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Dynamics Thermal Effect on Thermal Conductivity of EPS Insulation by Using Computational Modeling of Heat Transport

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Abstract **-** This paper investigates the dynamics of thermal effect on thermal conductivity, k-value, at different operating temperatures and moisture levels of polystyrene expanded insulation material (EPS) by using computational modeling of heat transport. In building energy analysis, the heat transfer, through its envelope, usually considers a constant single k-value and neglects the effect of the moisture content within the insulation when performing a building energy analysis assessment. In reality, the building envelope is subjected to the combined thermal and moisture gradients. Therefore, an accurate analysis requires a simultaneous calculation of both sensible and latent effects. The purpose of this paper is to analyze the dynamics thermal effect on k-value of EPS by using the conduction finite difference (CondFD). The results of this research show a slight difference in the thermal conductivity value of EPS insulation at different operating temperatures for different densities of the material. However, a greater difference has been observed at higher moisture contents compared with the dry sample when the thermal conductivity of the insulation was a function of temperature.

Keywords**:** Operating temperature; Moisture content; Thermal conductivity; Building insulation material; Building simulation.

1. Introduction

In Oman, due to the absence of regulation and standards, few buildings are insulated; consequently, they consume more energy than is necessary for their operation [1]. Thermal insulation is either organic or inorganic material or a combination of fibrous or particular materials. Such materials can be in the form of a film or sheet, either bloc or monolithic, as an open cell or closed cell, and can be chemically or mechanically bound or supported to slow down the rate of heat flow through a combination of modes (i.e., conduction, convection, and radiation) [2, 3].

The thermal conductivity (k-value) of building insulation materials is dependent on both temperature and moisture content. In practice, in a building energy assessment, constant thermal conductivity values are generally used for insulation material. K-values are typically evaluated under standard conditions (i.e., 24 °C and 50±10% RH) [3-5]. The manufacturer, regardless of the temperature and moisture content, provides a single k-value. However, when placed in a building envelope under real climatic conditions, their actual thermal performance differs from that predicted under standard laboratory conditions [6, 7]. This dependence was reported by several researchers over the last decades, while the thermal conductivity k-value of building insulation materials were generally found to increase with temperature and moisture content [8-13]. Abdou and Budaiwi [14] presented extensive research on the impact of operating temperature on the thermal conductivity of building insulation materials under various operating temperatures. Their results indicated that a higher operating temperature is always associated with higher thermal conductivity. Recently, Berardi and Naldi [15] investigated the impact of the temperature-dependent thermal conductivity of insulating materials on the effective building envelope performance. They conclude that, for most materials, the relationship between conductivity and temperature is found to be nearly linear, as is the case for inorganic fiber insulations (e.g., fiberglass and rock-wool) and some petrochemical insulating materials (e.g., extruded polystyrene), which shows a lower thermal conductivity at lower temperatures.

A number of researchers have conducted studies on moisture transfer and the thermal performance of insulation materials in the presence of moisture [6]. A recent paper focusing on the dynamic thermal response of building layers in relation to their moisture content reported that the presence of the moisture on the surface of building components, including the insulation material, affects its energy efficiency and causes deterioration, which subsequently causes a change in their thermal conductivity [7]. In fact, the accumulation of moisture in building materials leads to the increase of the building insulation material's thermal conductivity, k-value, as well as a decrease in their insulation capacity [16].

The novelty of this study is that it considers the dynamics thermal effect on the k-values of insulation material, which takes into consideration the dynamic change of the thermal gradient as a sensible effect on the overall heat transfer through the insulation material, which allows the accurate calculation of the k-value of the insulation. The results of this paper allow building engineers to accurately assess the thermal performance of building envelopes under real climatic conditions based on more realistic k-values of building insulation materials.

2. Variation of Thermal Conductivity of the Samples

A device based on the transient plate source has been designed to measure the thermal conductivity of the samples [1]. The designed equipment has been calibrated using the well-known k-values of three EPS samples provided by another company. Since the 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. The chiller was only used for the testing of 10°C, while the pump provided greater stability. The measurement as conducted on the samples at 10°C, 24°C, 37°C, and 43°C using the chiller at 10°C and the heater with a pump for the remaining temperatures. The results are summarized in Table 1. In order to moisturize the samples, an ultrasonic humidifier was utilized and a sample placed inside a small acrylic chamber designed to setup the moisture. The details of the experimental procedure are given by [1, 3].

Table 1: Comparison between the thermal conductivity of the three samples and the reference values.

Samples	Average measured thermal conductivity ($Wm^{-1}K^{-1}$)	Thermal conductivity reference ($Wm^{-1}K^{-1}$)	k-values difference (%)
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 EPS insulation material with four density levels—low (LD), high (HD), ultra-high (UHD), and super-high (SHD)—is shown in Fig. 1. The change of the thermal conductivity of all four samples is linear in shape, while it is affected by the operating temperature to varying degrees. In all cases, a higher temperature results in a higher thermal conductivity. Moreover, thermal conductivity decreases with the increase in sample density.

The effect of the moisture content of the k-value of EPS insulation with different densities was investigated at 10, 24, and 28 °C using the previously described apparatus. The findings revealed that the moisture content change at different operating temperatures had a minimal effect on the k-value for the EPS insulation materials designated as HD, UHD, and SHD, which are impermeable to moisture transfer due to their high densities. Therefore, this investigation was limited to the LD sample. The best-fit linear relationships between the k-value and moisture content at a specified operating temperature are shown in Fig. 2. It should be noted that obtaining significant data at operating temperatures beyond 28 °C was a challenge due to the evaporation from the sample that took place during the measurement process.

2. Simulation Environment for Hygrothermal Modeling

2.1. Simulation environment

Simulation programs are widely used for evaluating the energy, thermal, and hygrothermal performances of buildings [17]. Among the comprehensive list, EnergyPlus is considered a well-established, validated, and robust program [18]. EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, and plug and process loads in buildings, as well as water use. DesignBuilder software, the EnergyPlus graphical user interface, was selected for this study [20].

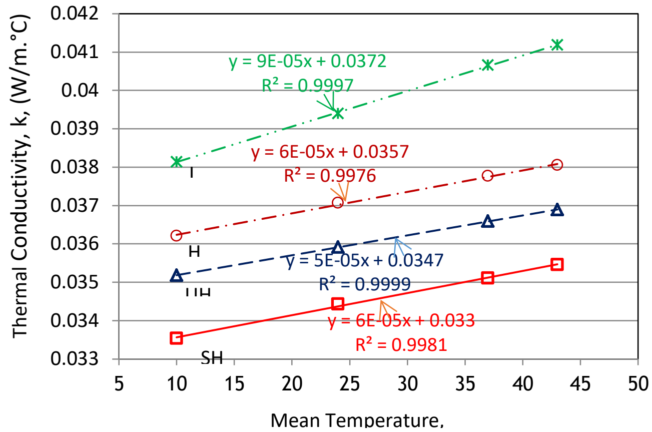

Fig. 1: Change of k-value with different densities vs. operating temperatures.

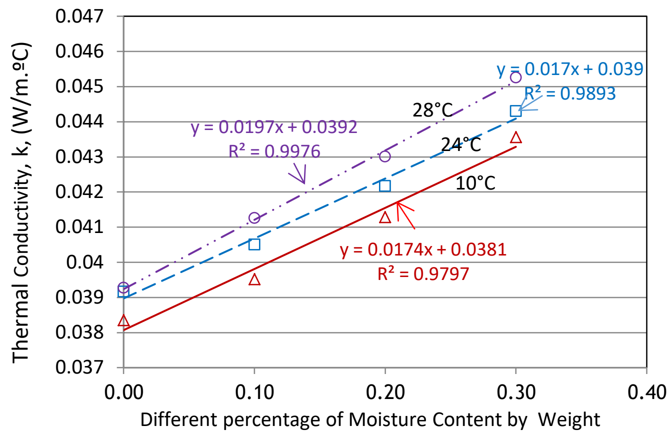

Fig. 2: Best-fit variation of k-values vs. moisture content level at 10, 24, and 28°C operating temperature.

2.2. Mathematical models

EnergyPlus uses three algorithms to calculate heat transfer for an opaque building envelope: conduction transfer function (CTF), conduction finite difference (CondFD) method, and a more advanced algorithm for heat and moisture transfer (HAMT algorithm) [18]. The heat conduction across the envelope is conveniently calculated using CTF method when the thermal properties of building materials are constant. However, when the thermal conductivity is dependent on either temperature, moisture, or both, advanced models such as CondFD or HAMT algorithms are necessary. In addition, EnergyPlus has the capability to model moisture transfer for opaque envelope using two models: 1) the effective moisture penetration depth (EMPD) model and 2) the HAMT algorithm. The EMPD model uses a simplified approach to model the moisture behavior near the surfaces of the building envelope. When moisture transfer across the envelope is of importance, the HAMT algorithm is a viable option. Detailed hygrothermal properties for building materials are, however, needed for the HAMT algorithm, which thus makes the model inputs a daunting task. For this study, CTF was used when the thermal conductivity was constant, and CondFD was used when the conductivity was dependent on temperature. The following section briefly describes the mathematical models of these two methods.

2.2.1. Conduction transfer function (CTF)

CTF is the default algorithm in EnergyPlus to determine heat transfer in the building envelope for cooling/heating load and energy calculations. The form of a CTF solution is shown by the following two equations: one for the interior and the other for the exterior surface [21]:

$$q''_{ki} = -Z_o T_{i,t} + Y_o T_{o,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + \sum_{j=1}^{ny} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \phi_j q''_{ki,t-j\delta} \tag{1}$$

$$q''_{ko} = -Y_o T_{i,t} + X_o T_{o,t} - \sum_{j=1}^{ny} Y_j T_{i,t-j\delta} + \sum_{j=1}^{nx} X_j T_{o,t-j\delta} + \sum_{j=1}^{n\phi} \phi_j q''_{ko,t-j\delta} \tag{2}$$

where q''_{ki} and q''_{ko} are heat flux at interior and exterior surfaces, respectively. Y_o, X_o and Z_o are exterior, cross and interior CTFs, respectively. T_i and T_o are the interior and exterior surface temperature, respectively. N_x, N_y and N_z are number of exteriors, cross and interior CTFs terms, respectively. ϕ_j is the flux coefficient. $n_{\phi j}$ is the number of flux history terms. The subscript t represents the current time, and δ is time step.

The CTF method is used when determining the level of heat conduction in a building envelope. However, this method fails when the thermal properties are variable, or when the results for the interiors of surfaces are needed.

2.2.2. Conduction finite difference (CondFD) method

The CondFD was developed to supplement the CTF. The CondFD algorithm is numerically solved using two schemes in EnergyPlus: 1) semi-implicit Crank-Nicholson scheme or 2) fully-implicit scheme where both are based on the Adams-Moulton solution approach. The governing equation for the heat conduction in a one-dimensional form can be written as follows (DesignBuilder):

$$C_p.\rho.\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k.\frac{\partial T}{\partial x}) \tag{3}$$

For a typical interior node "p", Equation (3) can be discretized using fully implicit numerical scheme as follows:

$$C_p.\rho.\Delta x \frac{T_p^{j+1} - T_p^{j}}{\Delta t} = \left(k_w.\frac{(T_w^{j+1} - T_p^{j+1})}{\delta x_w} + k_e.\frac{(T_e^{j+1} - T_p^{j+1})}{\delta x_e} \right) \tag{4}$$

where *j*: indicate a time step, *w*: west node, *p*: point node, *e*: east node

When equitation (4) is rearranged, T_p can be written in a point form where an iterative method, such as Gauss–Seidel, can be easily utilized. The CondFD algorithm can be used when thermal conductivity is a function of temperature. Such thermal conductivity is obtained from (DesignBuilder)

$$k = k_o + k_1(T_i + 20) \tag{5}$$

where k_o is the conductivity value at 20°C, k_1 is the change in conductivity per degree temperature difference from 20°C.

2.3. House Model

In modern urban planning adopted by the Ministry of Housing in Oman, the majority of the distributed plots are 600 m^2 in size. For this study, the authors selected a typical villa of one floor with a built-up area of 300 m^2. The building characteristics and types of systems used are listed in Table 1 below.

Table 1: Building characteristics and type of systems.

Characteristics	Description of the Base Case
Orientation	Front Elevation facing North
Number of floors	One floor

Floor- floor Height	3.5 m
Floor Area	300 m^2
Floor Dimension	20 x 15 m
Window Area	10% of the gross wall area, Uniformly Distributed
Window	6 mm Single Green Tinted Glazing
	Frame: Aluminum with no thermal break
Solar Absorbance	U-value= 5.788 $W/m^2 \cdot K$, SHGC=0.623, T_{vis}=0.749
Wall	13mm cement plaster + 50mm thermal insulation+ 200mm CMU hollow
	block + 15mm cement plaster, U-value= 2.388 $W/m^2 \cdot K$ (R=0.592 $m^2 \cdot K/W$
Roof	Tiles + 10mm Mortar + 50mm thermal insulation + 150mm reinforced
	concrete slab + 13mm Cement Plaster, U-value= 0.654 $W/m^2 \cdot K$ (R=1.529 $m^2 \cdot K/W$)
Floor	Slab on grade: Tiles + 150 mm slab on grade + 500 mm soil, U-value =0.781$W/m^2 \cdot K$ (R=1.28 $m^2 \cdot K/W$)
Occupancy Density	6 People
Lighting Power Density	4.5 W/m^2
Equip. Power Density	7 W/m^2
Infiltration	0.70 ACH
System Type	Split air-conditioning units (Constant-Volume DX AC)
Thermostat Setting	22ºC for Cooling (no heating is provided)
COP	2.6

3. Results and Discussion

In this study, the author employed several performance indicators, such as annual cooling energy consumption, Zone Sensible Cooling, Walls Heat Balance, and Roof Heat Balance. The following sections will cover the results for different cases using the above performance indicators.

2.4. Impact of the thermal conductivity under constant and variable temperature

Several performance indicators, as shown in the figures below, have been selected and assessed under constant and variable thermal conductivity of the insulation material. The reference case is related to k@24°C. The annual cooling energy consumption, as shown in Fig. 3, increases with the decrease of the density of the sample and the increase of the operating temperature, as compared to the reference value. Indeed, at 10°C, the annual cooling energy consumption is lower compared with the reference value. The maximum difference is obtained for the LD at 43°C at approximately 140 kWh. When the k-values of the insulations change with the operating temperature, the value is roughly between the k@24°C and the reference case. The maximum value is also found to be around 46 kWh. For the zone sensible cooling, as shown in Fig. 4, one can see that the difference is 277 kWh obtained for LD@43°C as compared to the reference case. In the case of variable k, the highest deviation is 88 kWh obtained for the LD sample. Fig. 5 shows the wall heat balance under constant and variable k-value of the insulation. Indeed, the maximum deviation from the reference case is obtained for LD at 43°C which is estimated to be 136 kWh. On the other hand, with the variable k case, the maximum deviation from the base case is around 120 kWh for the LD sample. The maximum deviation of the heat balance for the roof component at constant and variable k-value, as shown in Fig. 6, is estimated to be around 193 kWh. Meanwhile, for the variable k case, the maximum deviation is 147 kWh.

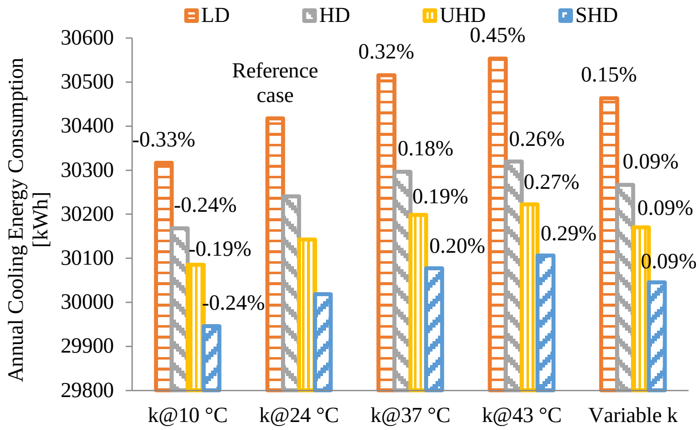

Fig. 3: Annual cooling energy consumption under constant and variable thermal conductivity.

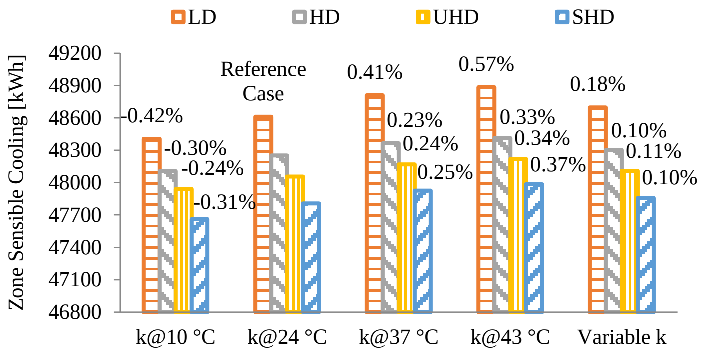

Fig. 4: Annual zone sensible cooling under constant and variable thermal conductivity.

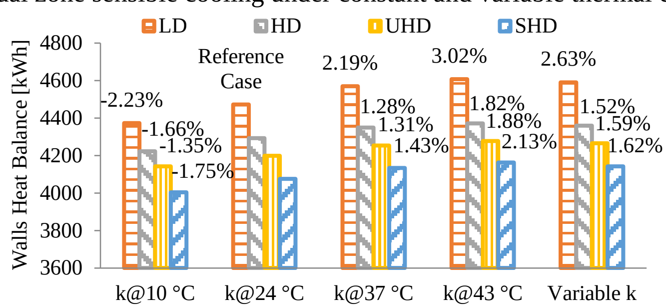

Fig. 5: Walls heat balance under constant and variable thermal conductivity.

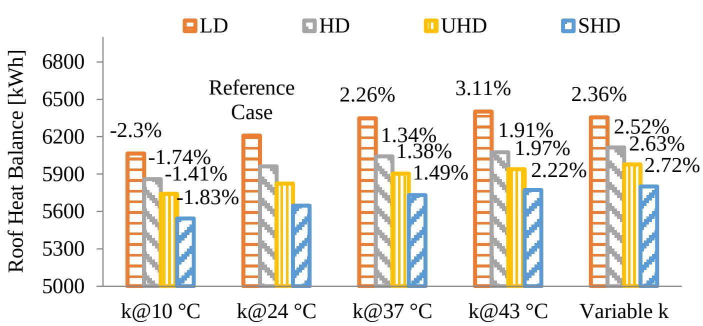

Fig. 6: Roof heat balance under constant and variable thermal conductivity.

2.4. Impact of the thermal conductivity under constant and variable temperature with different levels of moisture content

Figure 7 shows the annual cooling energy consumption for LD samples at different temperatures and when the k-value of the insulation changes with the temperature at different percentages of moisture content. The annual cooling load increases with the increase of temperature and moisture content. When the thermal conductivity of the sample is a function of temperature at 30 % of moisture content, the annual cooling energy is higher by around 480 kWh as compared to the base case. Figure 8 shows the annual zone sensible cooling at different temperatures and when k is a function of temperature for different moisture content. The maximum sensible cooling is obtained when the thermal conductivity is a function of temperature at 30% moisture content.

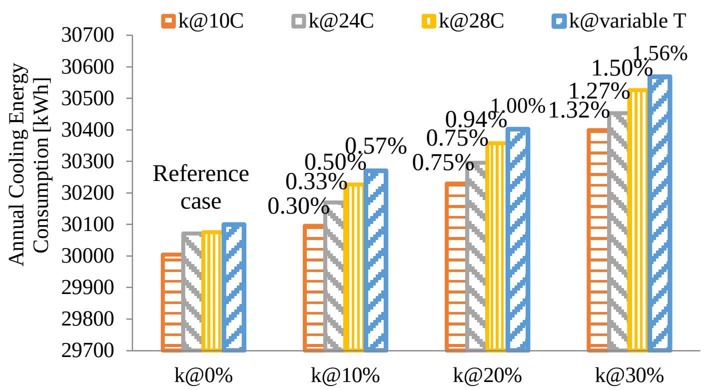

Fig. 7: Annual cooling energy consumption when thermal conductivity of LD is at different moisture contents by weight.

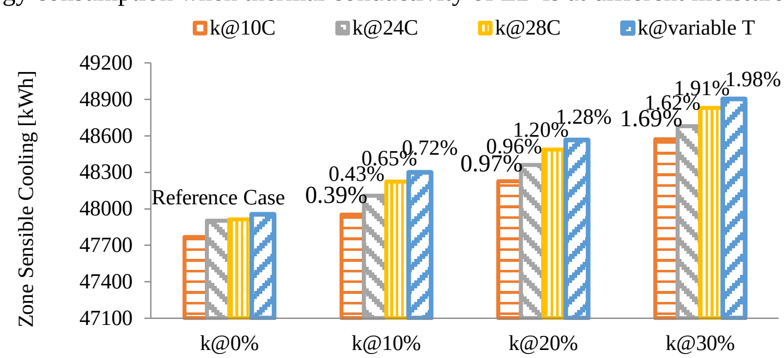

Fig. 8: Annual zone sensible cooling when thermal conductivity of LD is at different moisture contents by weight.

4. Conclusion

The accurate energy building assessment mainly depends on the accuracy of the overall heat transfer coefficient of the building envelope, which depends on the thermal conductivity of the layers of the assembly, particularly the insulation material. This study investigates the impact of changes in the thermal conductivity of the EPS material as a function of its temperature at different levels of moisture content. The results of the simulation indicate that slight changes were noticed when the thermal conductivity of the insulation depends on the temperature exclusively. Meanwhile, this dependence is more significant at various levels of moisture. Indeed, at high percentage of moisture content with variable k-value in term of operating temperature, the cooling energy consumption exhibits higher value compared with the reference case.

To improve future studies on measuring the dynamic hygrothermal response on the thermal conductivity of the insulation and its impact on building energy performance, it is worth employing a more appropriate model that takes into account the combined effect of temperature and moisture change. Moreover, this study should be also extended to other insulation materials, including fiberglass, mineral wool, cellulose, and polyurethane foam which could be more sensitive to the variation of the combined effect of temperature and humidity.

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