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THERMAL CONDUCTIVITY OF BUILDING MATERIALS: AN OVERVIEW OF ITS DETERMINATION

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Abstract: A range of instruments are available to measure thermal conductivity of building materials. Some of these tools are heat-flow meter, hot plate, hot box and heat transfer analyzer. Thermal conductivity data derived by using different instruments can be different from each other. Implication of these variations in thermal conductivity is significant in terms of commercial profile of the insulations and also in terms of calculating energy saving in large scale use of that specific insulation. Thus it is important to know which of the measuring instrument for thermal conductivity can produce relatively accurate and representative result. This paper firstly looks at the methods and instrument for measuring thermal conductivity of building materials and secondly compares and analyses the results of testing thermal conductivity of fibrous insulations using a heat analyzer and a hot plate.

1. Introduction:

Thermal conductivity is defined as the rate of heat transfer through the unit thickness of a material per unit area per unit temperature difference. The unit of thermal conductivity is w/m-ĸ. Thermal conductivity is lowest in gas phase of a material and highest in solid phase. Heat conduction in a solid phase occurs through the energy transport by flow of electrons and through molecular vibration. In steady state condition, thermal conductivity is a good indicator of the heat conduction through a material, but in transient condition, diffusivity (α in m^2/s) of a material gives a better indication of how quickly heat propagates through a material.

In transient condition, thermal conductivity data of a material is still needed since diffusivity is a function of conductivity and volume heat capacity. Thermal conductivity is usually measured in a steady state condition, however the process is time consuming and complex, especially in case of materials with higher heat capacity. A quicker method requires the measurement of heat transfer in transient condition since steady state cannot be reached in a short period of time. This paper compares steady state and transient methods of measuring thermal conductivity.

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2. Governing Thermal Equations:

The primary equation of thermal conductivity at macroscopic level based on Fourier's law is:

$$Q_x = -K_x A \partial T/\partial x \qquad [w] \qquad (1)$$
$$q_x = -k_X \partial T/\partial x \qquad [w/m^2] \qquad (2)$$

Where Q_x is heat transfer and q_x is heat transfer rate (W/m^2) in x direction per unit area (normal to the direction of heat flow); k_X is thermal conductivity (W/m.K) towards the x direction and $\partial T/\partial x$ is the temperature gradient in the same direction.

The internal thermal conductivity derived from the equation (1) or (2) is for steady state heat flow and temperature variation. Based on the Fouriers' law and the first law of thermodynamics, the following partial differential heat equation is developed for one dimensional transient heat flow where heat capacity of the conductive material is taken into account:

$$\partial^2 T/\partial x^2 + g/k = (1/\alpha)*(\partial T/\partial t) \qquad (3)$$

where α is the diffusivity of the conductive material, ∂T is differential temperature, K is conductivity and g is internal heat generation.

For three dimensional Cartesian co-ordinate system, the heat balance equation is as follows:

$$\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2 + g/K = (1/\alpha)(\partial T/\partial t) \qquad (4)$$

In steady state condition temperature difference is not changing in time ($\partial T/\partial t$), and if there is no internal heat generation, equation (3) and (4) can be written respectively as :

$$\partial^2 T/\partial x^2 = 0 \qquad (5)$$
$$\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2 = 0 \qquad (6)$$

The transient heat flow equations are used in dynamic thermal simulation software while the conventional measuring instruments for thermal conductivity are based on equation (1). Next section describes the conditions in measuring thermal conductivity based on time and determination of heat input.

3. Methods and States:

3.1 Measurement of Heat Flow and Conductivity:

- Absolute Method: In determining thermal conductivity, when heat flux is measured directly from power input.
- Comparative Method: When heat flux measurement is done indirectly during determining thermal conductivity.

3.2 Temperature Difference and Conductivity:

- Steady state: When temperature gradient does not change in time.
- Transient: When temperature gradient changes in time, it is called a transient method.

Next two sections look at instruments and methods in measuring conductivity.

4. Steady state methods for measuring thermal conductivity:

4.1 Hot Box :

Calibrated and Guarded hot box methods are used according to BS EN ISO 8990:1996 (1998). Thermal conductance and resistance are calculated on the basis of the power input in the metering box and the resultant difference of environmental temperature between hot and cold side boxes. However, thermal conductivity only for flat, opaque and homogeneous materials can be derived from thermal resistance data using the following equation:

$$\lambda = d/R_s. \qquad (7)$$

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Air temperatures can be used instead of environmental temperature when there is no significant different between air temperature and radiant temperature

4.1.1 Calibrated HotBox: In calibrated hot box (Figure 4.1, left) the envelope of the hot box is comprised of materials of high thermal resistance so that there is minimal heat loss (Φ_3) through the metering wall. If the flanking loss is Φ_4, and the total power input is Φ_p, then the equation for total heat flow rate Φ_1 through specimen will be,

$$\Phi_1 = \Phi_p - \Phi_3 - \Phi_4 \qquad (8)$$
where $\Phi_3 \le$ (10% of Φ_p)

The metering box walls are thermally insulated, air and vapour-tight. Thermopiles are used to determine heat loss through metering walls, thermocouples are used to measure specimen surface temperature. Electric resistance heaters are recommended for heat supply. Temperature of the cold side chamber is controlled by refrigeration unit.

4.1.2 Guarded Hot Box: In a guarded hot box (Figure 4.1, right), the metering chamber is surrounded by a guard box. The environment of guard box is controlled to minimize heat flow through the metering box wall and lateral heat flow in the specimen. If the lateral loss is Φ_2, and the total power input is Φ_p, then the equation for total heat flow rate Φ_1 through specimen will be,

$$\Phi_1 = \Phi_p - \Phi_3 - \Phi_2 \qquad (9)$$
where $\Phi_3 \le$ (10% of Φ_p)

4.1.3 Calculation for Calibrarted and Guarded Hot Box : The basic equation for U (thermal transmittance, w/m²-k) value are:
$$\Phi = U * A * dT, \qquad (10)$$
$$U = \Phi / A \, (T_2 - T_1) \qquad (11)$$
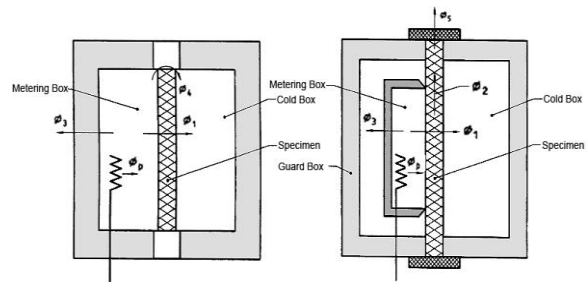$$R = [(T_1 - T_2) / \Phi] * A \qquad (12)$$

Figure 4.1 Calibrated and Guarded Hot Box (BS EN ISO 8990:1996, 1998)

Where A= surface area (m²) of insulation, R= thermal resistance (m²-K/w).

Determining the temperature difference can be complicated. If the thermal resistance of the specimen is much higher than its surface thermal resistance or if forced convection is used in such a way that h_c is greater than Eh_r then the difference of air temperatures in hot and cold side box contribute to negligible errors in measurements. In all other cases difference of environmental temperature has to be taken into account. The equation for environmental temperature T_n is:

$$T_n = (Eh_r * T'_r) / (Eh_r + h_c) + (hc * T_a) / (Eh_r + h_c)$$
$$(13)$$

Where, $h_c = 3.0$ w/m²k (heat transfer coefficient for convection), $h_{r\,=}\,4\sigma T^3{}_m$ (heat transfer coefficient for radiation),
$\sigma = 5.97 * 10^{-8}$ w/m²k⁴ (Stephan Boltzmann constant),
$T_m = (T'_r + T_s)/2$, and $1/E = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, ε and ε_2 are the emissivities of the baffle and specimen respectively. In absence of data for h_c, the following equation is used to determine T_n:

$$T_n = [(T_a * \Phi/A) + Eh_r (T_a - T'_r)T_s] / [(\Phi/A) + Eh_r (T_a - T'_r)] \qquad (14)$$
$$U = \Phi/A(T_{n1} - T_{n2}) \qquad (15)$$

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4.2. Guarded Hot Plate and Heat Flow Meter:

The hot and cold surfaces of hot plate and heat flow meter are directly in touch with the insulation surfaces which eliminate the need for measuring radiant heat. The U value is determined from Equation (10), (11) and (12). The critical issue is how the heat flow rates and temperature differences are accurately measured. Hot plate and heat flow meter uses different method for measuring heat flow rates according to BS EN 12667: 2001(2002). A brief description of both the equipments is provided below:
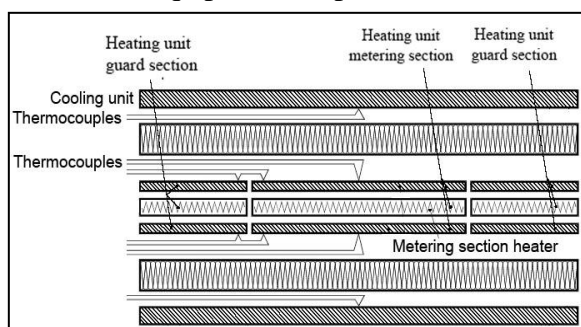

Figure 4.2.   Guarded Hot Plate (BS EN 12667:20012002)

4.2.1. Guarded hot plate apparatus: Here heat flow rate is determined from the power input to the heating unit. In a **t**wo-specimen guarded hot plate (see figure 4.2) two specimens are sandwiched between a central flat plate heating unit and two peripheral flat plate cooling unit (see figure 2a). Heating unit has a metering unit at the centre and two guard units on both sides. The cooling unit is similar to the size of the heating unit. Heat flow rate is determined by measuring the average electric power supplied to the metering area. Temperature difference can be measured from the surface thermocouples of the heating and cooling units. Thermal resistance is calculated from the equation (12). Thermal conductivity can be measured from the following equation:

$$\lambda_t, \lambda^* \text{ or } \lambda = U * d \qquad (16)$$

where, λ_t = Thermal transmissivity, λ^* = hygrothermal transmissivity and λ = thermal conductivity.

Equation (16) is valid for follwing criteria:
- The material is homogeneous,
- For homogeneous anisotropic material, the ratio of conductivity measured in a direction parallel to the surface and normal to the surface is not more than two (in any order), and
- At any one mean temperature thermal resistance is independent of the temperature difference across the specimen

4.2.2   Heat flow meter apparatus: Here density of heat flow rate is calculated by measuring heat flow through the insulation materials using heat flow meters. The measured heat flow is then multiplied by a calibration factor to get the density of heat flow rate. Thermal resistance is determined from the following equation:

$$R= (T_1-T_2) /(f * e_h) \qquad (17)$$

where: f is the calibration factor of the heat flow meter; e_h is the heat flow meter output; T_1 and T_2 are the temperatures at hot and cold sides. Thermal conductivity can be measured from the equation (16).

4.3. Pope, Zawilski and Tritt's method:

Pope, Zawilski and Tritt (2002) developed a

device that uses steady-state absolute thermal conductivity measurements in lessened time. Thermal conductivity measurements are made using electronics and data acquisition software that allows stabilization of temperature. Once temperature is stable, a

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small power of current is independently put into each strain gauge until the heat flow is uniform and stable. The power and ΔT are recorded. Then current through the heater is slightly increased, the temperature difference allowed to equilibrate, and then the power and ΔT are again recorded. This sequence is repeated several times, resulting in a power verses ΔT sweep at a given temperature. This power sweep is then fit to a straight line, the slope being proportional to the thermal conductivity. Measuring period is 24–48 hours.

4.4. Steady state hot-wire method (radial flow method):

In radial heat flow method heat is generated along the axis of a cylinder, when steady-state condition is reached, radial temperature isotherm is measured at two different radii. If there is no longitudinal heat loss, thermal conductivity λ is:

$$\lambda = [Q/(2\pi l \Delta T)] \ln(r_2/r_1) \qquad (18)$$

In practical applications, central heat source is of finite length, therefore end guard is used and correction is applied. This method is also applied as comparative method by having concentric cylinders of known and unknown conductivity with a central heat source. Slack and Glassbrenner (Tritt and Weston, 2005, p.194) used this method to measure thermal conductivity of germanium (figure 4.3, left) taking heat flow reading from power input (absolute method) and temperature readings at the centre and the periphery. One of the present authors also (Pruteanu, 2010) used the method (absolute) to measure thermal conductivity of straw using two concentric tubes (Figure 4.3, right). A hot wire method is especially
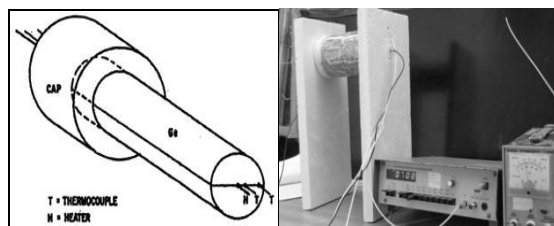

Figure 4.3. Slack and Glassbrenner's device (Tritt and Weston, 2005, p.194) and Radial flow device (Pruteanu,2010, p.11).

useful in high temperature where longitudinal methods can fail due to radiative heat losses from the heater and the sample surfaces.

5. Transient Methods:

5.1 Hot wire method for measuring thermal conductivity:

The transient hot-wire method (Figure 5.1) is used for measuring the thermal conductivity of liquids and low thermal conductivity materials (Carslaw and Jaeger, 1959). Here conductivity can be obtained as a function of temperature, time and heat flow without knowing the diffusivity and the distance. The mathematical model of hot wire method is based on the assumption that hot wire is a continuous line source and by providing constant heating power through thermal impulses it generates cylindrical coaxial isotherms in an infinite homogenous medium with initial equilibrium condition. The transient temperature can be expressed through the following equation:

$$T_{(r,t)} = [\ q/(4\pi\lambda)]*[\ln(4\alpha t/r^2) + r^2/(4\alpha t) - 1/4\{r^2/(4\alpha t)\} - \cdots - у] \qquad (19)$$

Where, λ is thermal conductivity (w/m-k), Q is power supply per unit length (W/m), α is thermal diffusivity of the conductive material, r is the radial position where

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temperature is measured, t is the time between the heat generation and measuring the temperature and У is Euler's constant Assuming that the terms inside the parentheses in equation (10) is negligible at a sufficient period of time and When equation (10) with good approximation as: $(r^2/(4\alpha t) \ll 1$, it is possible to express
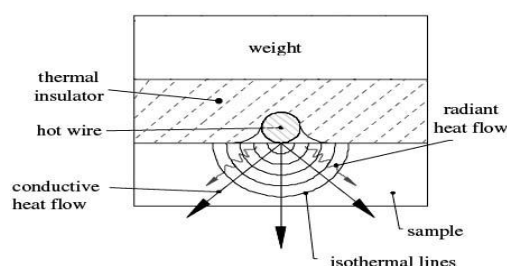

Figure 5.1. Transient hot wire apparatus (Franco, 2007, p.2499).

$$T_{(r,t)} = [Q/(4\pi\lambda)]*[\ln(4\alpha t/r^2) - У] \qquad (20)$$
$$T_{(r,t)} = [Q/(4\pi\lambda)]*[\ln t + \ln(4\alpha/r^2) - У] \quad (21)$$

Therefore temperature variation for time t_1 and t_2 can be expressed as:

$$\Delta T = [Q/(4\pi\lambda)]* [\ln(t_2/t_1)] \qquad (22)$$

5.2 Thermal Analyzer:

In thermal analyazers like Isomet 2140 or Quickline[tm]-30 transient line source (for needle probe) or transient plain source technique (for disc shaped surface probe) is applied based on ASTM D5334 - 08. Conductivity is determined from power input and time dependant temperature variation. The thermal equation applied is similar to those of transient hot wire and transient plain source method.

6 Advantages and Disadvantages of the methods:

6.1 Hot Box, hot plate and heat flow meter:

It is difficult to measure thermal conductivity of insulations in moist condition accurately in these equipments because of the moisture gradient created by the induced temperature difference (Clarke and Yaneske, 2009). These methods are also time-consuming. For dry insulations, hot box can provide reliable results although readings can be distorted due to radiation heat loss in very high temperature measurements. Hot plate and heat flow meter is not recommended for non-homogenous materials. Heat flow meter uses heat flux meters which are comparative instruments that calculate heat flux from temperature- there can be errors in heat flux reading in addition to any error induced by a hot plate method.

6.2 Transient Hot wire method:

Transient hot wire method can render inaccurate result for some insulation materials for two reasons: anisotropy and interlinked pore structure. For anisotropy, one-directional or radial heat transfer equation can provide incorrect result. For inter-linked pore structure (Lei et al, 2010), convection current is likely to be created by heated air during heat flux intervention by the hot-plate or hot-wire, while the transient equations do not take into account heat transfer by convection. For most other insulations, it provides quick and reliable results with smaller samples.

6.3 Steady state hot wire method:

Steady state hot wire method can provide inaccurate heat flow value for anisotropic

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materials due to heat loss towards the longitudinal direction since the governing equation is developed on the basis of infinite length of heat source. However, it is a useful method for some bulk insulation materials (refractory) because of reduced measuring time and need for smaller samples.

7. An experimental study of thermal conductivity:

Two of the present authors (Tucker S and Latif E) have carried out a comparison study of measured conductivity of various fibrous insulation materials in three hygrothermal regimes. For the purpose of this paper, comparison data at 23°C temperature and 50% relative humidity is presented in figure. The experiment was carried out with two devices: Isomet Heat Analyzer (transient method) and Fox 600 Hot Plate (steady state method). Conductivity measurements in steady state method were carried out by Gary Newman and Dick Salisbury of Plant Fibre Technology Ltd.

Measurements were taken by both equipments when the insulation materials had reached Equilibrium Moisture Content (EMC) with 23°C temperature and 50% relative humidity. EMCs for insulation materials were attained by exposing the material to the selected hygrothermal regime in climate chambers and by following the process prescribed in BS EN 12429 (1996).

It can be observed from Figure 5 that there are considerable agreements between the thermal conductivity data for glass wool, stone wool and lamb wool insulation measured by the two equipments. However, thermal conductivity data of hemp fibre and wood fibre insulation measured in Isomet Heat Analyzer is significantly higher than that in Fox 600 Hot Plate. It seems to be a significant finding that the two equipments

do not agree in readings only for cellulose based fibrous insulations. It is not possible without further research to ascertain the reason behind this discrpency. However, two assumptions can be made. It can be assumed that the hydrofillic nature of the cellulose insulation materials as opposed to the hydrophobic nature of the mineral and synthetic fibre insulation may contribute to this behaviour. It can also be assumed that, since steady state measurents require a temperature gradient of 20°C between the
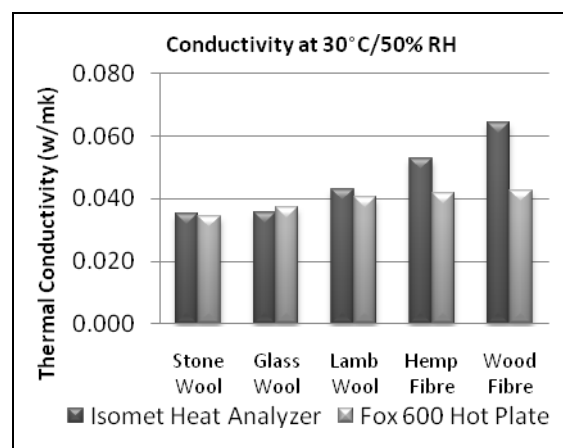

Figure 5. Conductivity measurements.

two sides of the sample insulation and since it takes at least about 72 hrs to reach steady state condition -moisture can be removed or migrated in the mean time resulting in measuring in a condition similar to dry state. In any case, steady state and transient methods provide different values for similar cellulose-based fibrous insulation materials in the stated thermal regime.

8. Conclusions:

Thermal conductivity of insulations can be determined by steady state and transient methods. Hot box, hot plate and heat flow meter devices are time consuming; require bigger samples and are not very accurate in measuring moisture dependent conductivity.

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However these methods are reliable in measuring dry thermal conductivity. There is not much data available on reliability of steady state methods which are relatively speedier. Transient methods are convenient for regular measurement of conductivity; moisture dependent conductivity might be measured without seriously affecting moisture gradient, however this method is not suitable for non homogenous materials. The authors' experiment shows that significant variations exist between certain transient method and steady state method in terms of the data obtained for thermal conductivity of cellulose-based fibrous insulation materials.

9. References:

BS EN 12429, "Thermal insulating products for building applications: Conditioning to moisture equilibrium under specified temperature and humidity conditions", British Standard Institute, 1996.

BS EN 12667:2001, "Thermal performance of building materials and products- Determination of thermal resistance by means of guarded hot plate and heat flow meter methods- Dry and moist products of high and medium thermal resistance", British Standards Institute, 2002.

BS EN ISO 8990:1996, "Thermal insulations- Determination of steady-state thermal transmission properties –Calibrated and Guarded hot box", British Standards Institute, 1998.

Carslaw, H.S., Jaeger, J.C., Conduction *of Heat in Solids*, second ed., Clarendon Press, 1959.

Clarke, J. A., Yaneske, P. P. "A rational approach to the harmonisation of the thermal properties of building materials", *Building and Environment,* 44, 2009, pp. 2046-2055.

Franco, A., "An apparatus for the routine measurement of thermal conductivity of materials for building application based on a transient hot-wire method", *Applied Thermal Engineering,* 27, 2007, pp. 2495-2504.

Lei, Z., Zhu, S., Pan, N., "Transient methods of thermal properties measurement on fibrous materials", *Journal of Heat Transfer,* 132, 2010, pp. 1-7.

Pope, A.L., Zawilski, B., Tritt, T.M., Description of removable sample mount apparatus for rapid thermal conductivity measurements, Cryogenics 41 (2001), 725-731, Elsevier Ltd., 2002.

Pruteanu, M., "Investigations regarding the thermal conductivity of straw", *Bulletin of the Polytechnic Institute of Jassy*, Construction. Architecture Section, Tome LVI(LX), Fasc. 3, 2010, pp. 9-16.

Tritt, T. M., Weston, D., "Measurement techniques and considerations for determining thermal conductivity of bulk materials", in Tritt, T. M. (ed.) *Thermal Conductivity:Theory, Properties and Applications*, New York, Spinger, 2005.

Xamán, J., Lira, L., Arce, J., "Analysis of the temperature distribution in a guarded hot plate apparatus for measuring thermal conductivity", *Applied Thermal Engineering,* 29, 2009, pp. 617-623.