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Research Paper

# The impact of changes in thermal conductivity of polystyrene insulation material under different operating temperatures on the heat transfer through the building envelope

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## HIGHLIGHTS

- The lower the material density is, the higher is the *k*-value.
- The *k*-value of the samples is affected by the temperature at the mid-thickness of the insulation.
- The change of the *k*-value can exhibit as much as 9.4% and 20% increase in *k*-value of the wall and roof.
- The change in heat accumulated within the wall and roof are 4% and 14% compared with the heat based on $k_{24}$.

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## ABSTRACT

The cooling/heating load calculation requires an accurate evaluation of the heat transfer through the envelope components of the building. This depends mainly on the accuracy of the thermal resistance of the different building envelope components, particularly the insulation materials. Indeed, the accuracy of the thermal conductivity ($k$) of the insulation material, which describes the ability of heat to flow across the material in the presence of a temperature gradient, has an important effect on the heat exchange between the building interior and the ambiance. In practice, the $k$-value is calculated under specific laboratory conditions at 24 °C, according to relevant ASTM standards. In reality, however, the thermal insulation materials comprising the building envelope are exposed to significant and continuous temperature and moisture changes, due to the variations in the external conditions, including the outdoor temperature, solar radiation, and air moisture content. In addition, the thermal resistance of most thermal insulation materials depends on the operating temperature, the location of the insulation layer within the assembly system, and the effective temperature. Indeed, empirical evidence shows that the change in the polystyrene insulation thermal conductivity with temperature at the mid-thickness of the insulation material during the daytime can be very significant. At high temperatures, in the order of 100 °C, commonly encountered in the roof insulations of buildings in hot climates such as Oman, the percentage increase of $k$-values relative to $k_{24}$ for wall and roof can be as high as 9.4% and 20%, respectively. This change affects the cooling load calculation when operating at temperatures exceeding 24 °C. This article evaluates the effect of changes in the conductivity of polystyrene insulation material, as a function of the operating temperature, on the cooling load calculation required by the building, and thus the sizing of the heating, ventilating, and air-conditioning equipment.



## 1. Introduction

Due to the absence of regulations and standards, few buildings in Oman are insulated; consequently, they consume more energy than 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

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**Nomenclature**

| | | | |
|---|---|---|---|
| $t_e$ | effective or operating outdoor temperature | $\varepsilon\Delta R/h_o$ | correction factor (zero for vertical surface) |
| $R_x$ | portion of thermal resistance measured from inward | $H_b$ | direct horizontal radiation |
| $R_{tot}$ | total thermal resistance of the envelope assembly | $H_d$ | diffuse horizontal radiation |
| $t_o$ | outdoor air temperature | $H$ | global horizontal radiation |
| $t_i$ | indoor air temperature | $\rho_{gr}$ | ground albedo |
| $\alpha$ | surface solar absorbance | $\theta$ | incident angle |
| $I_t$ | total solar radiation | $\beta$ | slope (90° for vertical wall and 0° for horizontal roof) |
| $h_o$ | outdoor surface conductance | | |

by a combination of modes (i.e., conduction, radiation, and convection) [1,2]. The thermal conductivity ($k$-value, W/m K) is defined as the rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area [3].

Thermal insulation materials, like other natural or man-made materials, exhibit temperature dependence properties that vary with their characteristics and the influencing temperature range [3]. For most materials, thermal conductivity increases with the increase in the influencing temperature [4]. Therefore, temperature-dependent thermal conductivity is an empirical relationship established through experimental measurements [5]. For a given aged material sample, the average conductivity mainly depends on density ($\rho$), temperature ($T$) and water content ($w$) [6].

The change in the thermal conductivity of materials has been the subject of extensive studies. Budaiwi et al., for example, investigated the impact of operating temperature on thermal conductivity, and consequently the change in the building envelope-induced cooling load [7]. On the other hand, Aldrich and Bond examined theoretically and experimentally the thermal performance of rigid cellular foam under different temperature conditions [8]. Their results demonstrated significant variations in the $k$-value with changes in 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 authors reported that, when temperature differences are significant, the thermal resistance declines by about 35–50% compared to that measured at small temperature differences. The impact of the temperature difference on the thermal conductivity of some insulation materials produced by Saudi insulation manufacturers has also been investigated [10]. Khoukhi and Tahat have examined the impact of the density, thermal conductivity, and moisture content of polystyrene insulation material and their effect on the cooling load required by space [11,12].

In addition to the operating temperature, the moisture content within the material is another major parameter affecting the thermal conductivity of insulation materials [13]. In extant studies, investigations of the performance of polyurethane insulation [14], fiberglass [15] and mineral wool [16] used for heating and cooling pipes subjected to underground water influences have been conducted. For example, the effective thermal conductivity of the wet fiberglass insulation was found to be many times higher than that of the dry insulation. Similarly, Budaiwi and Abdou investigated the impact of thermal conductivity change of moist fibrous insulation on the energy performance of buildings under hot-humid conditions. Their results revealed that the moisture behavior of the insulation layer is tangibly influenced by the moisture characteristics of other wall components [17]. Khoukhi's investigation of the effect of the moisture content on the thermal conductivity of polystyrene insulation led the author to conclude that the thermal conductivity of low-density sample increases with the increase in the moisture content [18].

Based on the findings presented above, it is evident that the cooling load calculation required for estimating the capacity of the HVAC system depends on the accuracy of the thermal conductivity of the insulation materials comprising the building envelope, which is a function of the operating temperature. However, at present, limited information is available on the variation in the building cooling load due to the changes in the thermal conductivity of building envelope insulation as a function of variations in the operating temperature.

Thus, the results yielded by this work will be of great help to material manufacturers, building designers, and building system engineers, as they will enable them to accurately predict the cooling/heating loads required by buildings for thermal comfort, while also allowing them to calculate the energy performance under hot-humid climatic conditions.

## 2. Measurement of thermal conductivity of samples

Prior to developing the experimental procedure for measuring the thermal conductivity of the samples at different operating temperatures, an experimental apparatus based on the transient plate source was designed (Fig. 1). The apparatus was subsequently calibrated using the known thermal conductivity values at 10 °C of three polystyrene insulation samples characterized by high, ultra-high, and super-high density (HD, UHD, and SHD, respectively) provided by another company [19].

A known voltage and current were supplied to the heater, and its surface temperature (inner surface of the specimen) was measured. Similarly, the increase in the outer surface temperature was also measured until the steady state was achieved. This allowed calculating the temperature difference required for calculations.

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

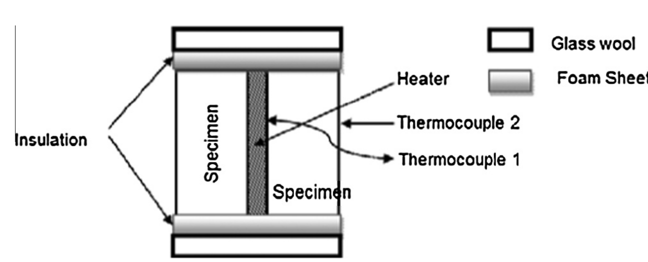


**Fig. 1.** Guarded hot plate.