) The steady state (guarded hot plate), in which heat from a source is allowed to pass through the material and steady measurements of temperature along the path of heat flow can be obtained from many literature as [1, 4, 9, 11]. The Fourier's law is expressed as:

$$Q = - k \cdot A \frac{\Delta T}{l} \qquad (1)$$

Thus the correct measurements of Q, l, A and ΔT will give a correct value of k. Heat loss, measurement errors and k dependency on temperature make this method impractical for some field applications. This is particularly true if k is very small as in the insulation materials which are used in buildings and space air conditioning.

b) The transient method offers a fast and reliable means of measuring good thermal conductivity. Heat is introduced into the material as a pulse of fixed constant rate, or programmed variable rate [3, 5, 14]. The temperature-time history at a preset fixed location in the solid within the specimen may be recorded. Transient flow methods of measuring thermal conductivity and diffusivity often involve the extraction of the desired results from mathematical equations. This could be quite tedious without the aid of a computer. The results may be more easily obtained from a simple straight-line graph [10]. Karim G. A. et al. [8] measured the effective thermal conductivity of some samples of oil sands using a transient technique over the relatively wide temperature range of -100 to 300 °C at atmospheric pressure. Bala et al [2] predicted the thermal conductivity of two-phase macro porous systems with different interstitial media. Mathematically, the system may be described as follows:

The Fourier equation is

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (2)$$

A theoretical solution for the temperature distribution within the specimen may be obtained in terms of thermal properties.

Proper design of the heat source configuration, specimen, location of the measuring point r_o, may significantly affect the validity of the results. Work had been performed on many different heat source configuration, r_o, and heat input and results were obtained for different pertinent conditions. Such a system has an added advantage of being made portable which can conveniently serve field test data evaluations.

The objective of this work is to evaluate the method in determining the thermal conductivity of building and insulating materials. The system is of a cylindrical heat source with a temperature measuring station located at the walls of the cylinder, and using a constant step power input. The calculated value of thermal conductivity is obtained by using numerical analysis to one-dimension equation. Constant heat flux is taken at outer surface of the probe and the outer surfaces of the sample are taken insulated as boundary conditions.

2- Theoretical work

Consider transient, one-dimensional heat conduction with constant properties and no internal heat generation. A transient temperature profile occurs within the solid. The material under consideration is as shown in Fig. 1. The governing equation 2 is converted into dimensionless form as:

$$\frac{\partial^2 \theta}{\partial \bar{r}^2} = \frac{\partial \theta}{\partial Fo} \qquad (3)$$

The initial temperature distribution is specified by

$$\theta(\bar{r},0) = 0 \qquad \text{at } Fo = 0 \qquad (4)$$

The boundary condition at $r = R_1$

$$\frac{\partial \theta(0,Fo)}{\partial \bar{r}} = -\frac{1}{1 - R_o} \qquad \text{at } Fo > 0 \qquad (5)$$

where $R_o = \frac{R_1}{R_2}$, $\bar{r} = \frac{r}{R_2}$

The insulated boundary condition is specified at $r = R_2$ for all times greater than zero by writing

$$\frac{\partial\theta(1,Fo)}{\partial \bar{r}} = 0 \qquad \text{at } Fo>0 \tag{6}$$

The finite difference form of the governing equation is given by

$$\theta_i^{n+1} = \theta_i^n \left[1 - 2F \right] + F \left\{ 1 - \frac{\delta}{2\bar{r}} \right\} \left[\theta_{i+1}^n + \theta_{i-1}^n \right] \tag{7}$$

where $\delta = \left[\frac{(R_2 - R_1)}{(n-1)} \right]$,

n = number of nodes with the requirement that $F \leq 0.5$

A grid network is needed to form the nodal points which represent the solid region and its boundary. In the finite difference solutions, it was necessary to initially assign arbitrary temperatures to all nodes within the grid. Then the finite difference equations were applied to each node to calculate new values of the nodal temperatures. Several iterations over the entire field are necessary to find the solution which satisfies the boundary conditions on all sides.

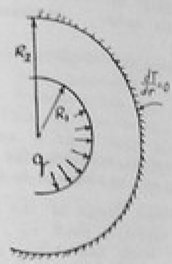

Fig. 1: Physical model of the system

To obtain the relation between temperature and time at $r = R_1$, one can follow;

$$Q = -KA \left.\frac{\partial T}{\partial r}\right]_{r=R_1} = \rho C_p V \frac{\partial T}{\partial t} \tag{8}$$

$$\left.\frac{\partial T}{\partial r}\right]_{r=R_1} = -\frac{q}{k}$$

$$\frac{\partial T}{\partial t} = \frac{\alpha A}{V} \quad \frac{q}{k} \tag{9}$$

From Equation (8), one can write

$$\frac{\partial \left\{ \theta \cdot \frac{q (R_2 - R_1)}{k} \right\}}{\partial \left\{ Fo \cdot \left[\frac{(R_2 - R_1)^2}{\alpha} \right] \right\}} = \frac{\alpha A}{V} \quad \frac{q}{k} \tag{10}$$

The value of $\frac{V}{A} = \frac{(R_2 + R_1)}{2}$

By integrating Eq. 9, one can write

$$\theta - \theta_1 = \frac{(R_2 - R_1)}{\frac{(R_2 + R_1)}{2}} \cdot \frac{k}{\rho C_p} \cdot \frac{t}{(R_2 - R_1)^2} \tag{11}$$

The value of thermal conductivity becomes

$$k = \frac{\rho C_p \ (R_2^2 - R_1^2) \ (\theta - \theta_1)}{2\,t} \tag{12}$$

3 Experimental work

The heat source consisted of a 100 mm long copper tube of 7.8 mm outside diameter. A coiled electrical heater was introduced from the inside tube (FIG. 2). A Cu-Co thermocouple was fixed to the inside of the tube. A 2 mm length of the heating tube was inserted into a solid conical cork to ensure good insulation characteristics of exposed surface of the specimen during the test operation, thus simulating the adiabatic wall conditions required at the exposed wall surface. Thermocouple leads were connected to a potentiometer. The leads of the heating coil were connected to a D.C power supply.

The materials tested were: styrofoam, glass wool, gypsum, red-brick and concrete. A specimen of 250 mm * 250 mm * 120 mm size was taken from each material in which a hole of 8 mm diameter was drilled at the center of each specimen to a depth of 100 mm to house the heating rod.

The test run was started when the initial temperatures of the specimen and probe were the same. The D.C supply was set-on at a pre-set constant voltage supply, and simultaneously, a stop watch was started. Temperature at the mid-length of the probe was measured at 30 second intervals for about 30 minutes.

From Eq. 8. The relation between measured temperature and time can be derived as:

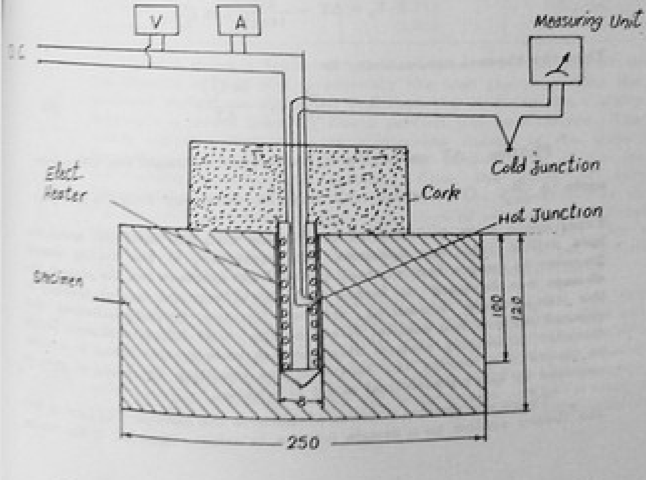

Fig. 2: Cross Section of the sample and heated cylinder system with instrumentation.

$$\left.\frac{\partial T}{\partial r}\right]_{r=r_o} = -\frac{Q}{k(2\pi r_o L)} = -\frac{ql}{2\pi k r_o}$$

$$\frac{\partial T}{\partial t} = -\frac{kA}{\rho CV}\left.\frac{\partial T}{\partial r}\right]_{r=r_o} \tag{13}$$

$$\frac{\partial T}{\partial t} = \frac{kA}{\rho CV}\,\frac{ql}{2\pi k r_o}$$

$$\frac{\partial T}{\partial t} = \frac{2kA}{\rho CV r_o}\,\frac{ql}{4\pi k} \tag{14}$$

$$\frac{\rho CV r_o}{2kA} = \frac{L r_o}{2\alpha} = \frac{L r_o^2}{2\alpha r_o} = \frac{r_o^3}{\alpha}\,\frac{L}{l} \tag{15}$$

The temperature rise at a point in an infinite mass of material heated by a perfect line source is [13]

$$T(r,t) = \frac{ql}{2\pi k}\; I\left\{\frac{r}{2(\alpha t)^{0.5}}\right\} \tag{16}$$

$$I(x) = C - \ln(x) + \frac{x^2}{2} - \frac{x^4}{8} + \ldots\ldots$$

If $x = \left\{\frac{r}{2(\alpha t)^{0.5}}\right\}$ is small, i.e large (t) and small (r), the terms of order x^2 and above may be neglected and

$$T(r,t) = \frac{ql}{2\pi k}\left\{C - \ln\frac{r}{2(\alpha t)^{0.5}}\right\} \tag{17}$$

Between times t & t_1, the temperature rise is therefore given by

$$T - T_1 = \Delta T = \frac{ql}{(4\pi k)}\cdot\ln\left(\frac{t}{t_1}\right)$$

Then the thermal conductivity is

$$k = \frac{ql}{(4\pi)}\cdot\frac{\ln\left(\frac{t}{t_1}\right)}{\Delta T} \tag{18}$$

Plotting ΔT versus (ln t), would yield a straight line with a slope equals to $\frac{q_l}{4\pi k}$, from which (k) may be evaluated from the given (q_l).

Experiments were modelled in accordance with the analytical model. the hole drilled into the specimen was equivalent to the heating element diameter to ensure heat contact between the specimen and the element. the element was designed to insure that end effects are minimal, specially at the temperature measuring station. Surface insulation insured that exposed surface has minimal effect on the radial diffusion of heat. Sample diameter to heating element diameter was made greater than 30 in order to insure that during the test run, the condition $T = T_{rase}$ at $r = \infty$, as required by the mathematical model is satisfied.

There are several sources of error in the method: The first is that the theory applies to a sample infinite in extent. However, if the testing interval is limited to the time before the heating is "felt" at the sample surface, then samples of practical dimensions behave as though they are infinite in size. The second is due to the contact resistance between the probe and the surrounding sample. The third is due to variation in the resistance of the heater wire with temperature (nonconstant power input). This error can be made negligible by using as the heater a wire with a low temperature coefficient of resistance. The fourth is due to dropping the higher terms in the I(x) series. This error is minimized by having the thermocouple close to the heater and by discounting the early part of the temperature-time record.

4- RESULTS AND DISCUSSION

A comparison between measured and calculated values of thermal conductivity is given in Table 1. Good agreement between measured and calculated values is found. The maximum error between them is 5.9%. Generally, numerical values of thermal conductivity is smaller than measured values.

Figure (3) shows the temperature rise against time for the samples of styrofoam, glass wool, gypsum, red-brick and concrete. The figure clearly indicates that the temperature rise increases with increasing time. The temperature rise for insulating materials is greater than that for building materials at the same time. This result is due to the fact that the insulating materials retarded the transfer of heat than the building materials.

Table (1) Comparison between measured and calculated values of thermal conductivity

MATERIAL	Density	Exp.results	Numerical Results
Styrofoam	11(kg/m3)	0.042(w/m k)	0.0396(w/m k)
Glass wool	20	0.044	0.0415
Gypsum	1850	0.424	0.4000
Red brick	1800	0.543	0.5230
Concrete	2200	0.818	0.7700

Figure(4) shows a temperature rise versus the logarithm of the time. The linearity of this plot is probably the best guarantee that the errors mentioned earlier are negligible, and that the probe in the vicinity of its mid-length is indeed behaving like a perfect line heat source. The figure clearly indicates that there is a discrete change in the slope of the Temperature-log(time) curve. The thermal conductivity of the insulating and building materials is obtained from the slope of each line. Dimensionless temperatures and log(Fourier) are represented as shown in Fig. (5). Figure 5 shows that the slope of all lines which represented the measured materials is constant. This means that the thermal conductivity of the building and insulating materials is not obtained from the slope of the dimensionless temperature-log(Fourier) diagram

Figure 6 shows a comparison between measured and calculated dimensionless temperature at different Fourier numbers. The calculated conductivities are noted to be lower than the experimental; probably this is due to that the energy equation which is used in obtaining the calculated temperature is only for pure conduction. While other modes affected the measured values of temperature. The present thermal conductivity for materials are compared with those previously obtained (Table (2)).

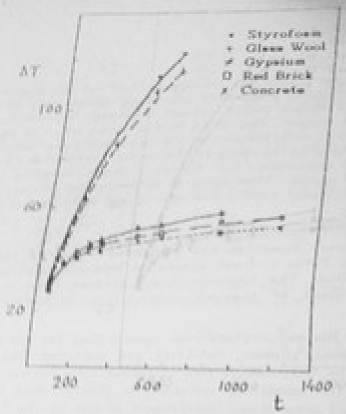

Fig.3: the temperature rise against time to the samples of styrofoam, glass wool, gypsum, red-brick and concrete

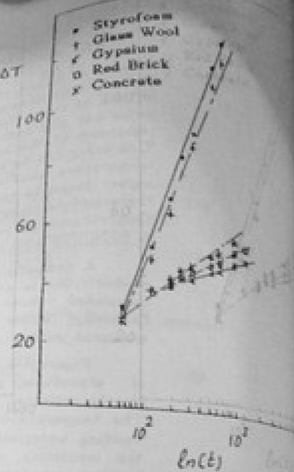

Fig.4: temperature rise versus the logarithm of the time for building and insulating materials

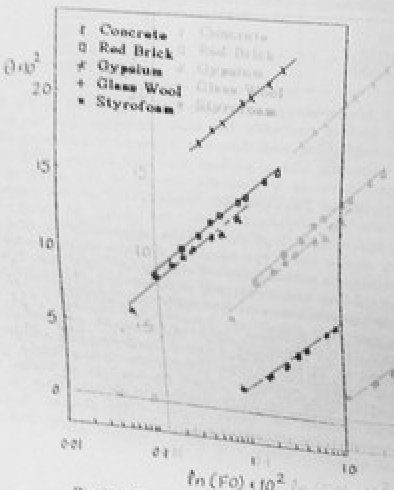

Fig.5: Dimensionless temperatures versus Fourier number for samples.

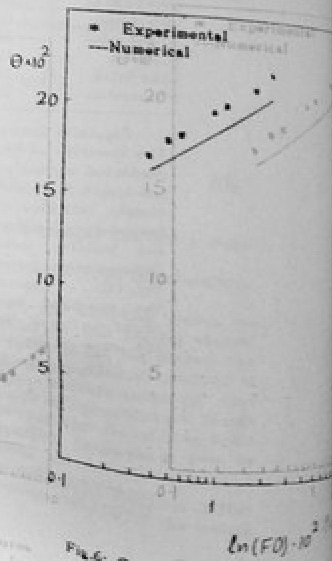

Fig.6: Comparison between measured and calculated dimensionless temperature at different Fourier numbers.

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