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Change of the Thermal Conductivity of Polystyrene Insulation in term of Temperature at the Mid Thickness of the Insulation Material: Impact on the Cooling Load

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***Abstract*—**Accurate prediction of the cooling/heating load and consequently, the sizing of the heating, ventilating, and air-conditioning equipment require precise calculation of the heat transfer mainly by conduction through envelope components of a building. The thermal resistance of most thermal insulation materials depends on the operating temperature. The temperature to which the insulation materials are exposed varies, depending on the thermal resistance of the materials, the location of the insulation layer within the assembly system, and the effective temperature which depends on the amount of solar radiation received on the surface of the assembly. The main objective of this paper is to investigate the change of the thermal conductivity of polystyrene insulation material in terms of the temperature at the mid-thickness of the material and its effect on the cooling load required by the building.

***Keywords*—**Operating temperature, polystyrene insulation, thermal conductivity, cooling load.

I. Introduction

IN the middle east region and particularly in Oman, buildings account for a major share of electric energy consumption. In the urban region more than 70% of electric energy is consumed by buildings [1] and the majority of this energy is used by the air-conditioning and ventilation systems [2]. A big portion of this energy is directly related to the heat transfer by conduction through the building envelope, which can be reduced by using effective thermal insulation material.

Most buildings in Oman are not well insulated due to the absence of regulation and standards. Therefore, buildings consume more energy than it is necessary for their operation. For skin-load dominated structures in Oman, using appropriate thermal insulation is the first step in achieving energy efficient buildings.

Thermal insulation is a material, or a combination of fibrous or particulate materials, that can be in the form of film or sheet, block or monolithic, open cell or closed cell, and can be chemically or mechanically bound or supported to retard the rate of heat flow by a combination of modes (i.e., conduction, radiation, and convection) [3].

Thermal insulation materials like other natural or man-made materials exhibit temperature dependence properties that vary with the nature of the material and the influencing temperature range. For most materials, the value of thermal conductivity increases as the influencing temperature increases. Therefore, temperature dependent thermal conductivity is an empirical relationship that is based on experimentation [4]. For a given aged material sample, the average conductivity mainly depends on the density (ρ), temperature (T) and water content (w) [5].

The impact of operating temperature on the thermal performance of insulation materials has been investigated by several researchers. The effect of temperature and density variation on thermal conductivity of polystyrene insulation material under Omani climate has been investigated by [6]. Reference [7] shows the impact of operating temperature on thermal conductivity, and consequently the change in the building envelope-induced cooling load, has been reported. Thermal conductivities of various insulation materials were measured at different operating mean temperatures. Results indicate that a higher operating temperature is always associated with higher thermal conductivity. Reference [8] has theoretically and experimentally investigated the thermal performance of rigid cellular foam under different temperatures. The result showed significant variations in the k-value with operating conditions. Another set of experiments was conducted on the thermal performance of fiberglass using an attic test module in a guarded hot box facility [9]. The result shows that at large temperature differences the thermal resistance was less about 35-50% than that of small temperature differences. The impact of temperature difference on the thermal conductivity of some insulation materials produced by Saudi insulation manufacturers has also been investigated [10].

Consequently, operating temperature has a significant influence on the thermal performance of insulation materials. The objective of this research is to investigate the change of the thermal conductivity of polystyrene insulation in terms of temperature at the mid-thickness of the insulation material and its effect on the amount of the cooling required by the space.

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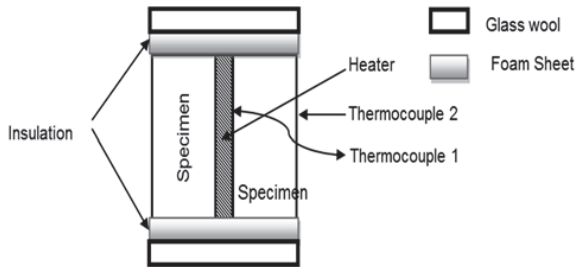

Fig. 1 Guarded hot plate

II. Experimentation

The guarded hot plate method has been used to measure the heat through the sample. In this method, a heater is fabricated to the surface dimensions of the specimen and two identical specimens are used as the heater is placed in the middle (see Fig. 1). This method allows us to safely assume that the power produced by the heater is distributed evenly and same amount of heat is passed through by each sample. A known voltage and current is then supplied to the heater and the temperature at the surface of the heater (inner surface of the specimen) is measured. Similarly, the temperature of the outer surface is also measured for the increment in temperature till it reaches the steady state. Then the temperature difference is taken and calculations are performed.

Since the thermal conductivity changes with the ambient (surrounding) temperature, all necessary precautions have to be taken to ensure that it will remain almost same throughout testing time. For this purpose, a special temperature control chamber is fabricated to maintain and to adjust the temperature as for the testing requirement. This control chamber is made of wood and insulated with high temperature heat proof material to prevent heat loss from the box.

The chiller is only used for the testing of 10°C along with the heat pump to provide more stability. All the other temperature conditions of 24°C, 37°C and 43°C were achieved by using the heater with the pump only. Although the temperature controlling of the heater is accurate, a separate thermometer is used for visual inspection of the reservoir's water temperature to have more confidence.

III. Results and Discussion

The designed experimental apparatus based on the guarded hot plate principle has been tested and calibrated using the known thermal conductivity values of three samples (HD, UHD and SHD) run at 10°C provided by another company. The thermal conductivity of the samples at 10°C is presented in Table I as reference values. To ensure accuracy, the samples have been tested three times over an extended period and the average values are shown in Table I.

It can be seen that the difference between the average measured thermal conductivity and the reference values of the three samples is within the acceptable range of accuracy. SHD sample presents less difference with 1.5%. Therefore, the designed apparatus is considered accurate enough to carry on the rest of the measurements.

TABLE I
Differences in Thermal Conductivity Values for the Three Samples

Sample	Average measured thermal conductivity [$Wm^{-1}K^{-1}$]	Thermal conductivity reference [$Wm^{-1}K^{-1}$]	Differences [%]
HD	0.03588	0.035	2.5
UHD	0.03329	0.032	4
SHD	0.03046	0.03	1.5

The impact of operating temperature on the thermal conductivity values of polystyrene insulation material with four levels of densities is illustrated in Fig. 2. It shows that thermal conductivity values of the four samples are affected in varying degrees with operating temperature. In all cases, higher temperature leads to higher thermal conductivity. The thermal conductivity also decreases with the increase of the density of the sample.

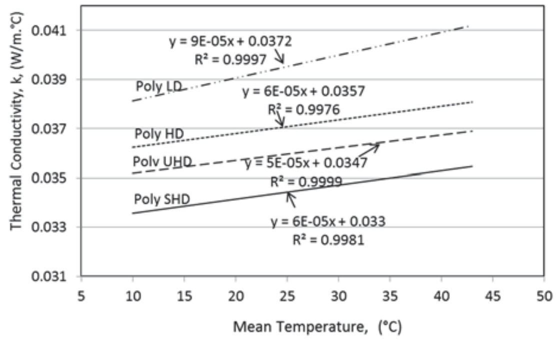

Fig. 2 Change of k-value measurement results of polystyrene with different densities vs. operating temperatures

Accurate sizing of the heating, ventilating, and air-conditioning equipment depends on the accuracy of the cooling load calculation which requires an accurate account of the actual heat transfer through envelope components. The thermal resistance of the thermal insulation materials is variably dependent on operating temperature, as illustrated in Section I. The temperature to which the insulation materials are exposed depends on several parameters including the thermal resistance of the material, the location of the insulation layer within the wall or roof assembly or system, and the effective or operating temperature. The last parameter is a function of several parameters including the outdoor air temperature, surface solar absorbance of the system (wall or roof), the total solar radiation on the surface of the system, and the outdoor surface conductance.

At steady-state conditions, the temperature at any location within the wall/roof can be given by

$$t_x = t_e - R_x/R_{tot}(t_o - t_i) \qquad (1)$$

where t_e= effective or operating outdoor temperature; R_x= portion of thermal resistance measured from inward, R_{tot}=total thermal resistance of the envelope assembly; t_o= outdoor air temperature; and t_i= indoor air temperature.

The effective outdoor temperature also known as sol-air temperature, is evaluated by considering both the outdoor air temperature and the amount of solar radiation absorbed by the surface, and is given by

$$t_e = t_o + \alpha\, I_t/h_o - \varepsilon\, \Delta R/h_o \quad (2)$$

where α= surface solar absorbance; I_t= total solar radiation, h_o= outdoor surface conductance; and εΔR/ho= correction factor (=zero for vertical surface). The amount of the solar radiation received on a surface is given by

$$I_t = H_b\left(\frac{\cos\theta}{\cos\theta_z}\right) + H_d\left(\frac{1+\cos\theta}{2}\right) + \rho_{gr}H\left(\frac{1-\cos\beta}{2}\right) \quad (3)$$

where H_b= direct horizontal; H_d= diffuse horizontal; H= Global horizontal; ρ_{gr}= ground albedo; θ= incident angle; and β= slope (= 90º for vertical wall and = 0º for horizontal roof). The incident angle is given by

$$\cos\theta = \sin(\varphi - \beta)\sin\delta + \cos(\varphi - \beta)\cos\delta\cos\omega \quad (4)$$

where ϕ and δ are the latitude of the site (=23.36°) and the declination, respectively. The declination is given by

$$\delta = 23.45\sin\left\{360\left(\frac{284+d_n}{365}\right)\right\} \quad (5)$$

where d_n is the day number of the year.

To investigate the change of the k-value of polystyrene insulation in term of temperature at the mid-thickness of the insulation material within a construction assembly, a common used wall construction is modeled. The wall is composed of a 200-mm thick concrete block layer, a 50-mm insulation layer, a 13-mm thick interior gypsum board and a 19-mm concrete stucco from the exterior with a total R-value of 2.79 m^2 C/W. The roof system is mainly composed of 200-mm thick concrete slab with a 15-mm plaster layer from the interior; a waterproof membrane is placed above a 50-mm thick concrete sloping screed. A 75-mm polystyrene insulation layer is placed over the waterproof membrane covered with a weather resistive barrier and a layer of 30-mm sandstone. The total R-value of the roof assembly is 2.4 m^2C/W.

Fig. 3 shows the hourly values of different components of solar radiation for June for Seeb location in Muscat. The curves in Fig. 3 represent the total vertical computed from the total horizontal, direct normal and diffuse horizontal from sun rise to sun set for June 15th. The total horizontal, direct normal, and diffuse horizontal have been obtained from [11].

Fig. 4 shows the hourly values of outside air temperature and wind speed obtained from the measurement in Seeb during June 15th 2015.

The change of the thermal conductivity of the polystyrene insulation in term of the temperature t_x at the mid-thickness of the insulation material during the day time and the increase of the k-values in percentage compared with the k_{24} is given by Tables II-V. One can see that this change is quite significant around noon and can exhibit as much as 9.4% and 20.1 % for the wall and the roof respectively, with α = 0.9 and this will definitely affect the cooling load calculation when operating at temperatures' higher than 24°C. The absorption coefficient α of the assembly has a significant effect on the change of the k-value of the insulation. For instance, the change of α from 0.9 to 0.5 leads to the decrease of the k-value from 0.04309 to 0.04178 W/m°C and from 0.04727 to 0.04378 W/m°C for the wall and the roof respectively.

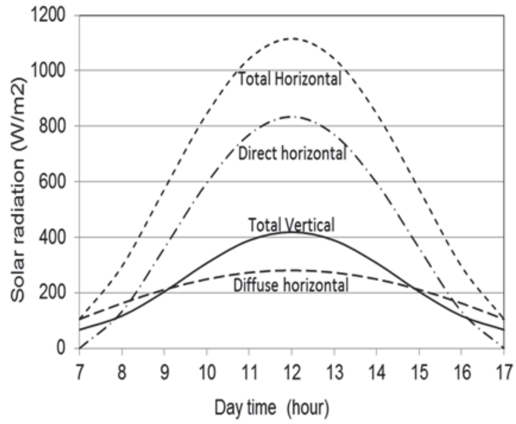

Fig. 3 Hourly values of different components of solar radiation for the 15th of June for Seeb location in Muscat

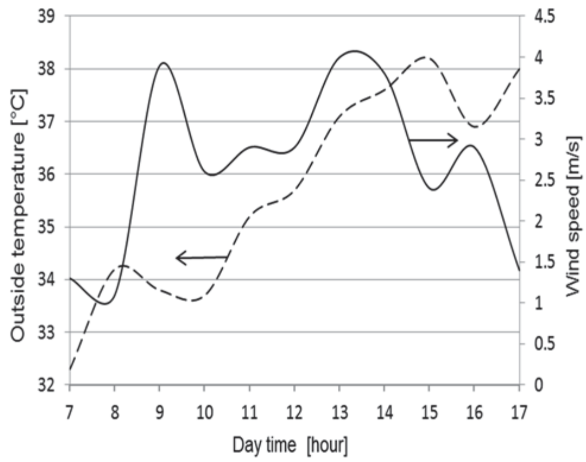

Fig. 4 Hourly values of outside temperatures and wind speed for the 15th of June for Seeb location in Muscat

Fig. 5 shows the peak of the cooling load obtained on July at 11:00 pm for the dark color of the envelope (α=0.9) and light color of the envelope (α=0.5). The effect of α on the change of the cooling load is quite significant at noon and can exhibit more than 2 kW. It is also clear that the accumulated heat through the wall/roof assembly is affected by the k-values of the wall/roof assembly. In fact, the effect is more significant for the horizontal surface (roof) compared with the vertical surface (wall).

TABLE II
CHANGE OF THERMAL CONDUCTIVITY OF POLYSTYRENE IN TERM OF TEMPERATURE AT THE MID-THICKNESS OF THE INSULATION FOR THE WALL DURING THE DAY TIME (α=0.9)

Time	t_x [°C]	$k(t_x)$ [W/m°C]	Increase k- value [%]
7:00 am	36.49	0.04048	2.7
8:00	48.9	0.0416	5.6
9:00	44.06	0.04117	4.5
10:00	57.37	0.04236	7.5
11:00	62.8	0.04285	8.8
12:00	65.4	0.04309	9.4
1:00 pm	57.31	0.04236	7.5
2:00	53.54	0.04202	6.6
3:00	52.9	0.04196	6.5
4:00	42.72	0.04104	4.2
5:00	43	0.04107	4.2

TABLE III
CHANGE OF THERMAL CONDUCTIVITY OF POLYSTYRENE IN TERM OF TEMPERATURE AT THE MID-THICKNESS OF THE INSULATION FOR THE ROOF DURING THE DAY TIME (α=0.9)

Time	t_x [°C]	$k(t_x)$ [W/m°C]	Increase k-value [%]
7:00 am	26.06	0.0395	0.3
8:00	62.82	0.04285	8.9
9:00	60.38	0.04263	8.1
10:00	95.06	0.04576	16.2
11:00	106.04	0.04375	18.8
12:00	111.9	0.04727	20.1
1:00 pm	89.84	0.04529	15
2:00	80.07	0.04441	12.7
3:00	76.5	0.04409	11.9
4:00	48.25	0.04154	5.3
5:00	37.23	0.04055	3

TABLE IV
CHANGE OF THERMAL CONDUCTIVITY OF POLYSTYRENE IN TERM OF TEMPERATURE AT THE MID-THICKNESS OF THE INSULATION FOR THE WALL DURING THE DAY TIME (α=0.5)

Time	t_x [°C]	$k(t_x)$[W/m°C]	Increase k- value [%]
7:00 am	33.72	0.04023	2.1
8:00	41.21	0.04091	3.9
9:00	38.39	0.04066	3.2
10:00	45.76	0.04132	4.9
11:00	49.26	0.04163	5.7
12:00	50.92	0.04178	6
1:00 pm	46.86	0.04142	5.1
2:00	44.89	0.04124	4. 7
3:00	44.73	0.04123	4.6
4:00	38.65	0.04068	3.2
5:00	39.16	0.04072	3.4

TABLE V
CHANGE OF THERMAL CONDUCTIVITY OF POLYSTYRENE IN TERM OF TEMPERATURE AT THE MID-THICKNESS OF THE INSULATION FOR THE ROOF DURING THE DAY TIME (α=0.5)

Time	t_x [°C]	$k(t_x)$[W/m°C]	Increase k- value [%]
7:00 am	27.53	0.03968	0.7
8:00	43.48	0.04111	4.3
9:00	44.58	0.04121	4.6
10:00	63.14	0.04288	8.8
11:00	69.75	0.04348	10.3
12:00	73.10	0.04378	11.1
1:00 pm	61.65	0.04275	8.5
2:00	56.23	0.04226	7.3
3:00	53.59	0.04202	6.7
4:00	37.97	0.04062	3.1
5:00	29.8	0.03988	1.2

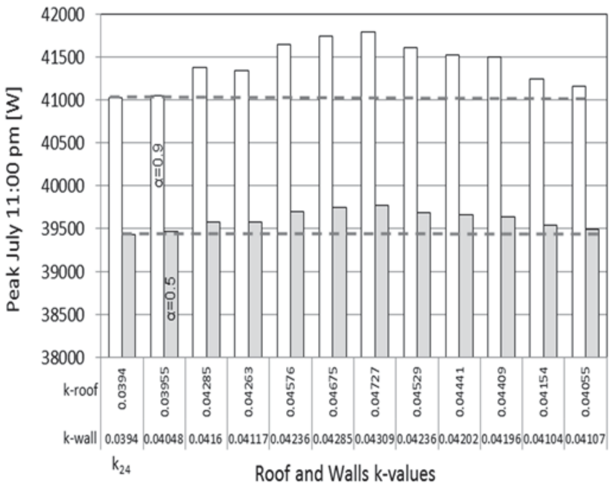

Fig. 5 Change of k-values at 24 ºC and in term of t_x for the 15th of June for Seeb location in Muscat

IV. CONCLUSIONS

The effect of the operating temperature on the thermal conductivity of polystyrene insulation material was investigated using the developed experimental apparatus based on the guarded hot plate principle. It has been found that the k-value of the polystyrene insulation is affected by the change in operating temperature. In all cases, higher temperature leads to higher thermal conductivity. The result also shows that the lower the material density is, the higher is the thermal conductivity.

The polystyrene insulation material can exhibit as much as 9.4% and 20% increase in thermal conductivity at noon for the wall and the roof, respectively for $\alpha = 0.9$ compared with the k_{24}.

The effect of the absorption coefficient, dark and light colors, on the change of the cooling load is quite significant and may exhibit more than 2 kW at noon. It is also clear that the accumulated heat through the wall/roof assembly is affected by the k-values of the wall/roof assembly. In fact, the effect is more significant for the horizontal surface (roof) compared with the vertical surface (wall).

The results of this study call for the need to require from thermal insulation material manufacturers to provide the k-values of their insulation materials at different operating temperatures for different densities of the samples to allow building designers to assess accurately the energy requirements of buildings.

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