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MEASUREMENT OF THERMAL CONDUCTIVITY OF THERMALLY LOW-CONDUCTING MATERIALS

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ABSTRACT

The thermal conductivity of a building material is a necessary parameter in estimating the cooling load of a building. Cooling load estimates are quite important in selecting building materials especially in hot-climate areas as in Qatar or the Middle East. Commercial equipment for measuring thermal conductivity are quite expensive, and usually not available in the local market. This paper presents a cheap method for measuring thermal conductivity. An apparatus was build and tests were conducted to measure the thermal conductivity of a thermostone brick, a concrete brick, and a red-clay brick. Results of the tests have yielded a conductivity of 0.383 W/(m ^{O}C) for the thermostone brick, 1.443 W/(m ^{O}C) for the concrete brick, and 0.633 W/(m ^{O}C) for the red-clay brick.

NOMENCLATURE

Q	:	Heat transfer rate generated by heater
Q_i	:	Heat transfer rate through side i
Q_i^e	:	Heat transfer rate through edge i
ΔT_i	:	Temperature difference across side i
A_i	:	Area of side i
R_i	:	Thermal resistance per unit area of side i
R_i^*	:	Total thermal resistance of side i
t_i^w	:	Thickness of wood for side i
t_i^i	:	Insulation thickness for side i
k_i^w	:	Thermal conductivity of plywood of side i
k_i^i	:	Thermal conductivity of insulating material of side i
k, K	:	Thermal conductivity

L : Length of an edge
q : Heat flux
ΔT : Temperature difference
Δx : Thickness along heat flux
A : Area

INTRODUCTION

The thermal conductivity of a building material is an important parameter in estimating the cooling load of a building for the sizing of air-conditioning equipment or for estimating the energy consumption of such a building.

There are quite a few methods to measure the thermal conductivity of a material. One of the methods uses the hot-guarded plate, where the sample material is put between two plates; one held at a high temperature and one at a lower temperature so as to invoke a heat flux between the plates. The hotter plate is usually heated by an electric heater and the colder plate is usually cooled by a coolant. Details of such a method is found in the ASTM standard C-177 and also in reference 1. A commercial apparatus to measure thermal conductivity using this method is available, but it is quite expensive. A supplier from the USA has quoted a price in the range of $ 60,000. The apparatus was needed to measure the thermal conductivity of thermostone, concrete, and red-clay bricks in order to perform an economic and thermal performance study of thermostone and red-clay in Qatar.

Another method for measuring thermal conductivity is that using the guarded box, and details of which are described in the ASTM Standard C-277. This method usually employs an insulated box and the test sample divides the box into two smaller boxes; one hot and one cold. The hot box contains an electric heater while the cold box is cooled by circulating a liquid coolant or it is air cooled by means of a small fan.

The method described here is a slight modification of the guarded box, where we employ only one heating box and the sample constitute one of the walls of the box. The outside of the test sample is directly exposed to an air-conditioned environment which is maintained at more or less 22 °C, and therefore no cooling is needed. The box contains a heater to maintain a higher temperature of the wall of the test sample on the inside. Since for low conducting materials, the heat flux across the sample could be small and there is a risk of not reaching steady state, the size of the heater, the dimensions of the box and the thermal properties of the rest of the walls of the box are quite important.

The thermal conductivity of a material is defined by the Fourier law, $q = -k\ (\Delta T/\Delta x)$, where k is the thermal conductivity, q is the heat flux (heat rate per unit area), Δx is the thickness in the direction of heat flow, and ΔT is the temperature difference across the thickness. To measure k, one measures q, ΔT, and Δx; and calculates k as $k=-q\Delta x/(\Delta T)$.

DESCRIPTION OF THE APPARATUS

The apparatus is composed of a guarded box that contains an electrical heater and a fan for air circulation. The electrical heater used is the goot QUICK HEAT SOLDERING IRON TQ-80 with a maximum power of 200 W from TAIYO ELECTRIC IND. CO. Ltd. of Japan, and is bought from the local market. It is attached to a variable power supply unit from ARMFIELD TECHNICAL EDUCATION CO. Ltd. of England. This power supply is used in the company's heat conduction or convection apparatus, and is available in the heat transfer laboratory of the University of Qatar. The variable supply unit has a digital meter that reads the power supply to the heater in Watts. The fan is used to increase the heat transfer coefficient inside the box and to supply air velocities commonly used to simulate wind conditions.

A simplified schematic of the box is given in Fig. 1. As can be seen from the figure, one wall of the box contains the test sample and the rest are made of a plywood (k=0.115 W/m^{o}C) sheet of 12 mm thickness and one or more sheets of extruded polystyrene (k=0.03 W/m^{o}C) for insulation.

The outside of the box is exposed to an air-conditioned space in the heat transfer laboratory which is maintained at more or less 22 ^{o}C. Thermocouples are attached on each wall (on the inside and on the outside) to measure the temperature difference. They are also put inside and outside the box to measure ambient temperatures. These thermocouples are attached to a FLUKE Hydra data acquisition unit which has 20 channels for reading the temperatures.

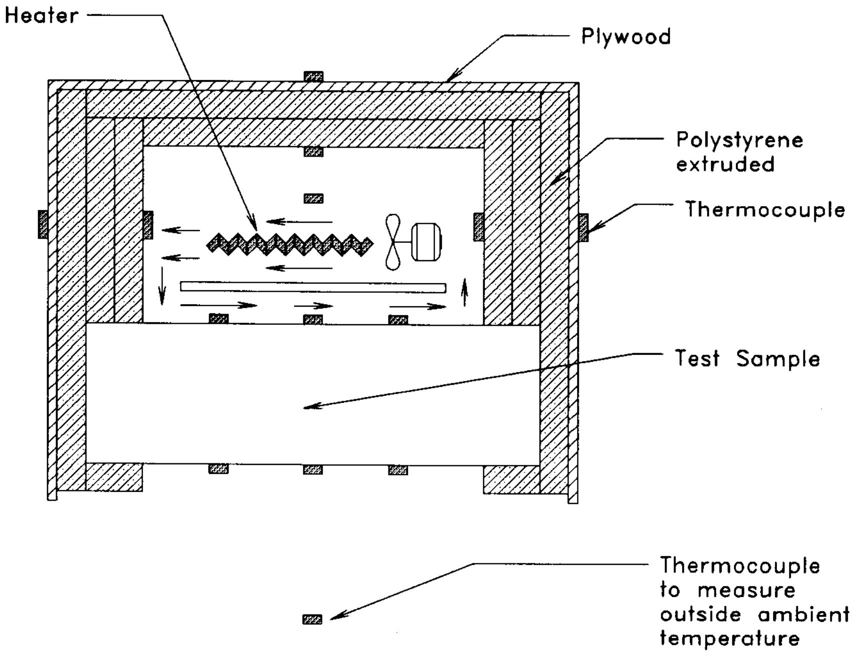

Fig. 1: Description of the box used to measure thermal conductivity

To find the thermal conductivity of the test sample, the heat flow through every side of the box is estimated and in order to account for the multi-dimensionality of the heat flow through the box, the heat through the edges of the box is also estimated by using the formula given by Carslaw and Jaeger [4] for a two-dimensional corner as shown in Fig. 2. If Q denotes the heat rate generated by the heater, Q_i denotes the rate of heat flow through side i, with $i=1$ corresponding to the side where the test sample is located, and Q_i^e denotes the rate of heat flow through edge i, then

$$Q_1 = Q - \sum_{i=2}^{6} Q_i - \sum_{i=1}^{12} Q_i^e \tag{1}$$

where Q_i is calculated as follows:

$$Q_i = \frac{\Delta T_i}{R_i^*} = \frac{\Delta T_i}{R_i / A_i} \tag{2}$$

Here R_i^* denotes the total thermal resistance of side i, R_i denotes the total thermal resistance per unit area for side i, A_i denotes the area of side i, and

ΔT_i denotes the temperature difference across side i. The total thermal resistance is calculated as:

$$R_i^* = \frac{t_i^w}{A_i k_i^w} + \frac{t_i^i}{A_i k_i^i} \tag{3}$$

where for each side i, t_i^w, t_i^i , k_i^w, and k_i^i denote the thickness of the plywood sheet, the total thickness of the insulation sheets, the conductivity of plywood, and the conductivity of the insulating material respectively. For a given edge and referring to Fig. 2, Carslaw and Jaeger [4] give the following formula

$$Q_i^e = KL\left\{\frac{2a}{\pi b}\tan^{-1}\frac{b}{a} + \frac{2b}{\pi a}\tan^{-1}\frac{a}{b} + \frac{2}{\pi}\ln\left(\frac{a^2+b^2}{4ab}\right)\right\}\Delta T, \tag{4}$$

where K denotes the conductivity of the material making the edge, L denotes the length of the edge, and ΔT denotes the temperature difference across the walls making the edge.

The wall temperature difference ΔT_i as well as the heat rate generated Q are read at steady-state conditions. We have made sure that this is the case by adjusting the power supply to a fixed value, and by monitoring the temperature difference for each wall as well as the temperature inside the box with time. When steady-state conditions are reached, all measured temperatures must cease changing with time.

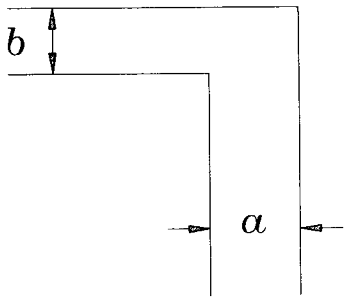

Fig. 2: Description of two-dimensional corner or "edge"

APPLICATIONS

We have used the apparatus shown in Fig. 1 to measure the thermal conductivity of a thermostone brick, a concrete brick, and a red-clay brick. Schematics of these bricks are given in figure 3 through 5 respectively. Since the bricks do not have the same dimensions, we have built three boxes, and detailed dimensions, needed for heat transfer analysis, for these boxes are presented in Tables 1 through 3.

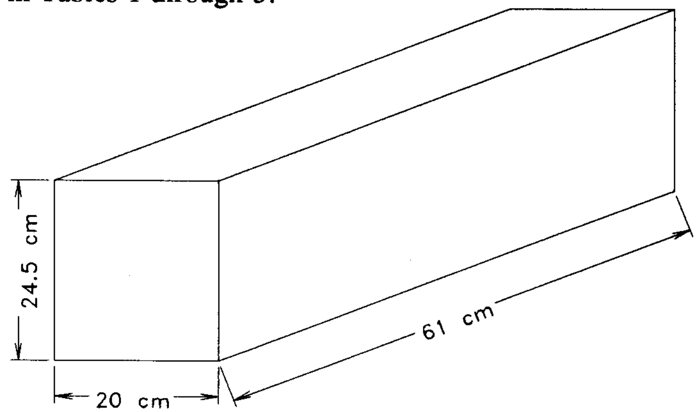

Fig. 3: Detailed description of a thermostone brick

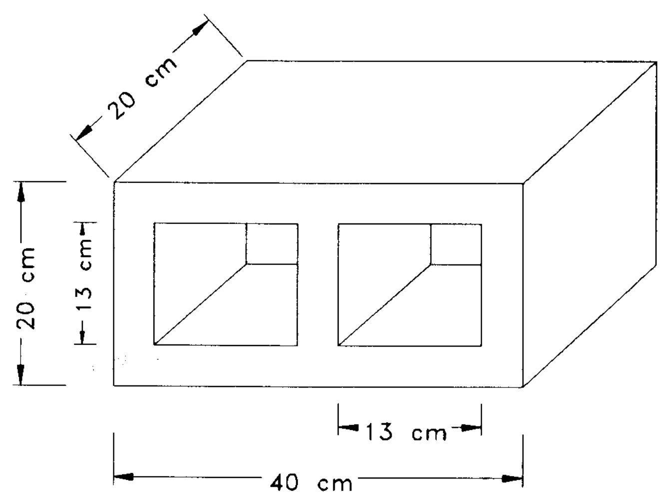

Fig. 4: Detailed description of a concrete brick

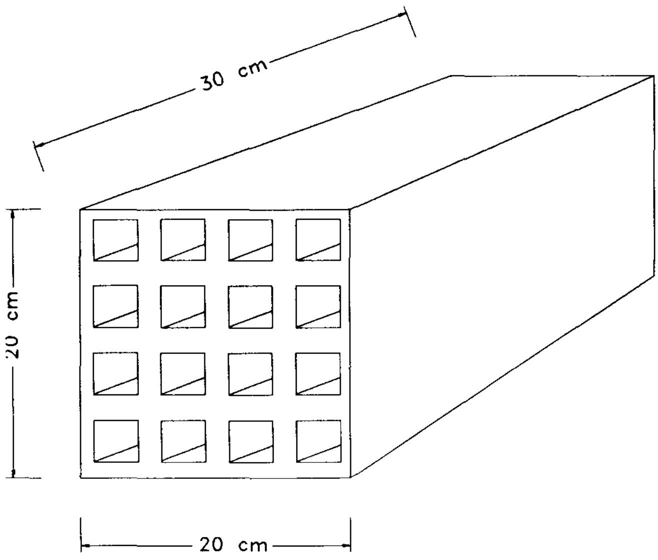

Fig. 5: Detailed description of a red-clay brick

Figures 6 through 8 present the ambient temperature inside the box, the inside-wall average temperature of the test sample, the outside-wall average temperature of the test sample, and the outside ambient temperature as functions of time for the three bricks tested. For the three tests conducted, the heater was initially set to generate heat at its maximum rate which was about 30 W. Then after the ambient temperature has reached a value close to 50 °C or more, the heat rate of the heater was reduced to the necessary value that leads to the desired steady state conditions. The heater was set to generate 15 W for the thermostone brick, 10.9 W for the red-clay brick, and 14 W for the concrete brick. The ambient temperature of the laboratory was about 22 °C.

The initial heating of the box at high heating rate is for reducing the time it takes for steady-state conditions to be reached. As we can see from figures 6 through 8, steady-state conditions have been reached in about less than 4 hours. The time it takes for steady-state to be reached depends on how the test is conducted. If no initial heating of the box is performed, steady state conditions may take as much as 8 hours to be reached.

Table 1: Detailed Dimensions of the Box Used for Measuring the Thermal Conductivity of a Thermostone Brick

Sides	Insulation thickness (m)	Plywood thickness (m)	Total thickness (m)	Height (m)	Width (m)	Area (m^2)
1-Sample	0.00	0.000	0.200	0.43	0.52	0.2236
2-Door	0.08	0.012	0.092	0.43	0.52	0.2236
3-Top	0.08	0.012	0.092	0.29	0.52	0.1508
4-Bottom	0.08	0.012	0.092	0.29	0.52	0.1508
5-Left	0.08	0.012	0.092	0.43	0.29	0.1247
6-Right	0.08	0.012	0.092	0.43	0.29	0.1247

Table 2: Detailed Dimensions of the Box Used for Measuring the Thermal Conductivity of a Concrete Brick

Sides	Insulation thickness (m)	Plywood thickness (m)	Total thickness (m)	Height (m)	Width (m)	Area (m^2)
1-Sample	0.00	0.000	0.200	0.335	0.326	0.1092
2-Door	0.08	0.012	0.092	0.335	0.326	0.1092
3-Top	0.12	0.012	0.132	0.326	0.285	0.0929
4-Bottom	0.12	0.012	0.132	0.326	0.285	0.0929
5-Left	0.12	0.012	0.132	0.335	0.285	0.0955
6-Right	0.12	0.012	0.132	0.335	0.285	0.0955

Table 3: Detailed Dimensions of the Box Used for Measuring the Thermal Conductivity of a Red-Clay Brick

Sides	Insulation thickness (m)	Plywood thickness (m)	Total thickness (m)	Height (m)	Width (m)	Area (m^2)
1-Sample	0.00	0.000	0.195	0.322	0.43	0.1385
2-Door	0.08	0.012	0.092	0.322	0.43	0.1385
3-Top	0.08	0.012	0.092	0.280	0.43	0.1204
4-Bottom	0.08	0.012	0.092	0.280	0.43	0.1204
5-Left	0.12	0.012	0.132	0.322	0.28	0.0902
6-Right	0.12	0.012	0.132	0.322	0.28	0.0902

The exact value of heat generated inside the box was found more or less by trial and error. It was adjusted such that the average temperature of the sample is about 33.5 °C. Usually the thermal conductivity of a building material is measured at an average temperature of 30 °C. We have increased this value a little in order to account for the hot summer days in Qatar as can be seen from Fig. 9. Figure 9 shows typical variation of the temperature for a 24-hour period in Doha during the month of August.

A simple program was written to calculate the thermal resistances of all sides of the box and the heat flux through each side, and a summary of the results are given in tables 4, 5 and 6. It also calculates the thermal conductivity of the sample, and the results for concrete, thermostone, and red-clay are shown in table 7. As can be seen from the table, the conductivity of the thermostone is much smaller than that of concrete. These results are also in good agreement with a similar study done in Saudi Arabia using a commercial apparatus [1] which uses guarded plates for measuring thermal conductivity rather than the guarded box which is used in this study.

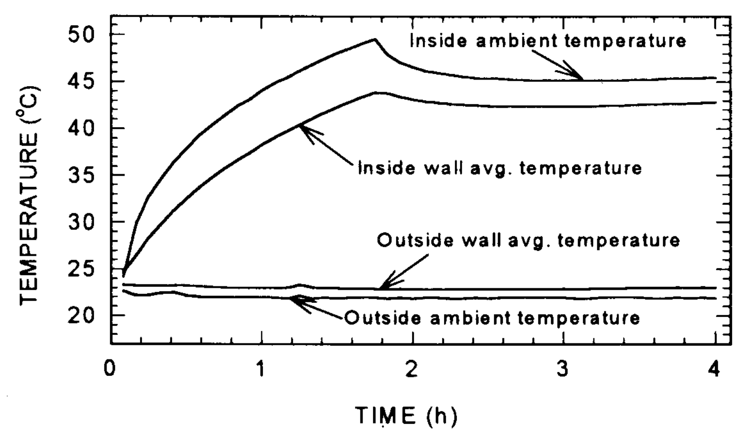

Fig. 6: Inside and outside wall average temperature of thermostone along with inside and outside ambient temperature versus time

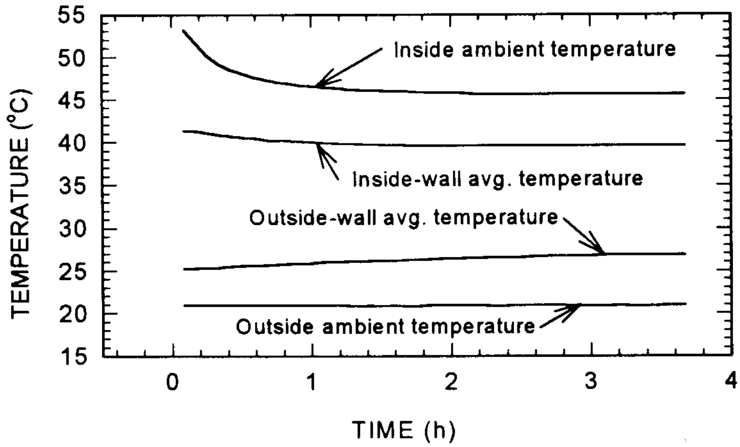

Fig. 7: Inside and outside wall average temperature of concrete along with inside and outside ambient temperature versus time

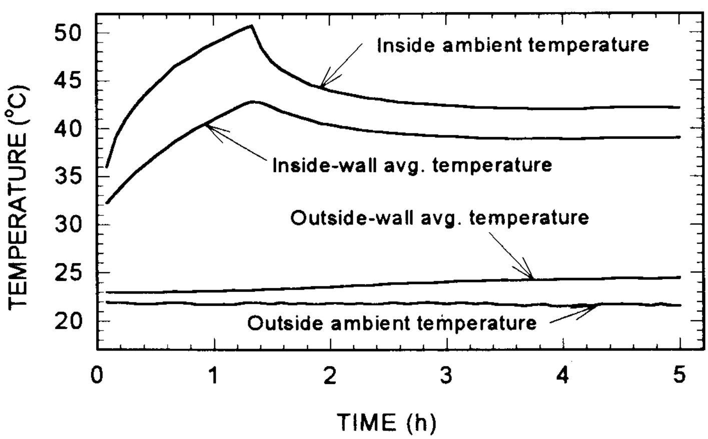

Fig. 8: Inside and outside wall average temperature of red-clay along with inside and outside ambient temperature versus time

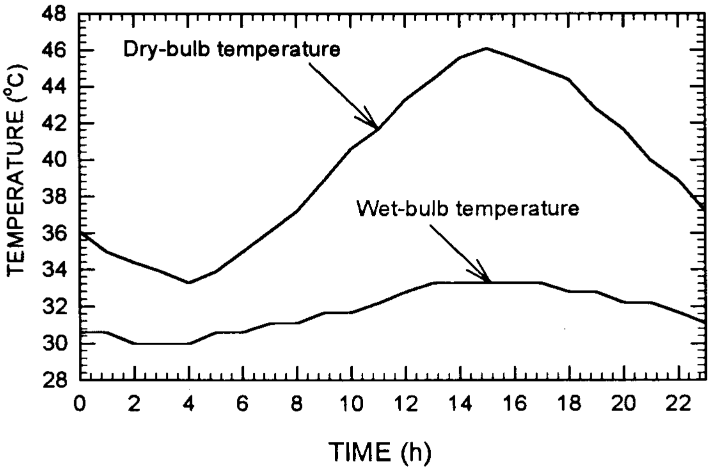

Fig. 9: Typical daily temperature variation in Doha, Qatar during the month of August

Table 4: Thermal Resistances and Heat Flow Through Each Side of the Box for Thermostone Brick When Heat is Generated at 15.5 W

Sides	R^* °C/W	ΔT °C	$R=AR^*$ (m^2 °C)/W	Q (W)
1-Sample	2.34	19.78	0.52	8.461
2-Door	12.39	21.90	2.77	1.767
3-Top	18.38	20.30	2.77	1.105
4-Bottom	18.38	20.60	2.77	1.121
5-Left	22.22	21.30	2.77	0.959
6-Right	22.22	21.50	2.77	0.966
Edges	-	-	-	1.120

Table 5: Thermal Resistances and Heat Flow Through Each Side of the Box for Concrete Brick When Heat is Generated at 14 W

Sides	R^* $^oC/W$	ΔT ^0C	$R=AR^*$ $(m^2\ ^oC)/W$	Q (W)
1-Sample	1.270	12.7	0.1400	10.008
2-Door	25.373	22.8	2.7710	0.899
3-Top	44.175	23.7	4.1043	0.536
4-Bottom	44.175	23.5	4.1043	0.532
5-Left	42.988	23.2	4.1043	0.540
6-Right	42.988	23.5	4.1043	0.547
Edges	-	-	-	0.938

Table 6: Thermal Resistances and Heat Flow Through Each Side of the Box for Red-Clay Brick When Heat is Generated at 10.9 W

Sides	R^* $^oC/W$	ΔT ^0C	$R=AR^*$ $(m^2\ ^oC)/W$	Q (W)
1-Sample	2.22	14.73	0.31	6.626
2-Door	20.01	19.50	2.77	0.974
3-Top	23.02	19.10	2.77	0.830
4-Bottom	23.02	17.70	2.77	0.769
5-Left	45.52	20.00	4.10	0.439
6-Right	45.52	18.70	4.10	0.411
Edges	-	-	-	0.851

Table 7: Results for Thermal Conductivity of Materials Tested

Type of Brick	Thermostone Brick	Concrete Brick	Red-Clay Brick
Thermal Conductivity	0.383 W/(m ^oC)	1.443 W/(m ^oC)	0.633 W/(m ^oC)

CONCLUSIONS

We have built a cheap apparatus to measure thermal conductivity of building materials. We have used the apparatus to measure the thermal conductivity of concrete bricks, red-clay bricks, and thermostone bricks. The thermal conductivity of a thermostone brick was found to be 0.383 W/(m

°C), that of a concrete brick was found to be 1.443 W/(m °C), and that of a red-clay brick was found to be 0.633 W/(m °C).

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