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EFFECT OF TEMPERATURE AND DENSITY VARIATIONS ON THERMAL CONDUCTIVITY OF POLYSTYRENE INSULATION MATERIALS IN OMAN CLIMATE

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The thermal and energy performance of buildings depends on the thermal characteristics of the building envelope and particularly on the thermal resistance of the insulation material used. The ability of a thermal insulation material to transmit heat in the presence of a temperature gradient is determined by its thermal conductivity. The thermal conductivity values of building insulation materials are generally given at 24°C according to ASTM standards. Actually, such a material when used in a building envelope is exposed to significant and continuous temperature changes, essentially due to the changes in outdoor temperature and solar radiation, especially in harsh climate. The main objective of this study is to investigate the relationship between the temperature and the thermal conductivity of polystyrene, which is widely employed as a building insulation material in Oman, at various densities, using the developed experimental setup based on the guarded hot plate method. The results show that higher temperatures lead to higher thermal conductivities and the lower is the material density, the higher is the thermal conductivity. The envelope-induced cooling load for a simple building is also calculated, and it is shown that a lesser cooling load is needed for a high-density insulation.

Keywords: *building insulation, thermal conductivity, polystyrene, cooling load.*

Introduction. Heat transmission through a building envelope represents the major component of the total thermal load of the building. In Oman, buildings consume the major share of electric energy. In some regions with lesser industrial activities, more than 70% of electric energy is consumed by buildings. For instance, the annual energy consumption of an insulated typical detached single-family house in Dhahran, which has meteorological conditions identical to those in Muscat, was estimated to be around 153 $\text{kW}\cdot\text{h/m}^2$ [1].

Due to the prevailing harsh climatic conditions, the bulk of this energy (about 60%) is used in air-conditioning and ventilation systems [2]. The energy consumed in an air-conditioning process is directly related to the building thermal load. Heat transfer by conduction through the walls and roofs represents the major component of the total thermal load of buildings. This can be reduced by using an effective thermal insulation material for the building envelope.

Thermal insulation materials are fibrous and are used, in particular, in the form of films or sheets, blocks or monoliths, open or closed cells that can be chemically or mechanically bound or supported to retard heat transfer by conduction [3]. Thermal insulation materials, like other natural or man-made materials, exhibit temperature dependence of their properties that vary with the nature of the material and the temperature range. For most materials, the value of the thermal conductivity increases with temperature. There are empirical relationships for the temperature-dependent thermal conductivity based on experimental data [4]. For an aged material specimen, the average conductivity depends mainly on the density, temperature, and water content [5].

The impact of the operating temperature on the thermal performance of insulation materials has been studied by numerous researchers. Khoukhi and Tahat experimentally investigated the effect of the operating temperature on the behavior of the thermal conductivity of polystyrene insulation materials in the Oman climate. It was found that the thermal conductivity increases with the operating temperature [6]. Aldrich and Bond theoretically and experimentally studied the thermal performance of rigid cellular foam at different temperatures [7] and revealed significant variations in the thermal conductivity depending on the operating conditions. Another set of experiments was conducted on the thermal performance of glass fiber, using an attic test module in a guarded hotbox facility [8]. The results showed that at large temperature

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differences the thermal resistance was about 35–50% less than that at small temperature differences. The impact of the temperature difference on the thermal conductivity of some insulation materials produced by Saudi insulation manufacturers was investigated in [9].

In addition to the operating temperature, the material moisture content which is influenced by the ambient humidity level is another major factor affecting the thermal conductivity of insulation materials [10]. The higher is the material moisture content, the higher is the thermal conductivity [11].

The objective of the paper is to experimentally determine the thermal conductivity of new locally produced polystyrene insulation materials with four different densities: low (LD), high (HD), ultra-high (UHD), and super-high (SHD), at different operating temperatures, using the developed experimental setup based on the guarded hot plate method. The impact of the thermal conductivity variation on the envelope-induced cooling load is also investigated. The results should be of great importance for material manufacturers, building owners, and designers who take an interest in the attainment of higher building thermal performance and energy efficiency.

Measurement Apparatus and Procedure. The method based on the guarded hot plate has been used to measure heat passage through a specimen. In this method, a heater is designed according to the dimensions of the specimen, two identical specimens are used, and the heater is placed between them along with a thermocouple (Fig. 1). This method assumes that the power produced by the heater is distributed equally in each specimen. All other surfaces are well insulated; thus, only the main ones will conduct heat. A given voltage and current are supplied to the heater, and the temperature on its surface (on the inner specimen surface) is measured. The second thermocouple is used outside of the specimen in line with the first one, so that the temperature of the outer surface is also measured until it reaches the steady-state value. Then the temperature difference is found and the calculations are performed. Yet another thermocouple is used to measure the ambient temperature to verify the testing environment. The used thermocouples are of K type.

Since the thermal conductivity changes with the ambient (surrounding) temperature, all necessary precautions have to be taken to ensure almost the same temperature throughout the testing time. For this purpose, a special temperature control chamber is fabricated. This chamber shown in Fig. 2 is made from wood and insulated with a high-temperature heat-proof material to prevent heat losses from the box. A water reservoir shown in Fig. 3 is used together with a chiller and a heater-embedded water circulator pump. An aluminum radiator is installed on the back plate of the box. Water circulates in the radiator, transferring heat to the chamber. A fan is mounted on the radiator to allow heat to be extracted more efficiently and to circulate evenly throughout the chamber. Due to the change in the water temperature, required ambient conditions have been achieved, so that specimens could be tested for the thermal conductivity at different stable conditions.

The chiller is used only for testing at 10^{o}C along with the pump to provide a higher stability. All other temperatures, namely, 24, 37, and 43^{o}C, were achieved by using the heater with the pump. Although the temperature control of the heater is accurate, a separate thermometer is used for visual inspection of the reservoir water temperature for a higher reliability. A variable power supply to the heater is carried out with a very high accuracy and stability. The voltage and current are displayed directly, so the power generated by the heater can easily be calculated. All the thermocouples were connected to a data logger which measures the values with an interval of 15 s. The results from the data logger are displayed directly in the computer, which allows real time chart plotting to identify the attainment of a steady state. Then the final values from the thermocouples were used to calculate the temperature gradient and, hence, the thermal conductivity k. Every specimen was tested three times at four different temperatures to verify the accuracy of the measurements.

The designed experimental apparatus based on the guarded hot plate principle has been tested and calibrated, using three specimens (HD, UHD, and SHD) with the known thermal conductivities at $T = 10^{o}$C [6]. The thermal conductivities of the latter specimens at 10^{o}C are presented in Table 1 as the reference values k_r. To ensure a sufficient accuracy, the specimens were tested three times over an extended period of time, and the average values $\overline{k}$ are also shown in the table. It can be seen that the difference Δk between the average measured thermal conductivity and the reference one for these three specimens is within an acceptable range of accuracy and the SHD specimen is characterized by the least difference equal to 1.5%. Therefore, the designed apparatus is considered to be sufficiently accurate for carrying out subsequent measurements.

Then the thermal conductivity of the investigated specimens was measured at four different mean temperatures, namely, at 10, 24, 37, and 43^{o}C. Figure 4 shows the change in the thermal conductivity (as an average value for the operating temperatures) for these specimens. In all cases, a higher temperature leads to a higher thermal conductivity, and the thermal conductivity decreases with increase in the density of the specimens.

Impact of the Thermal Conductivity Variations on the Envelope-Induced Cooling Load. A typical one-story residential building ($20 \times 20 \times 3$ m^3) located in Muscat was modeled. The house was assumed to operate at a typical residential

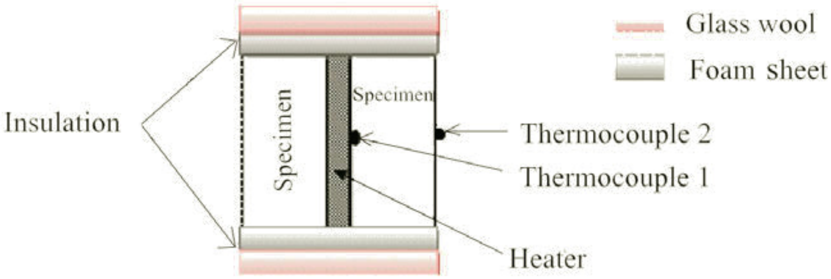

Fig. 1. Guarded hot plate [6].

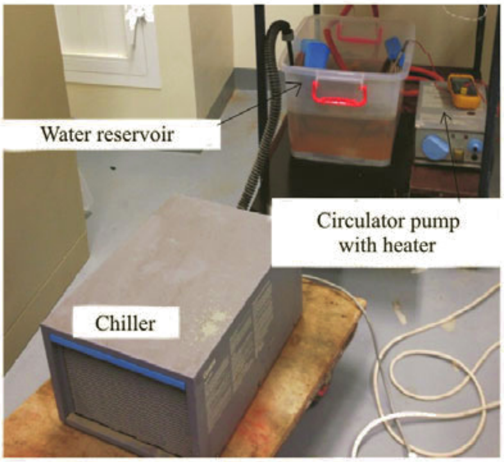

Fig. 2. Wooden box fabricated from a heat-proof material [6].

Fig. 3. Experimental setup with a water reservoir, chiller, pump, and a heater [6].

TABLE 1. Thermal Conductivity of Three Reference Specimens [6]

Samples	k, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	k_r, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	Δk, %
HD	0.03588	0.035	2.5
UHD	0.03329	0.032	4
SHD	0.03046	0.03	1.5

load profile with an average air tightness of 0.5 ACH. Windows are tinted, double glazed, and distributed uniformly over 15% of the wall area. Dark and light surfaces of the external envelope of the building are considered in the simulation. The measured thermal conductivities and the cooling loads *P* calculated by using the computer program Carrier for all types of insulation materials are given in Table 2. This table shows that the average cooling load increases with the average thermal conductivity and decreases with increase in the density of the insulation for a given operating temperature. The color of the external wall of the building also affects the cooling load required by the building. Indeed, a building with a light external wall needs a lesser cooling load compared with a dark one which absorbs more heat.

The differences in the cooling loads between the LD and SHD specimens at 24°C are as much as 0.574 kW (light external wall color) and 0.825 kW (dark external wall color), which represents an increase by 5 and 6%, respectively. The difference in the cooling load required by the building with the use of the LD insulation material at 10°C and 43°C with

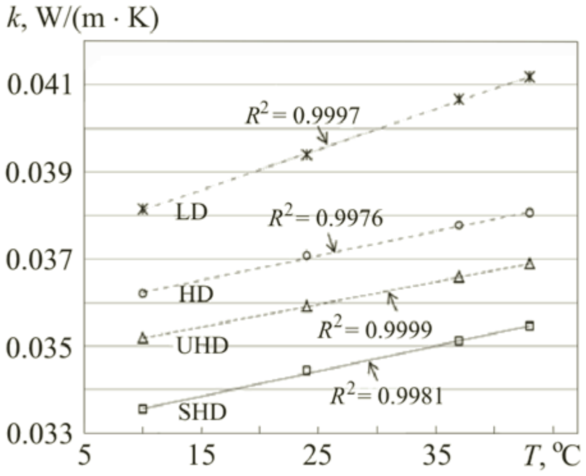

Fig. 4. Thermal conductivity of four polystyrene materials with different densities vs. the operating temperature.

TABLE 2. Average Cooling Loads for Specimens of Light and Dark Colors

Specimen	T, °C	k, $W \cdot m^{-1} \cdot K^{-1}$	P, kW	
			Light	Dark
LD	10	0.03814	11.601	13.880
	24	0.03939	11.753	14.072
	37	0.04066	11.881	14.301
	43	0.04118	11.949	14.367
HD	10	0.03621	11.381	13.565
	24	0.03702	11.485	13.686
	37	0.03776	11.560	13.802
	43	0.03805	11.610	13.849
UHD	10	0.03518	11.263	13.371
	24	0.03591	11.347	13.494
	37	0.03658	11.422	13.605
	43	0.03689	11.458	13.654
	10	0.03442	11.075	13.095
	24	0.03442	11.179	13.247
	37	0.03511	11.256	13.360
	43	0.03546	11.297	13.421

external light and dark wall colors are 0.348 and 0.487 kW, i.e., 3 and 3.5%, respectively. This difference may significantly affect the cooling load calculations, especially over a long period of time.

Conclusions. The dependence of the thermal conductivity on the operating temperature of polystyrene insulation with four different densities has been investigated, using a developed experimental apparatus based on the guarded hot plate. The results show that the thermal conductivity increases with temperature and the lower is the material density, the higher is the thermal conductivity.

It is shown that the cooling load depends on the operating temperature, and a lesser cooling load is needed for a higher insulation density. The cooling load depends also on the color of the external wall (light or dark). More accurate data on the thermal conductivity of a building insulation material would lead to more precise cooling load calculations, especially over a long period of time. As this takes place, appropriate selection and precise optimization of the cooling/heating systems can be achieved.

The results show the need for thermal insulation material manufacturers to provide the values of the thermal conductivity of their insulation materials at different operating temperatures for different densities of the materials, which will allow building designers to accurately estimate the energy requirements of buildings.

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