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Measurements of thermal properties of insulation materials by using transient plane source technique

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Abstract

The paper reports on the measuring technique and values of the measured thermal properties of some commonly used insulation materials produced by local manufacturers in Saudi Arabia. Among the thermal properties of insulation materials, the thermal conductivity (k) is regarded to be the most important since it affects directly the resistance to transmission of heat (R-value) that the insulation material must offer. Other thermal properties, like the specific heat capacity (c) and density (ρ), are also important only under transient conditions. A well-suited and accurate method for measuring the thermal conductivity and diffusivity of materials is the transient plane source (TPS) technique, which is also called the hot disk (HD). This new technique is used in the present study to measure the thermal conductivity of some insulation materials at room temperature as well as at different elevated temperature levels expected to be reached in practice when these insulations are used in air-conditioned buildings in hot climates. Besides, thermal conductivity values of the same type of insulation material are measured for samples with different densities; generally, higher density insulations are used in building roofs than in walls. The results show that the thermal conductivity increases with increasing temperature and decreases with increasing density over the temperature and density ranges considered in the present investigation.

Keywords: Energy conservation; Thermal insulation; Hot disk; Thermal properties; Measurement; Saudi Arabia

1. Introduction

The use of thermal insulation is regarded as one of the most effective means of energy conservation in buildings. The thermal resistance offered by an insulation layer increases with increasing layer thickness and decreasing thermal conductivity. Under dynamic conditions (as the case is in most practical applications), insulation materials also play an important role in affecting other thermal characteristics such as the decrement factor, time lag and peak transmission loads.

Many types of insulation materials are available which differ with regard to thermal properties and many other material properties as well as cost. Different insulating practices are available depending upon the overall structures of walls and roofs.

The R-values used to design building walls and roofs structures depends strongly on the thermal conductivity of insulation materials. Besides, thermal analysis procedures of building components or the building as a whole, which provide alternatives to heat transmission measurements in laboratory and prototype situations, need thermal property values as input to their calculations.

Tabulated values of thermal properties of insulation materials are available in the open literature. Manufacturers' claimed values of thermal properties of locally produced insulation materials could also be found in brochures and leaflets. Such data values are very useful but must be used with extreme care. Accuracy of these property values is sometimes questionable since complete

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and important information are often lacking. On many occasions, thermal conductivity values are quoted for insulation types without giving the density and temperature of the materials tested. Material with aging effects also depend upon manufacturing and storing conditions. In general, the "effective" conductivities depend on density, temperature, moisture content as well as the constituents and voids present in their structures. Radiation characteristics across these voids add to the complexity of the problem. Therefore, it is very important to have a database for insulation as well as building material properties and especially for those materials produced and used locally.

The present study uses a new and accurate experimental technique for measuring the thermal conductivity of some commonly used insulation materials produced by local Saudi manufacturers. The effects of temperature and density on the thermal conductivity are also examined. Other thermal properties like the density and specific heat (and hence the thermal diffusivity) are measured too. Comparisons with manufacturers' claimed values of properties are made.

2. Methods for measuring thermal conductivity

Thermal techniques are broadly classified under steady state methods and transient methods. Among the steady state methods, the guarded hot plate (GHP) may be regarded as the most commonly used technique for measuring the thermal conductivity of insulation materials. In principle, its operation is based on establishing a steady temperature gradient over a known thickness of a sample and to control the heat flow from one side to the other. The GHP and other steady state techniques suffer from major drawbacks. Drawbacks are that they require a long time to establish a steady state temperature gradient across the sample, and that this temperature gradient is required to be large. The sample size is also required to be large and that the contact resistance between the thermocouple and the sample surface is considered a major source of error.

The transient techniques, on the other hand, measure a response as a signal is sent out to create heat in the sample. Therefore, these techniques are distinguished mainly by the short time required to obtain the desired results. Among these techniques is the laser flash that is mainly used for measuring the thermal diffusivity of good-conducting solid materials. Another transient technique is the hot wire that is conveniently used for measuring the thermal conductivity of liquids and polymers. An extension of the Hot Wire technique is the hot strip that can be used to measure the thermal diffusivity and conductivity of solid non-electrically conducting materials.

The most recent development of the hot strip method is the transient plane source (TPS) technique. It is also called the Gustafsson probe or the hot disk (HD), Halldahl [1]. The TPS sensor can be regarded as a strip wound into a number of concentric circles then coated on both sides by a thin polymer with good chemical resistance and mechanical properties. The concentric circles are made into a double spiral so the current can be led from one end to the other. The TPS sensor is placed between two pieces of the sample material to be tested. One of the main advantages of transient techniques over steady state techniques is that the influence of the contact resistance can be removed in the analysis of experimental data. This enables accurate measurements over a wide range of thermal conductivity and therefore a wide range of different materials. The fact that the TPS sensors are covered by a polymer coating also allows measurements of electrically conducting materials. However, in the present study, the TPS technique will be used mainly for measuring the thermal conductivity and specific heat of insulation materials.

3. Previous studies

A short review of some previous studies with emphasis on those conducted on locally manufactured and used insulation and building materials in Saudi Arabia.

Abdelrahman et al. [3] used a guarded hot plate to measure the thermal conductivity values of some of the building materials commonly used in Saudi Arabia and compared the results with the data reported in the literature. The measurements were conducted at an average sample temperature of about 40 °C. The results showed that the measured thermal conductivities lied on the higher side of the range of the values reported in handbooks. Differences could be attributed to the effect of material density, amount of moisture content and the mean temperature.

Al-Hammad et al. [4] used the guarded hot plate for measuring the thermal conductivity of insulation materials. The tests were conducted at a mean temperature of 35 °C; a temperature believed to be most suitable for insulation application in buildings in hot climates. Comparison of test measurements was also made with published values measured mainly at a standard mean temperature of 24 °C. Despite the expected effect of this mean temperature difference on the resulting thermal conductivity values, the comparison has shown in general close agreement between measured and published values. This could well be attributed to possible cancellation resulting from the aging effect on the insulation materials. Al-Hammad et al. [4] reported that the insulation materials they tested were new (obtained within four months of their manufacture), while the published values were design values for materials with an age of at least five years. It is noted here that aging acts to increase (i.e. deteriorates) the conductivity while reducing temperature acts to decrease the conductivity; two opposing effects.

Budaiwi et al. [5] measured thermal conductivities of insulation materials at different operating mean temperatures using a computerized heat flow meter. Their results indicate that higher temperature leads to higher thermal conductivity values and that higher insulation density generally results in lower thermal conductivity.

Bouguerra et al. [6] used transient plane source (TPS) technique (same technique used in the present study) to measure the thermal conductivity, diffusivity and heat capacity of highly heterogeneous and porous building materials (wood concrete mixtures) at room temperature. It was shown that the thermal conductivity and diffusivity decrease while the heat capacity increases with increasing volume fraction of wood aggregates.

4. The hot disk thermal constants analyzer

4.1. Description

The hot disk thermal constants analyzer (HD), manufactured by hot disk AB, is a system designed for measuring the thermal transport properties, i.e. thermal conductivity, thermal diffusivity and specific heat, of a sample. Based on the theory of the transient plane source technique (to be outlined later), the HD utilizes a sensor element in the shape of a double spiral, see Fig. 1. This sensor acts both as a heat source for increasing the temperature of the sample and a "resistance thermometer" for recording the time-dependent temperature increase. The spiral is supported by Kapton for protection and electrical insulation.

The sensor is sandwiched between two halves of the sample (see Fig. 1). During a pre-set time, 200 resistance data points are taken and from these the relation between temperature and time is established. In experiments, it is often necessary to ignore the recorded data during the first few seconds, due to the initial thermal-mass influence of the sensor itself. A few parameters, like "Output of Power" to increase the temperature of the spiral, the "Measuring Time" for recording 200 points and the "Size of the Sensor" are used to optimize the settings for the experiment so that thermal conductivities from 0.005 W/m K to 500 W/m K can be measured. Using Kapton insulated disk elements, a temperature range from 30 K to 450 K can be covered.

The main advantages of the hot disk are accuracy, wide range of conductivity measurement, that it produces results in a relatively very short time (10 s to 10 min), and that it can use different sensor sizes to accommodate different sample types. The only requirement on the geometry of the sample is that the surface facing the sensor should be fairly plane. The HD can in one transient recording measure thermal conductivity, diffusivity and specific heat without the influence of thermal contact resistance [2]. Further, the sample sizes required by the hot disk are usually very much smaller than those used in other techniques.

4.2. Standard measurements and sample size requirements

The hot disk sensor is placed between two sample pieces that can be considered infinite in all directions seen from the sensor. Only a moderately smooth sample surface is required for this test method. The thermal contact resistance between the sensor surface and sample surface will cause a constant temperature difference to build up across the thin interface (gas or vacuum). This constant tempera-

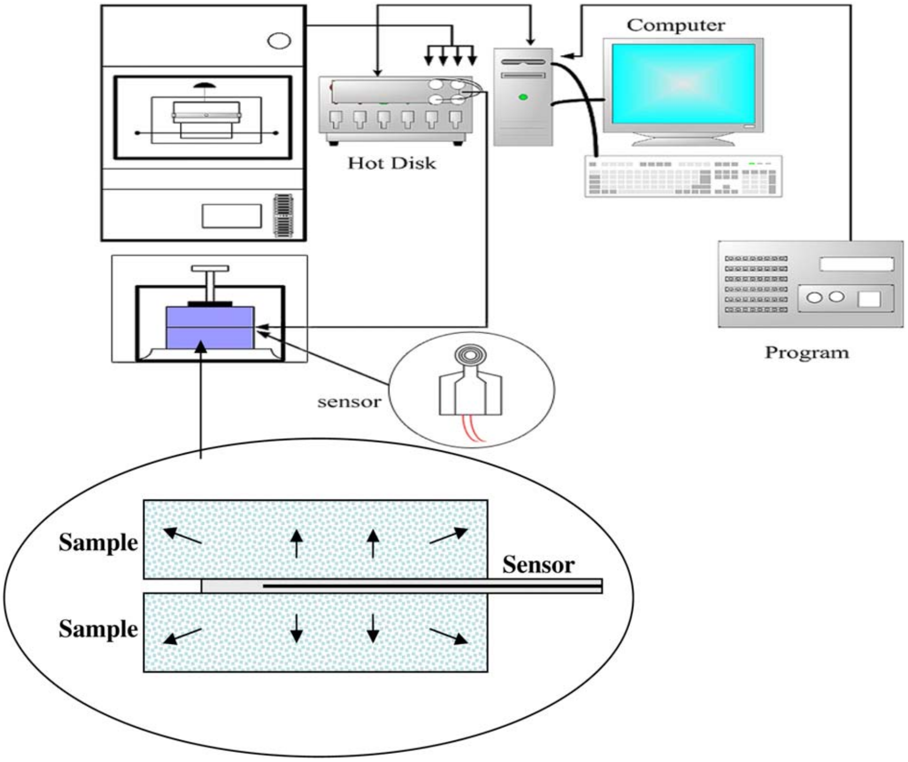

Fig. 1. A block diagram of the hot disk system.

ture step will not affect the measured sample properties since its influence is discarded in the calculations. This is an advantage in a transient method compared to steady state methods.

With regard to the sample size required in transient methods, the distance into the sample that has to be reached by heating from the sensor must not be larger than the available sample size. This will, of course, depend on the sample thermal diffusivity and measuring time ; as a rule of thumb, the "probing depth" (D), can be estimated as [1]

$$D = 2(\alpha t)^{1/2} \tag{1}$$

where α is the thermal diffusivity in mm^2/s and t is the measuring time in s.

The user must make sure that the measurement time is selected such that

$$\begin{aligned} &\text{sample width} > D + \text{sensor diameter} + D \\ &\text{sample thickness} > D \end{aligned} \tag{2}$$

In addition, there are other requirements that should be followed in order to make a better measurement; when optimizing the best combination of sensitivity coefficients for the estimation of the thermal conductivity and thermal diffusivity property, the following requirement is obtained: for a given sensor dimension and a sample with a certain thermal diffusivity, an optimal experimental time is given by the following dimensionless relation:

$$0.3 \leqslant \alpha t/r^2 \leqslant 1 \tag{3}$$

where r is the sensor radius [7]. The relations (1)–(3) can be used together to select a suitable combination of measurement time (s) and sensor radius (mm) for a certain sample.

It should however be noted that the above-mentioned conditions (1)–(3) may for highly conducting materials require impractically short measurement times, in particular if the sample dimension is limited. On the other hand, there are also interesting materials of low conductivity that are too small or thin to allow measurements even with the basic TPS method. The TPS method has, therefore, undergone recent developments to cover these sample sizes and shapes as outlined in [1,2,8].

4.3. Theory

As mentioned before, the hot disk utilizes a sensor element in the shape of a double spiral which acts both as a heat source for increasing the temperature of the sample and a resistance thermometer for recording the time-dependent temperature increase of the heat source itself. Usually, the sensor element is made of a 10 μm thick nickel-metal double spiral which is supported by a material to protect its particular shape, give it mechanical strength and keep it electrically insulated. The polyamide (Kapton) and Mica are such materials to use. The encapsulated Ni-spiral sensor is then sandwiched between two halves of the sample (solid samples) or embedded in the sample (powders and liquids). During a pre-set time, 200 resistance recordings are taken to establish the relation between the temperature and time.

To theoretically describe how the hot disk behaves, the heat conduction equation is solved assuming that the hot disk consists of a certain number of concentric ring heat sources located in an infinitely large sample. If the hot disk is electrically heated, the increase in its resistance as a function of time can be given as [8]

$$R(t) = R_0[1 + \Omega\{\Delta T_{\mathrm{i}} + \Delta T_{\mathrm{ave}}(\tau)\}] \tag{4}$$

where R_0 is the resistance of the disk just before it is being heated (i.e. at time $t = 0$), Ω is the temperature coefficient of the resistivity (TCR), ΔT_{i} is the constant temperature difference that develops almost momentarily over the thin insulating layers which are covering the two sides of the hot disk sensor material (nickel) and which make the hot disk a convenient sensor, $\Delta T_{\mathrm{ave}}(\tau)$ is the temperature increase of the sample surface on the other side of the insulating layer and facing the hot disk sensor (double spiral).

From Eq. (4), the temperature increase recorded by the sensor is obtained

$$\Delta T_{\mathrm{ave}}(\tau) + \Delta T_{\mathrm{i}} = [\{R(t)/R_0\} - 1]/\Omega \tag{5}$$

Here, ΔT_{i} is a measure of the "thermal contact" between the sensor and the sample surface with $\Delta T_{\mathrm{i}} = 0$ representing perfect "thermal contact"; ΔT_{i} becomes constant after a very short time Δt_{i}, which can be estimated as

$$\Delta t_{\mathrm{i}} = \delta^2/\kappa_{\mathrm{i}} \tag{6}$$

where δ is the thickness of the insulating layer and κ_{i} is the thermal diffusivity of the layer material.

The time-dependent temperature increase is given by the theory as

$$\Delta T_{\mathrm{ave}}(\tau) = [P_0/(\pi^{3/2}ak)]D(\tau) \tag{7}$$

where P_0 is the total output of power from the sensor, a is the overall radius of the disk, k is the thermal conductivity of the sample that is being tested and $D(\tau)$ is a dimensionless time-dependent function with

$$\tau = (t/\Theta)^{1/2} \tag{8}$$

In this equation, t is the time measured from the start of the transient recording; Θ is the characteristic time defined as

$$\Theta = a^2/\alpha \tag{9}$$

where α is the thermal diffusivity of the sample.

By making a computational plot of the recorded temperature increase versus $D(\tau)$, a straight line is obtained, the intercept of which is ΔT_{i} and the slope is $P_0/(\pi^{3/2}ak)$ using experimental times much longer than Δt_{i}. Since α and by that Θ are not known before the experiment, the final straight line from which the thermal conductivity is calculated is obtained through a process of iteration. In this way it is possible to determine both the thermal conductivity and the thermal diffusivity from one single transient recording.

4.4. Standard specifications

The standard specifications quoted for the hot disk are [8]:

Temperature range: 30–450 K using Kapton insulated disk elements; 400–1000 K using disk elements insulated with Mica.
Radius of disk spiral: to select disk sensors for situations with different probing depths, several disk elements are available with radii from 0.492 mm to 29.40 mm.
Sensor material: the double spiral is made of nickel.
Sample size: depends on the diameter of the disk elements and the material under study. Minimum size is a sample piece of diameter/thickness 1.5–2 mm.
Thermal conductivity range: 0.005–500 W/m K.
Reproducibility: thermal conductivity ±2%, thermal diffusivity ±5%, specific heat ±7%.
Manufacturer: hot disk AB, Sweden.

5. Collection of test samples

There are many Saudi manufacturers that produce different types of thermal insulation materials with different densities for use in buildings and other applications. These insulation materials are: molded polystyrene, extruded polystyrene, injected polystyrene, polyurethane board, glass fiber, rock wool, and loose fill perlite.

6. Measurement procedure

The first part of the experiments involved measuring the thermal conductivity of all insulation material samples at room temperature. Measurements were carried out for two specimens of each test sample; this was repeated three times for each specimen and, then, mean values of thermal conductivity were obtained by averaging. The specific heat was also measured but this was done only for the "rigid" insulation materials; namely, polystyrene (all types) and polyurethane board. The values of specific heat of the "soft" insulation materials; namely, glass fiber, rock wool and loose fill perlite, were not measured by this procedure for reasons to be discussed later.

The second part of the experiments involved measuring the thermal conductivity of the rigid insulation materials at different mean temperatures in the range 22–65 °C. The measurements were carried out for different densities and were repeated three times for each sample.

The density of a specimen was simply determined by dividing the measured mass of the specimen by its volume. The mass of the specimen was measured by a precision balance having a resolution of 0.1 g. The length, width and thickness of the specimen were measured by using a steel caliper having a resolution of 0.1 mm.

7. Experimental results and discussion

The thermal conductivity of an insulation material does not only depend on its density, temperature and moisture content but also depends on the material atomic and molecular structure, porosity, anisotropy, structural faults and defects. The specific heat is mainly defined by the composition. Therefore, the thermal conductivity of a material may vary over a relatively substantial range, while its specific heat does not change.

Table 1 summarizes the values of the measured properties of the insulation materials under investigation at room

Table 1
Thermal properties of insulation materials measured at room temperature; showing comparison with manufacturers' claimed conductivity values

Material	Density (kg/m^3)	Thermal conductivity (W/m K)		Specific heat (J/kg K)	Diffusivity m^2/s
		Measured	Manufacturer		
Molded polystyrene	19 ± 1	0.036 ± 0.0002	0.034	1280 ± 50	1.48E−06
	23 ± 1	0.034 ± 0.0009	0.033	1280 ± 50	1.15E−06
	38 ± 1	0.033 ± 0.0002	0.032	1280 ± 50	6.78E−07
Extruded polystyrene	28 ± 1	0.032 ± 0.0003	0.032	1280 ± 50	8.93E−07
	34 ± 2	0.031 ± 0.0003	0.032	1280 ± 50	7.12E−07
Injected polystyrene	20 ± 2	0.034 ± 0.0004	0.034	1280 ± 50	1.33E−06
	34 ± 1	0.033 ± 0.0008	0.032	1280 ± 50	7.58E−07
Polyurethane board	28 ± 1	0.024 ± 0.0005	0.023	1537 ± 39	5.58E−07
	33 ± 2	0.022 ± 0.0003	0.023	1537 ± 39	4.34E−07
Lightweight concrete	551 ± 3	0.155 ± 0.0031	0.120	882 ± 54	3.19E−07
Perlite (loose fill)	94 ± 4	0.054 ± 0.0017	0.04–0.06[b]	1090[a]	5.27E−07
Glass fiber (axial)	30 ± 1	0.042 ± 0.0006	0.035	960[a]	1.46E−06
	95 ± 1	0.038 ± 0.0008	0.034	960[a]	4.17E−07
Rock wool (axial)	50 ± 1	0.042 ± 0.0002	0.042	840[a]	1.00E−06
	120 ± 1	0.040 ± 0.0010	0.037	840[a]	3.97E−07
Glass fiber (radial)	30 ± 1	0.034 ± 0.0012	–	960[a]	1.18E−06
	95 ± 1	0.046 ± 0.0023	–	960[a]	5.04E−07
Rock wool (radial)	50 ± 1	0.042 ± 0.0016	–	840[a]	1.00E−06
	120 ± 1	0.049 ± 0.0012	–	840[a]	4.86E−07

[a] ASHRAE values [9].
[b] Values were quoted for a density range of 32–400 kg/m^3.

temperature. Manufacturers' claimed values of thermal conductivity are also given and will be compared later. It is noted that the density of a given insulation material may vary for different samples supplied by the same manufacturer (for the same material and claimed density). Therefore, the values shown in the table are based on average densities ± a tolerance (relatively small) in order to cover the range of densities as measured for different samples of the same insulation material and of the same density category. The measured thermal conductivity values are presented based on average data ± a standard deviation. The same is done for the specific heat except for the last three insulation materials; namely, perlite, glass fiber and rock wool where the values quoted are not the measured values but obtained from the literature. The main reason for this is that these materials are anisotropic, i.e. materials with direction-dependent thermal conductivity. Perlite, being of the loose fill type, may be regarded to exhibit anisotropic behavior especially when it is non-homogeneous.

The only difference between measurements carried out on isotropic and anisotropic materials is that the sample pieces and the hot disk sensor should (in the latter case) be properly oriented in relation to the main "crystal" directions [8]. If it is assumed that the main directions in the material under investigation are orthogonal and can be described in terms of, for example, *a*-, *b*- and *c*-axes, this experimental technique covers only the case when the properties along the *b*- and *c*-axes are identical but different from those of the *a*-axis. It is important to orient the sample pieces and the hot disk sensor correctly in relation to the main directions in the anisotropic material. Only one measuring position of the sensor is possible in this case and for this reason it is necessary to know the specific heat of the anisotropic material in order to evaluate the transport properties along the two directions [8].

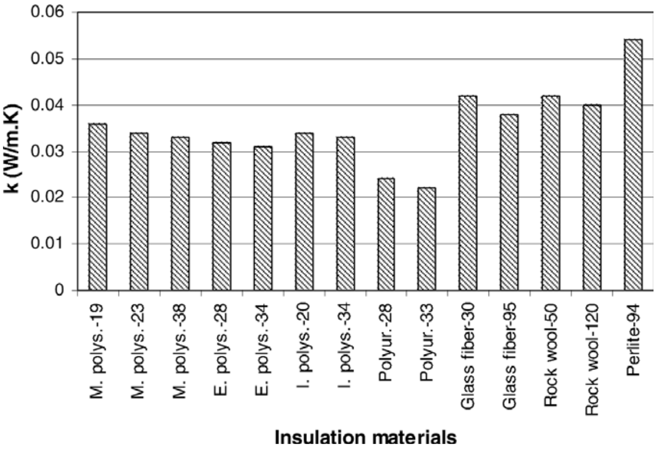

Fig. 2. Thermal conductivity measured at room temperature.

Following the above procedure, it is important to note that the thermal conductivity values given for the glass fiber and rock wool are the ones measured in the "axial" direction and the "radial" direction, respectively, for the sample under investigation. The axial direction complies with the direction of heat flow through these materials when used as layers in practical applications. The radial direction conductivities are shown for comparison and will be discussed later.

Fig. 2 presents the average data values of the measured thermal conductivity in bar-chart form for different densities of insulation materials at room temperature. It is noted that the value for the lightweight concrete has been excluded from the figure for clarity reasons (since it is relatively higher). It is seen that, for the same type of insulation, the change in the thermal conductivity due to change in density is relatively small; the thermal conductivity decreases with increasing density.

Table 2 summarizes the values of thermal conductivity of selected insulation materials measured at different mean temperatures. Fig. 3 presents the same values in graphic form. The materials are: polystyrene (molded, extruded and injected) and polyurethane board. Two different densities were also used for molded polystyrene and polyurethane. An experimental oven was used to control and maintain the sample temperature at a required temperature while its thermal conductivity was recorded. Apart from the room temperature (22 °C), the conductivity was measured at elevated temperatures of 35, 50 and 65 °C. This covers the practical range of use in hot climates.

The measurements show that, the thermal conductivity increases with increasing temperature. The increase is relatively large at low temperatures and then levels off a further increase in temperature. The relation becomes practically linear at temperatures above 35 °C. The conductivity of polyurethane is affected more by temperature than the conductivity of polystyrene.

Table 2
Thermal properties of insulation materials measured at different temperatures

Material	Density (kg/m^3)	Temperature (°C)			
		22	35	50	65
Molded polystyrene	19	0.0355 ± 0.0003	0.0385 ± 0.0006	0.0402 ± 0.0002	0.0423 ± 0.0004
	38	0.0330 ± 0.0002	0.0343 ± 0.0002	0.0382 ± 0.0013	0.0404 ± 0.0006
Extruded polystyrene	34	0.0312 ± 0.0006	0.0324 ± 0.0009	0.0340 ± 0.0002	0.0352 ± 0.0006
Injected polystyrene	34	0.0332 ± 0.0002	0.0358 ± 0.0004	0.0380 ± 0.0002	0.0387 ± 0.0005
Polyurethane board	28	0.0244 ± 0.0000	0.0286 ± 0.0002	0.0305 ± 0.0006	0.0320 ± 0.0002
	33	0.0220 ± 0.0004	0.0266 ± 0.0003	0.0291 ± 0.0001	0.0298 ± 0.0006

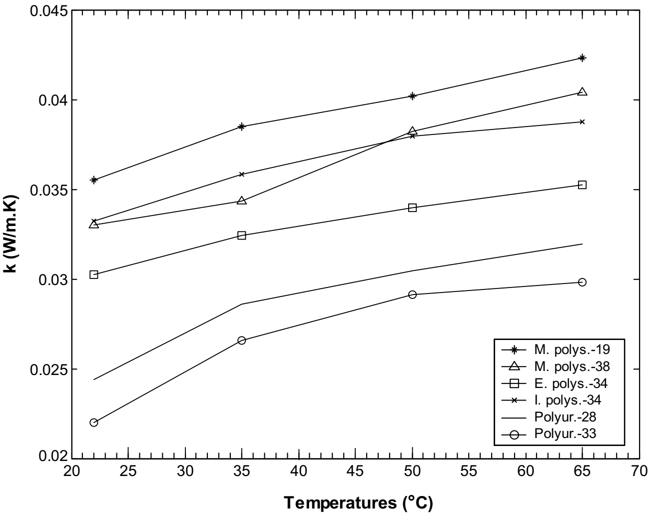

Fig. 3. Thermal conductivity measured at different temperatures.

The conductivity of polyurethane increased by over 30%, while that of polystyrene increased by an average of about 20% over the whole temperature rang. By increasing the temperature from 22 °C to 35 °C (a variation that can easily occur in practice), the conductivity of polyurethane increased by about 19% and that of polystyrene increased by an average value of about 7%. Such relatively large increase in thermal conductivity with a modest increase in temperature, especially for polyurethane, should be noted and must be accounted for in building thermal analysis. This will decrease the wall and roof *R*-values and, hence, increase the cooling transmission loads in hot climates proportionally. Calculating the detailed temperature variations through building components, this temperature-dependent conductivity can be incorporated (within the iteration procedure) for more accurate estimation of the transmission load. A linear conductivity-temperature relation may be assumed for a small temperature range; a simple polynomial fit might be more appropriate to use for a temperature range exceeding about 20 °C.

Manufacturers' claimed values of the thermal conductivity are also summarized in Table 1 and are compared with the measured values at 22 °C. Close agreement between the two sets of results is found for the polyurethane and all types of polystyrene and for all densities. An average difference between measured and claimed values for these insulation materials is calculated at about 3%; such a difference lies within the experimental errors. However, a much larger difference of nearly 30% is found for the lightweight concrete. For the glass fiber, the measured conductivities are 20% and 12% higher than the claimed values for the lower and higher densities, respectively. The measured conductivity for the rock wool agrees well with the claimed value at the lower density; for the higher density, the measured value is 8% higher than the claimed one.

It is noted that for the highly anisotropic insulation materials; namely, the glass fiber and rock wool, the thermal conductivities measured in the "axial" direction differ in general by a substantial amount (about 20%) compared to those measured in the "radial" direction, see Table 1. It is also interesting to note that increasing density of insulation materials acts in general to decrease the conductivity; this also applies to the glass fiber and rock wool but for the axial direction. The opposite behavior is obtained for these insulation materials for the radial direction. The results show that increasing density acts to increase the radial thermal conductivity. Future studies are required to consider samples of the same materials but with many different densities so that conductivity values in the axial and radial directions can be correlated with density as well as mean operating temperatures.

8. Conclusions

The hot disk thermal constants analyzer (HD) technique is used in the present study to measure the thermal conductivity of some insulation materials, produced by Saudi manufacturers, at room temperature as well as at different elevated temperature levels expected to be reached in practice. The results indicate that the thermal conductivity increases with increasing temperature. Polyurethane is affected more than polystyrene. Thermal conductivity decreases with increasing density over the temperature and density ranges considered. The increase in conductivity due to increase in temperature is relatively large, while the change due to change in density is relatively small. The measured thermal conductivity values at 22 °C is in close agreement to manufacturers' claimed values. The average difference is about 3such a difference lies within the aging and storage conditions of the sample. A much larger difference of nearly 30% is found for the lightweight concrete. For the glass fiber, the measured conductivities are 20% and 12% higher than the claimed values for the lower and higher densities, respectively. The measured conductivity for the rock wool agrees well with the claimed value at the lower density; for the higher density, the measured value is 8% higher than the claimed one.

The thermal conductivities of the highly anisotropic insulation materials measured in the "axial" direction differ in general by a substantial amount (about 20%) compared to those measured in the "radial" direction. For the axial direction, increasing density of insulation materials acts in general to decrease the conductivity. The opposite behavior is obtained for these insulation materials for the radial direction. The results show that increasing density acts to increase the radial thermal conductivity.

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