



Mathematical Modeling of the Thermal Performance of Nano-Structured Foam as Building Insulation in Hot Arid Regions



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ABSTRACT

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This work presents a theoretical model that describes the thermal resistance of nano-structured foam used as a building insulation panel. In this context, nano-structured foams are emerging as a promising option for improving thermal performance in hot, arid regions. The method of the study is based on the heat transfer across a finite thickness of the nano-thermal insulation. The work includes the calculation of thermal resistance by finding the effective thermal conductivity of the material, which accounts for three modes of heat transfer: conduction, convection, and radiation. The key results show that thermal resistance values for the PU-CO₂ layers were between 24 and 32 m²·K/W. Meanwhile, the U-values were between 0.03 and 0.04 W/m²·K. Further results indicate that the diameter of the nano-pores and their number significantly influence the thermal conductivity. Smaller pores decrease gas-phase conduction, and decreasing pore diameter and porosity reduces the radiative component of k . Overall, the solid part contributes about 50% to the total k , while the gas-phase contribution is around 40%, and the radiation part is less than 10%. In addition, decreasing the pressure of the gas inside the pores reduces the k by more than 50%, and increasing the temperature leads to an increase in k of 10%.

1. INTRODUCTION

Nano-insulation materials (NIMs) are advanced thermal insulation materials characterized by a nanostructure that reduces effective thermal conductivity. Nano-porous insulators are homogeneous materials and characterized by their open or closed nanostructure cells that achieve high-performance thermal insulating qualities [1]. Common NIMs are nano-gels (silica gel and aerogel), nano-clays, nano-reflective panels, nano-foamed materials, and nano-composites [2]. Nano-porous materials are made by reducing the pore size below 200 nm [3]. The gas molecules only collide with the pore wall instead of each other. As a result, the intermolecular collision is eliminated, and the least conductive thermal insulating material exists [4]. The NIM closed-pore structure includes gases like air, argon (Ar), and CO₂ [5]. The NIM usually has an overall thermal conductivity of less than 4 mW/(m·K) in the pristine condition [6].

The nano-structured foams exhibit unique thermal properties that make them suitable as insulation for different purposes. The thermal performance of nano-structured foams depends on several factors, mainly [7]:

(1). Structure of the material: The nanostructure of the foam reduces thermal conductivity, which improves the thermal performance. Where nano-structured foams have extremely low thermal conductivity, which reduces heat transfer to the minimum extent.

(2). Stability of the material: Nano-structured foams exhibit

high thermal stability, making them suitable for applications at high temperatures.

Nano-structured foams can be implemented in a variety of applications in hot and dry regions, including building insulation, to reduce energy consumption and improve thermal comfort, and to insulate pipes in industrial systems and improve the efficiency [8, 9]. Besides the benefits in heat reduction, NIMs have many advantages, such as [10]:

(1). Lightweight: This feature makes the material easy to install and handle.

(2). Moisture resistance: The material is highly resistant to moisture. This makes it suitable for applications in humid environments.

(3). Low cost: It can be less expensive with the expanding in markets and the developing in raw materials.

Recently, several researchers have introduced a set of models for the behavior and performance of nano-porous materials, including the heat transfer phenomenon. Gangåssæter et al. [11] presented a review of the studies that involved air-filled nano-structured thermal insulation materials for building purposes. The common materials are aerogels, vacuum insulation panels, and hollow silica nano-spheres. The study introduced available modeling for thermal conductivity, including the Knudsen effect. The study advised making materials with a very low solid state and radiation conductivity. Lowering the gas thermal conductivity would be a good opportunity to make a nano-pore-based high-performance thermal insulation material at atmospheric

pressure. Many structural parameters can be modified, like porosity, pore diameter, and shell thickness. Jelle et al. [12] proposed an understanding of the governing thermal transport mechanisms based on the Knudsen effect in hollow silica nano-spheres (HSNS) through theoretical concepts and experimental laboratory explorations. The idea is that the heat transport by gas conductance and gas/solid state interactions decreases with decreasing pore diameters in the nano-range as predicted by the Knudsen effect. The inner diameters of the synthesized HSNS ranged between 85 and 213 nm. Correspondingly, the thermal conductivities have been measured between 14 and 30 mW/(m·K), respectively. Van de Walle and Janssen [13] introduced a 3D model to predict the effects of pore sizes and gas pressures on the effective thermal conductivity of nano-porous materials. The framework is applied to predict the thermal conductivity of nano-cellular polymethyl methacrylate foam. Results indicate the potential improvements when decreasing the pore size from the micrometer to the nanometer range, resulting in up to 40% reduction for high-porosity materials. By reducing the gas pressure below the atmospheric pressure, the mean free path will increase since there are fewer molecules present to collide with. This leads to a decrease in the bulk gaseous thermal conductivity. However, the effect of reducing pressure appears clearly at relatively large pore sizes.

Apostolopoulou-Kalkavoura et al. [14] investigated the heat transfer features through cellulose nanomaterials. The study described the methodology and the formation of the nano-cellulose aerogel foam, which exhibits very low conductance. A suitable approach to determine the thermal conductivity through pores is presented, which explains the role of the Knudsen effect and phonon scattering. When the pore diameter is less than the mean free path (i.e., less than 50 nm), the gaseous thermal conductivity is limited. On the other side, the thermal conductivity of the solid part can be related to phonon scattering at walls, and it can be minimized by dominating the conjugated surfaces. Furthermore, the shape and thickness of pore walls make an important contribution to phonon scattering through the foam. Zhu et al. [15] presented a review of the studies that investigated the thermal resistance of silica gel theoretically. The review showed a brief introduction of heat transfer characteristics in silica aerogels, including the multi-component and multi-mode coupling effect, size effect, and multi-scale effect. Some aspects discussed the heat transfer mechanism via gas phase, solid phase, and thermal radiation. The review presented common models for predicting the gaseous thermal conductivity in nano-scale pores, gas-contributed thermal conductivity, the apparent thermal conductivity of the solid skeleton, and finally the effective thermal conductivity. Lou et al. [16] introduced a review on the performance of aerogel insulation. The study presented the formulation and modeling of common relations used to calculate the thermal conductivity through nano-scale aerogel materials. In conclusion, further studies are required to satisfy an accurate mathematical description of the material, especially those terms to be neglected (convection effects and coupling terms). Also, attention is required for the complex particle aggregation structures and nano-scale radiative heat transfer modeling.

Vafaeva et al. [17] proposed a method to determine the thermal conductivity of nano-ceramic insulation coating on the surface of a heat pipe. The research subject is the thermal conductivity features of nano-ceramic thermal insulation located on the surface of a round-section pipeline. The

research method involves the laws of steady-state heat conduction and heat transfer for a two-layer cylindrical wall. The findings indicate that for a steel pipeline with an insulation thickness of 3.5 mm, the thermal conductivity coefficient of the liquid nano-ceramic thermal insulation material amounted to 0.0145 W/(m·K). Minor discrepancies in magnitudes may be attributed to the extended period of usage. Akdağ et al. [18] studied different insulation materials regarding their thermal conductivity values (λ -values). The research suggested a hollow block with dimensions of $300 \times 300 \times 100 \text{ mm}^3$ as a construction material prototype. Subsequently, various insulating materials were placed in the identified hollows of the prototype, such as Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyurethane (PU), Glass Wool (GW), Rock Wool (RW), Perlite (PLT), Mineral-Based Insulation Material (MLT), and Vacuum Insulation Panel (VIP). The λ -value of the prototype was determined by two different numerical analysis programs (COMSOL and ANSYS) with different insulation materials. In conclusion, the VIP insulated block was the best choice, which exhibited approximately 4.5 times higher thermal insulation performance compared to the prototype due to the role of the nano-porous structure. Fu et al. [19] developed a method to prepare gradient nanostructure aramid aerogel with core layers of average pore diameters of 150 nm and 600 nm, respectively. The effective thermal conductivity was calculated using the Fourier thermal conduction formula. Experiments and simulations reveal that the gradient nanostructure creates high interfacial thermal resistance at heat transfer interfaces, resulting in a radial thermal conductivity as low as 0.0228 W/(m·K).

The research gap of the current study is specifically seeking to determine the overall thermal conductivity of a nano-structured foam panel, which depends on many parameters, including pore diameter, porosity, and gas conditions (pressure and temperature) inside the pores. The objective is to find the corresponding thermal resistance and U-value that are related directly to the air-conditioning demand for a building in a hot region. The study analyzes the heat transfer across a limited thickness of the nano-foamed thermal insulation.

2. MATHEMATICAL MODELING

The methodology of the work is based on theoretical modeling of one-dimensional steady-state heat transfer for conduction, convection, and radiation across a limited thickness of homogenous nano-structured rigid foam. The modelling includes some practical correlations as well for the Knudsen number and specific constants for gaseous conduction.

In this work, the mathematical expressions for the calculation of the effective thermal conductivity of NIM have been presented to demonstrate a suitable procedure for analyzing the thermal performance of the materials of the building, including the NIM.

The heat transfer (Q) across any element of the building (wall or roof) is determined by the Fourier heat transfer formula, as follows [20]:

$$Q = UA\Delta T \quad (1)$$

where,

U : Overall heat transfer coefficient (W/(m²·K))

A : Surface area (m²)

ΔT : Temperature difference across the sides of the element (K)

The overall heat transfer coefficient (U) can be found based on thermal resistances of the construction layers, as follows:

$$U = \frac{I}{R_m + R_i} \quad (2)$$

where,

R_m : Thermal resistance of the wall with main construction material (m²·K/W)

R_i : Thermal resistance of the layered insulation material (m²·K/W)

The thermal resistance is given by:

$$R = \frac{x}{k} \quad (3)$$

where,

x : Thickness of the material (m)

k : Thermal conductivity of the material (W/(m·K))

The values of thermal conductivity of main construction materials are known, but the problem is with the thermal conductivity values of NIMs, which differ according to many conditions. The effective thermal conductivity of nano-porous insulation material is represented by [11]:

$$k_{tot} = k_{cond} + k_{conv} + k_{rad} + k_{coup} + k_{leak} \quad (4)$$

where,

k_{cond} : Thermal conductivity due to conduction heat transfer

k_{conv} : Thermal conductivity due to convection heat transfer

k_{rad} : Thermal conductivity due to radiation heat transfer

k_{coup} : Thermal conductivity due to coupling effects between different components in the material

k_{leak} : Gas leakage thermal conductivity in the material

The thermal conductivity values due to coupling effects and gas leakage have less contribution due to the tight nano-structure in the homogenous single-phase material. Therefore, these terms can be omitted.

The conduction term in the porous part is attributed to the solid conduction and gas conduction [21], thus:

$$k_{tot} = (k_{solid} + k_{gas}) + k_{conv} + k_{rad} \quad (5)$$

The convection term is normally not taken into account when dealing with porous thermal insulation material, because it is assumed that there are no effective holes in the materials through which a pressure difference could make air movement and moisture leak [22]. Hence, the effective thermal conductivity can be given by:

$$k_{eff} = k_{solid} + k_{gas} + k_{rad} \quad (6)$$

The solid term (k_{solid}) is connected to the lattice vibration at the atomic scale. This term can be measured experimentally as a contribution of the solid part, which is relatively low because of the low bulk densities in nano-porous material [22]. Note that for porous media, the effect of porosity should be included. The gaseous term (k_{gas}) is the thermal conductivity

of the gas part, which results from the collision between gas molecules that convey the heat through them. In case the length of the pore is close to the mean free path, then the heat transfer from side to side is limited. And the collision is decreased between the gas particles and the pore walls. Thus, the heat transfer due to intermolecular collision will be less and becomes less probable as the pore size becomes smaller. This is often referred to as the Knudsen effect.

The gaseous conduction in nano-insulation can be expressed by [23]:

$$k_{gas} = \frac{\varphi k_{gas,st}}{1 + \beta Kn} \quad (7)$$

where,

φ : Porosity

$k_{gas,st}$: Thermal conductivity of gas at standard ambient conditions (W/(m·K)).

β : Dimensionless constant (between 1 and 2 for most gases [24])

This constant can be determined from [25]:

$$\beta = \frac{5\pi}{32} \frac{9\gamma - 5}{\gamma + 1} \quad (8)$$

where, γ is the specific heat ratio of the gas.

The Knudsen number (Kn) is related to the mean free path length (L) and the dimension where the gaseous transport takes place (δ).

$$Kn = L / \delta \quad (9)$$

The dimension δ can be assumed approximately equal to the pore diameter in nano-porous media [24]. The average distance a gas molecule travels before colliding with another gas molecule is called the mean free path length (L), and it can be calculated by [26]:

$$L = \frac{k_B T}{\sqrt{2} \pi d^2 P} \quad (10)$$

where,

k_B : Boltzmann constant (1.38×10^{-23} J/K)

T : Temperature of the medium (K)

d : Diameter of the pore (m)

P : Pressure of the medium (Pa)

The mean free path of air is around 100 nm at normal pressure and temperature [26]. This means that for pore sizes above 100 nm, most gas molecules will collide with each other and thus a high gas contribution to the total k-value. For pore sizes in the range of the mean free path and below, the walls would interrupt the gaseous heat transfer [27].

The radiation term k_{rad} is connected to the emittance of electromagnetic radiation in the infrared wavelength region from the wall surface. Usually, the radiation through the nano-insulation layers is low and takes the order 10^{-3} . However, the radiation part of the thermal conductivity at ambient conditions can be expressed as [13]:

$$k_{rad} = \frac{16 \sigma T^3 S_{MFP}}{3} \quad (11)$$

where, σ is Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}$). The term S_{MFP} is approximately [13]:

$$S_{MFP} = 4 \times 10^{-5} \varphi \left(\frac{d}{L} \right) \quad (12)$$

Hence, the final form of effective k-value of nano-insulation with respect to the mixing rule of composite material will be;

$$k_{eff} = (1 - \varphi) k_{solid} + k_{gas} + k_{rad} \quad (13)$$

Note that in the hot summer, the temperature of the exposed surfaces may reach up to $80 \text{ }^\circ\text{C}$ [28]. This leads to rise the temperature of the outer insulated foam. The thermal conductivity of foamed insulation material changes with the increasing of temperature. The change in the k-value is due to the variation in the contribution of thermal radiation and changes in the gas and solid components within the foam structure at higher temperatures. For gas and radiation, the temperature effect is already included in the calculation. For conductive heat transfer, it is assumed that the thermal conductivity of the solid component changes according to a formula extracted from certain sources [29, 30], as follows:

$$k_T = k_{st} \left(1 + 5 \times 10^{-3} T \right) \quad (14)$$

where, k_T is the solid thermal conductivity at a certain temperature in $^\circ\text{C}$, while k_{st} is the solid thermal conductivity at standard room temperature.

3. RESULTS AND DISCUSSION

3.1 Operational conditions

The current study served two common foamed insulation materials, PU and EPS. The work suggested several parameters that contribute to the effective thermal conductivity value, such as porosity, diameter of the pore, pressure of the gas inside the pores, and type of gas inside the pores. The aim is to achieve the optimal k-value. This will be determined by analyzing the optimal outcomes obtained from varying the thermal conductivity with respect to these factors. Therefore, the overall calculation included 720 cases. Table 1 provides detailed information for the conditions under consideration.

Table 1. Features of the nano-insulation materials (NIMs)

Feature	Value
Material	PU of $k = 0.03 \text{ W/(m}\cdot\text{K)}$ [31]
	EPS of $k = 0.04 \text{ W/(m}\cdot\text{K)}$ [32]
Type of gas	Air of $k = 0.025 \text{ W/(m}\cdot\text{K)}$ [33]
	CO_2 of $k = 0.015 \text{ W/(m}\cdot\text{K)}$ [33]
Porosity (%)	80, 85, 90, 95, 99
Diameter of pore (nm)	50, 100, 150, 200
Pressure of the gas (kPa)	10, 50, 100
Temperature of the gas (K)	300, 350, 400

Note: PU: Polyurethane; EPS: Expanded Polystyrene.

3.2 Effect of pore diameter and porosity

In general, the diameter of the pores and their quantity

significantly influence the thermal conductivity value. Results show that larger pores increase gas-phase conduction, which increases the overall thermal conductivity, but tiny pores can reduce it due to enhanced phonon scattering. However, there is a specific relationship that depends on pore size, pore distribution, material type, and the presence of gases within the pores.

Figure 1 shows the gaseous thermal conductivity at standard conditions (ambient at $25 \text{ }^\circ\text{C}$ and atmospheric pressure) and for PU foam with air inside. In general, the gaseous thermal conductivity increases with increasing porosity. For 100 nm foam, it can be observed that by increasing the porosity, the k-value of the gas-phase has increased by 20–25% when the porosity is 0.99, compared to 0.8. The increase was higher when the foam had large pore diameters (150–200 nm). Since the low k-value is the goal for better thermal insulation, it is recommended not to exceed a diameter of 100 nm to satisfy low k-values for the gas-phase conduction, which is below $10 \text{ mW/(m}\cdot\text{K)}$. Note that the current results of k-values were approximately close to those obtained by Schlanbusch [22], with a difference in the values that does not exceed $\pm 15\%$. The comparison of k-values with Notario et al. [34] showed a difference by $\pm 10\%$.

The effect of radiation within the pores was illustrated in Figure 2, at standard conditions. In general, the radiative thermal conductivity increases with increasing porosity. The increase due to the porosity at small-sized pores (50 nm) was imperceptible. But by increasing the diameter and porosity, the k-value has increased by 30–35% as a comparison between porosities of 0.8 and 0.99. The increase was even more at higher pore diameters (200 nm). However, the contribution of the radiation part is still ineffective on the total thermal conductivity value due to the low radiative k-values (less than $2 \text{ mW/(m}\cdot\text{K)}$). The last point is also mentioned by Van de Walle and Janssen [13], where they found that the radiation through the nano-foamed layer is low and it takes the order 10^{-3} .

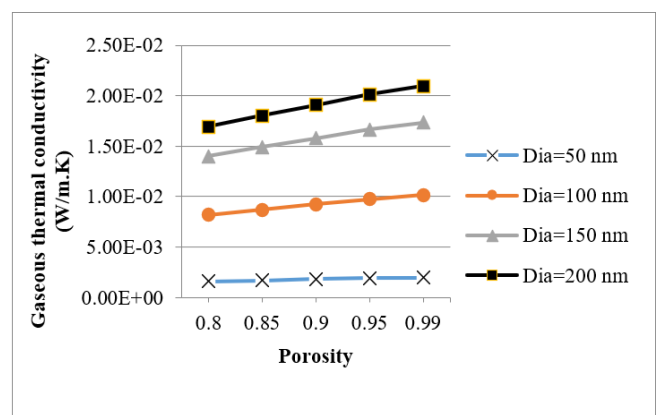


Figure 1. Gaseous thermal conductivity at standard conditions (Polyurethane with air inside)

The behavior of the total thermal conductivity value is shown in Figure 3. In general, the total thermal conductivity decreases with increasing porosity. This behavior includes the contribution of the solid part of the conduction besides the gaseous and radiative parts. The thermal conductivity value of a solid is certainly greater than that of a gas. By increasing the porosity, there is a decrease in the amount of solid material, which is replaced by an amount of gas. Therefore, the total k-value decreases. The decrease in k-value was extremely high

at higher porosity, 0.99, and a lower diameter, 50 nm. Also, the results show that the contribution of the solid part thermal conductivity was small at large pores 200 nm due to the relatively high k-values more than 20 mW/(m·K) caused by gaseous heat transfer. Usually, the foamed insulation material has high porosity with a small amount of solid. That explains why the solid contribution to the total thermal conductivity is not too high. The current results show that among all, the solid part contributes by 50% to the total k-value. The gas-phase contribution is around 40%, and the radiation part is less than 10%. For higher porosities, the contribution of the gas phase is greater than that of the solid part. This behavior is also mentioned by Notario et al. [34], where they referred to similar ratios with $\pm 10\%$ difference.

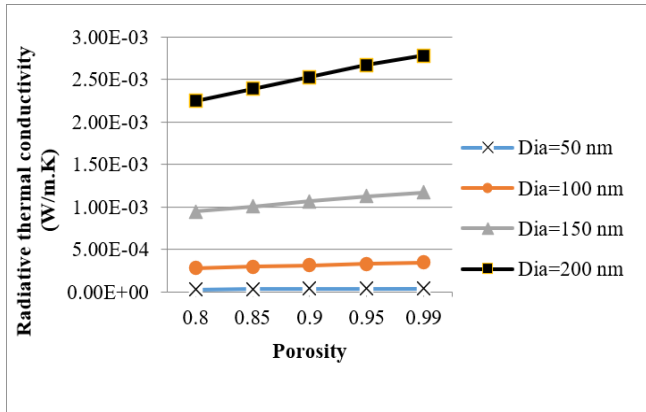


Figure 2. Radiative thermal conductivity at standard conditions (Polyurethane with air inside)

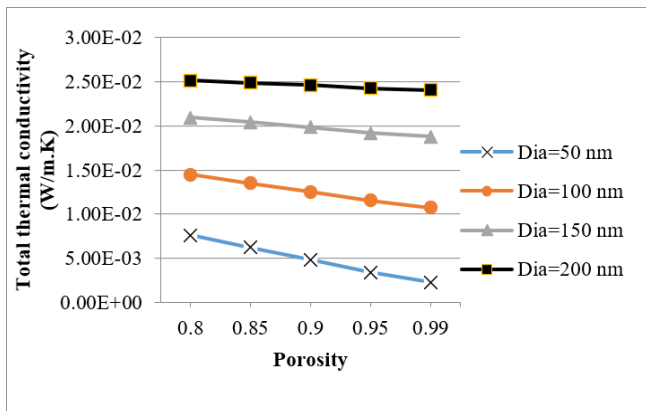


Figure 3. Total thermal conductivity at standard conditions (Polyurethane with air inside)

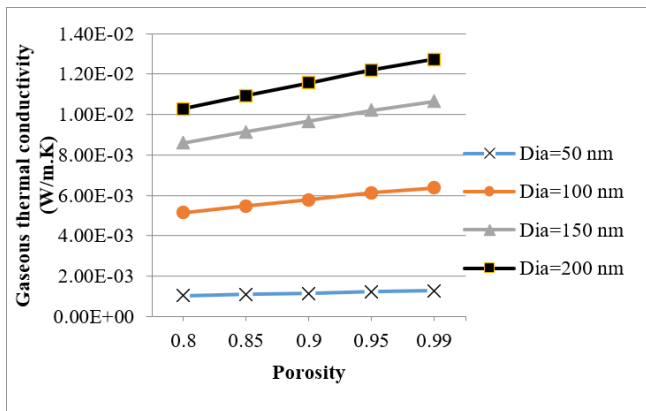


Figure 4. Gaseous thermal conductivity at standard conditions (Polyurethane with CO₂ inside)

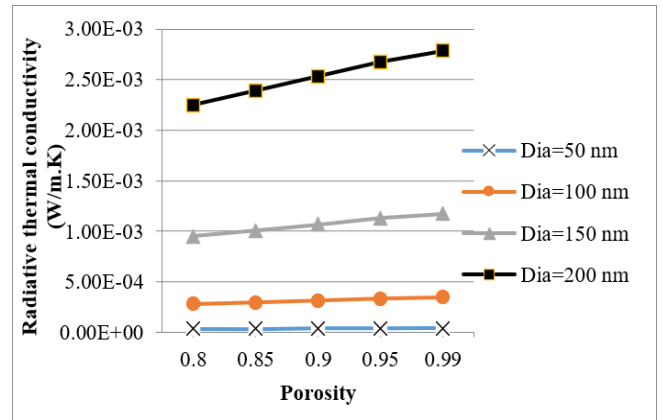


Figure 5. Radiative thermal conductivity at standard conditions (Polyurethane with CO₂ inside)

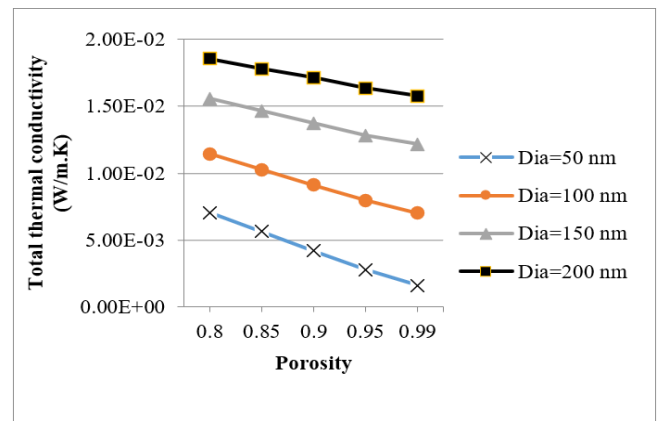


Figure 6. Total thermal conductivity at standard conditions (Polyurethane with CO₂ inside)

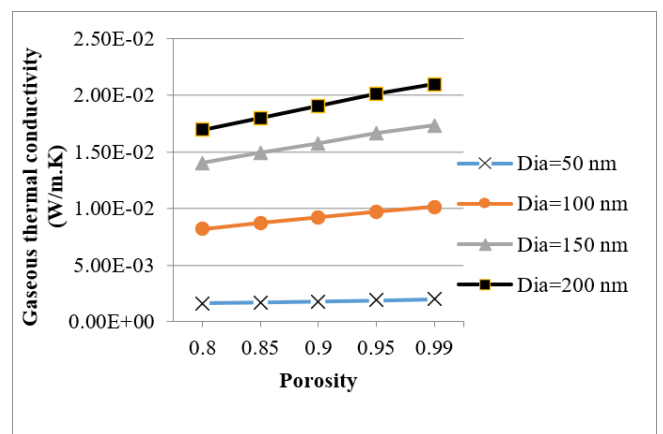


Figure 7. Gaseous thermal conductivity at standard conditions (Expanded Polystyrene with air inside)

The study has been extended to involve another gas inside the pores, which is CO₂. The corresponding results are shown in Figures 4-6 for gaseous, radiative, and total thermal conductivity values, respectively. The results show similar behavior to that of pores containing air, but with lower values of gaseous thermal conductivity in general by 30–40%. The decrement is due to the lower thermal conductivity of CO₂ compared to the air. Radiative thermal conductivity through CO₂ pores shows the same values as in air pores. While the total thermal conductivity shows lower values in general by 20–30%.

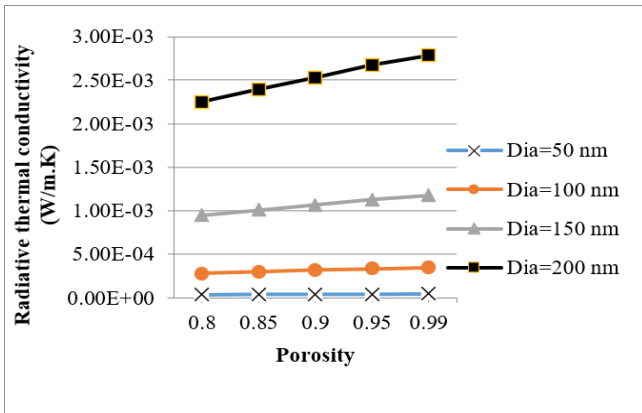


Figure 8. Radiative thermal conductivity at standard conditions (Expanded Polystyrene with air inside)

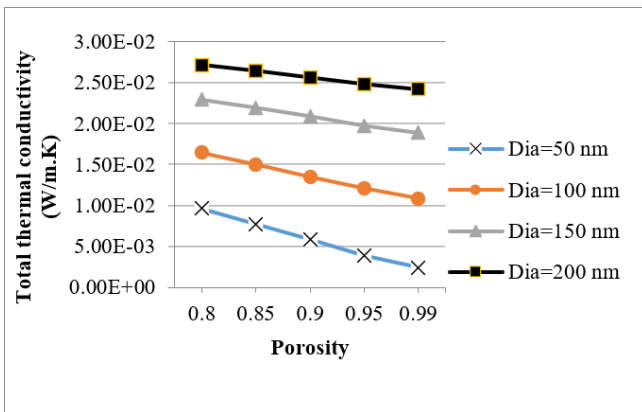


Figure 9. Total thermal conductivity at standard conditions (Expanded Polystyrene with air inside)

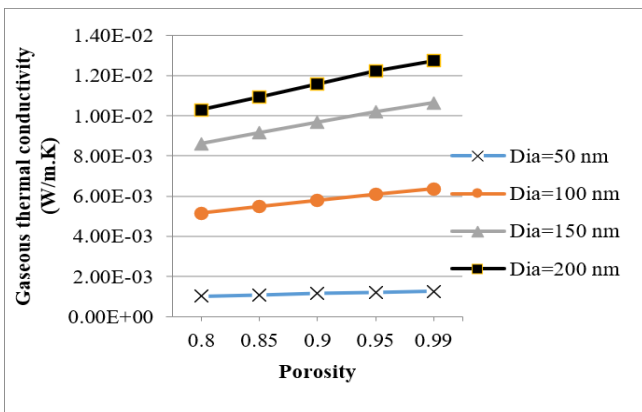


Figure 10. Gaseous thermal conductivity at standard conditions (Expanded Polystyrene with CO₂ inside)

Figures 7-12 show the results in the case of using EPS as a base solid material in place of the PU foam. The results show higher total thermal conductivities in general by 10% due to the higher thermal conductivity of EPS (solid part) compared to the PU. However, it is found that EPS foam cell sizes are generally two orders of magnitude larger [35]. This means greater thermal conductivity values. Gaseous thermal conductivity values through EPS pores show the same values as in PU foam in the case of similar pore diameters and porosities. The radiative thermal conductivities through the pores show similar values as in PU foam since the suggested formulas ignore the emissivity of the solid walls and corresponding reflection effects. However, the reflecting

surfaces are of similar order as the dominant infrared wavelength, and infrared scattering becomes an important consideration for small cell sizes. The relatively large cells would appear to offer limited infrared scattering potential [35].

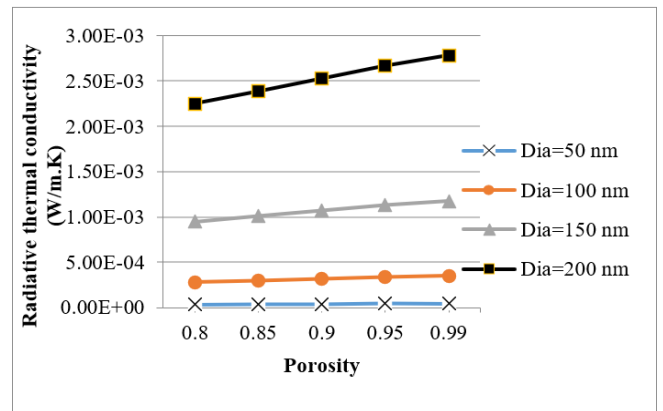


Figure 11. Radiative thermal conductivity at standard conditions (Expanded Polystyrene with CO₂ inside)

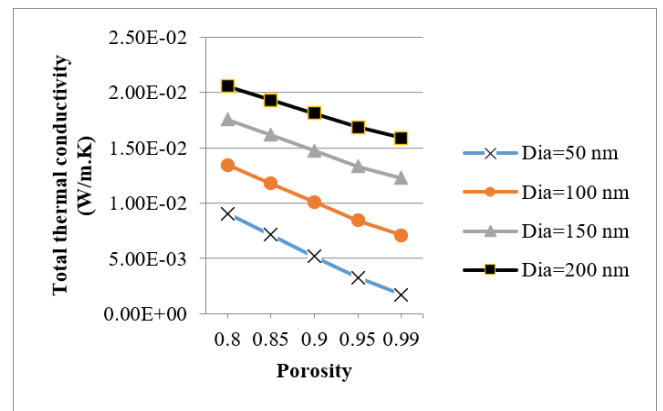


Figure 12. Total thermal conductivity at standard conditions (Expanded Polystyrene with CO₂ inside)

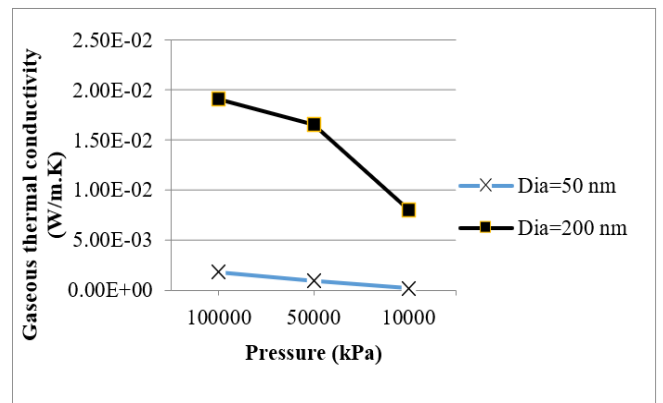


Figure 13. Gaseous thermal conductivity at different pressures (Polyurethane with air inside)

3.3 Effect of gas pressure inside the pores

In gases, thermal conductivity increases with the pressure rise due to the increase in the molecular collisions [36]. Figure 13 shows the gaseous thermal conductivity at standard temperature 25 °C with a range of air pressures inside the PU foam pores (porosity of 0.9), between 10 and 100 kPa. The results show that decreasing the pressure of the gas inside the

pores leads to a decrease in the k-value. This is attributed to an increase in the mean free path length, which increases the Knudsen effect number, thus decreasing the gaseous k-value. This decrease in the k-value is observed more at a higher pore diameter (200 nm) than the small size (50 nm). On average, reducing the pressure from the atmospheric level to 10 kPa decreases the gas-phase thermal conductivity by 60–80%. Regarding this, Van de Walle and Janssen [13] revealed that the gaseous thermal conductivity in nano-pores could be reduced from the usual value of around 0.02 W/(m·K) at atmospheric pressure to about 0.01 W/(m·K) at low pressures below 10 kPa. Another consideration is the convective heat transfer coefficient, which is decreased by 25% when the pressure decreases from the atmospheric level to 10% of it [37].

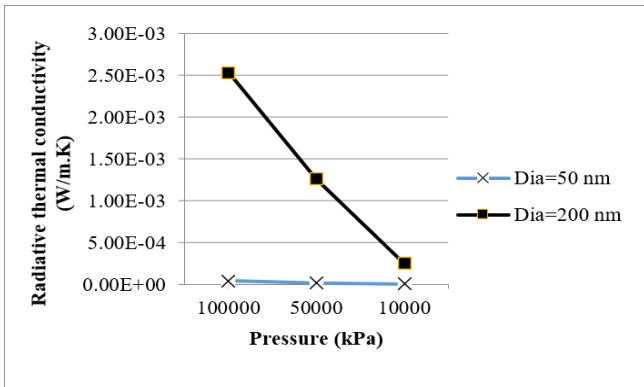


Figure 14. Radiative thermal conductivity at different pressures (Polyurethane with air inside)

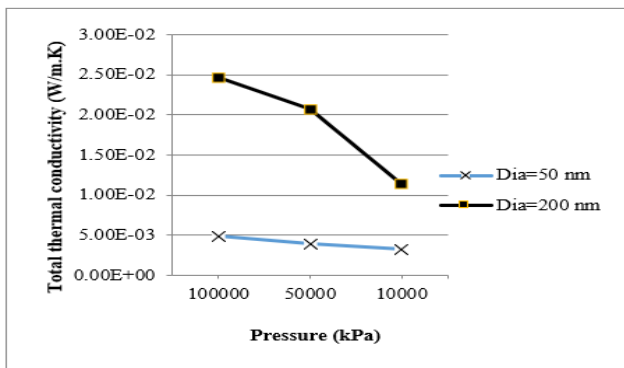


Figure 15. Total thermal conductivity at different pressures (Polyurethane with air inside)

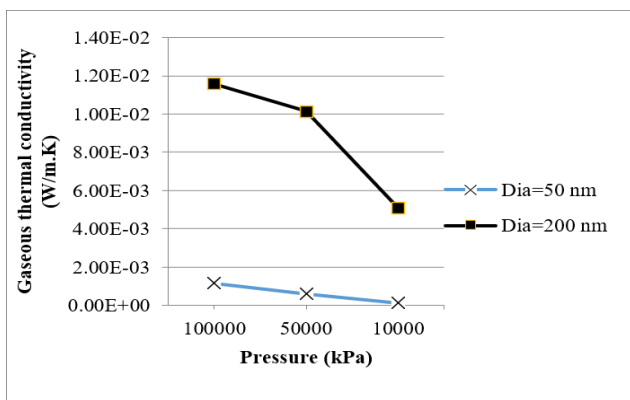


Figure 16. Gaseous thermal conductivity at different pressures (Polyurethane with CO₂ inside)

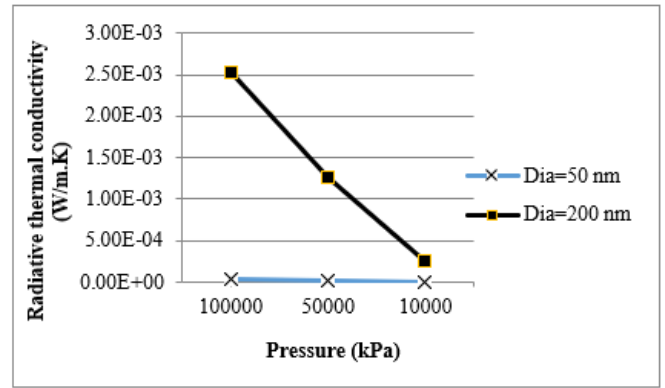


Figure 17. Radiative thermal conductivity at different pressures (Polyurethane with CO₂ inside)

Figure 14 shows the radiative thermal conductivity with a range of air pressures inside the PU foam pores. The radiative k-value is also decreased by reducing the pressure from the atmospheric level to 10 kPa, where the decrease was more than 90%. This is attributed to the increase in mean free path (MFP) length, which decreases (S_{MFP}) in the formula of radiative k-value. The physical reason is that when the distance between objects is comparable to the MFP, radiative heat transfer can be significantly influenced by photon tunneling and interference effects [38]. Figure 15 shows the total thermal conductivity with a range of air pressures inside the PU foam pores. As a result of decreasing both gaseous and radiative thermal conductivities, the total k-value is decreased by reducing the pressure from the atmospheric level to 10 kPa, where the decrease was more than 50%. This may be the maximum limit of reduction by pressure, where Schlanbusch [22] stated that for silica aerogels, thermal conductivity less than 0.01 W/(m·K) can be achieved at low pressures, 5 kPa and below. Note that further decreasing the total k-value requires decreasing the thermal conductivity of the solid component.

The study expanded by replacing the air inside the pores with CO₂. The corresponding results are shown in Figures 16, 17, and 18 for gaseous, radiative, and total thermal conductivity values, respectively. The results show similar behavior to that of pores containing air, but with lower values in general due to the lower thermal conductivity of CO₂ compared to air. Figures 19-24 show the results in the case of using EPS in place of the PU. The results show higher thermal conductivities due to the higher k-value of EPS (solid part) compared to the PU.

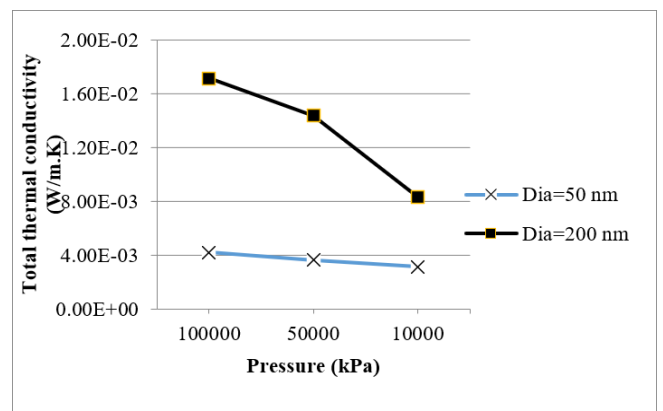


Figure 18. Total thermal conductivity at different pressures (Polyurethane with CO₂ inside)

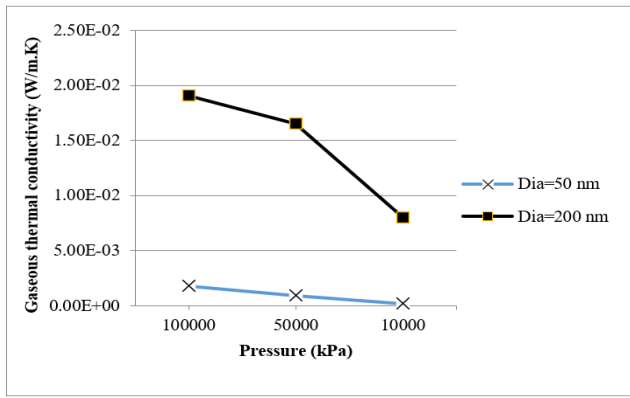


Figure 19. Gaseous thermal conductivity at different pressures (Expanded Polystyrene with air inside)

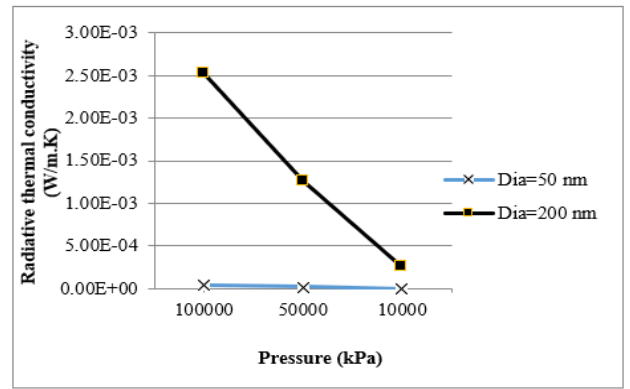


Figure 23. Radiative thermal conductivity at different pressures (Expanded Polystyrene with CO₂ inside)

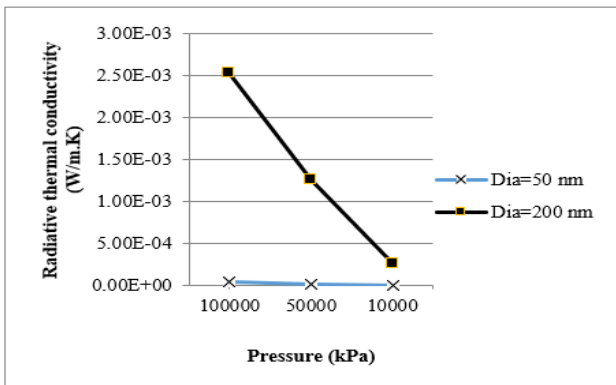


Figure 20. Radiative thermal conductivity at different pressures (Expanded Polystyrene with air inside)

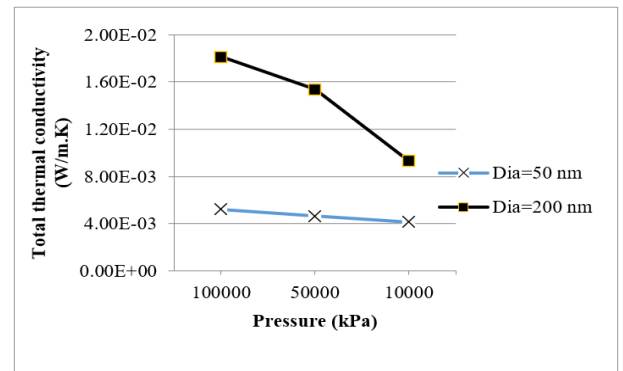


Figure 24. Total thermal conductivity at different pressures (Expanded Polystyrene with CO₂ inside)

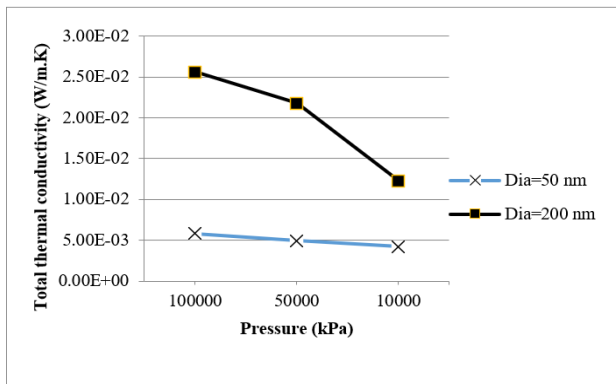


Figure 21. Total thermal conductivity at different pressures (Expanded Polystyrene with air inside)

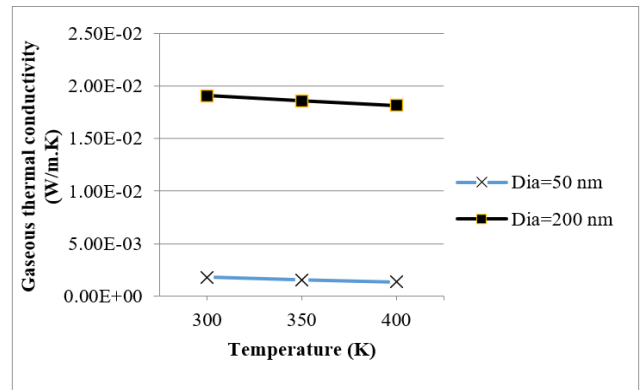


Figure 25. Gaseous thermal conductivity at different temperatures (Polyurethane with air inside)

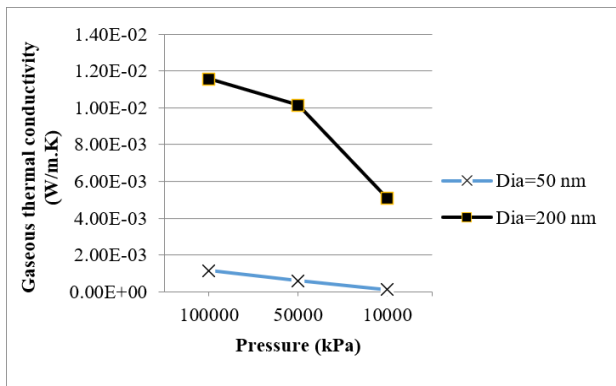


Figure 22. Gaseous thermal conductivity at different pressures (Expanded Polystyrene with CO₂ inside)

3.4 Effect of gas temperature inside the pores

In a gas, the mean free path increases with a rise in temperature under constant pressure. This occurs because a higher temperature causes the gas to expand, increasing the average distance between molecules and therefore the distance a molecule travels between collisions [39]. Since the MFP increases, the Knudsen number increases, and the gaseous k-value decreases according to the related formula. Figure 25 shows the gaseous thermal conductivity at standard pressure (100 kPa) with a range of air temperatures inside the PU foam pores (porosity of 0.9), between 300 and 400 K. The results show that an increase in the temperature of the gas inside the pores leads to a decrease in the k-value. This decrease in the k-value is observed more at the lower pore diameter (50 nm)

rather than the bigger size (200 nm). On average, raising the temperature from the standard level to 400 K decreases the gas-phase thermal conductivity by 10–20%.

Several studies [40-42] stated that increasing the temperature in porous media generally enhances convection heat transfer, due to increased nanoparticle motion, which in turn boosts the thermal conductivity of the gas within the pores. Anyways, the k-value depends on some other factors as well, like diameters of pores, concentration, and porosity of the medium [43]. However, for gases in nano-foams, especially at very small cell sizes, where the Knudsen effect is dominant, the mean free path of gas molecules is comparable to the cell size, which decreases the k-value by restricting gas-phase heat conduction [21, 44].

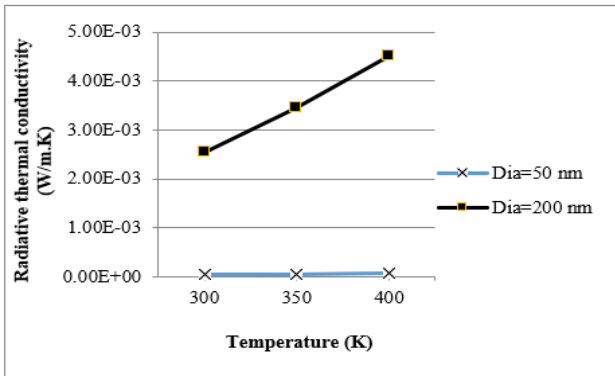


Figure 26. Radiative thermal conductivity at different temperatures (Polyurethane with air inside)

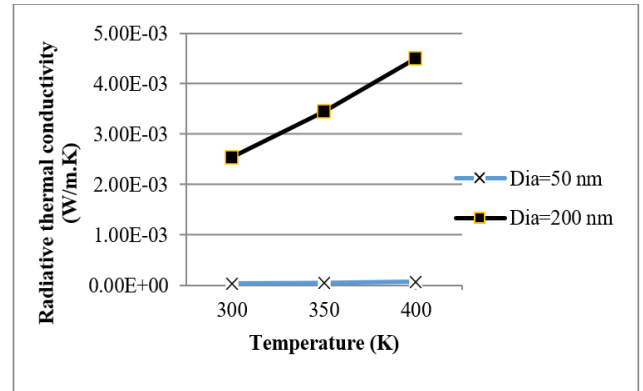


Figure 29. Radiative thermal conductivity at different temperatures (Polyurethane with CO₂ inside)

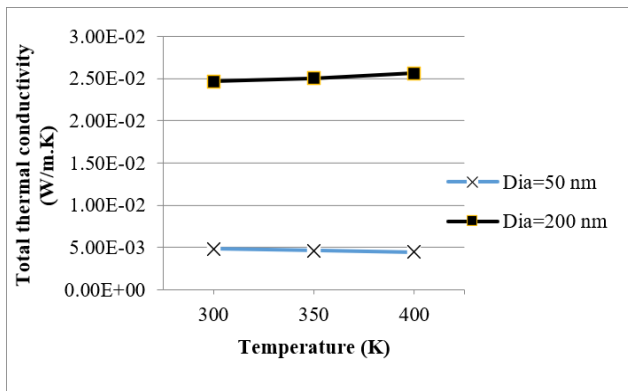


Figure 27. Total thermal conductivity at different temperatures (Polyurethane with air inside)

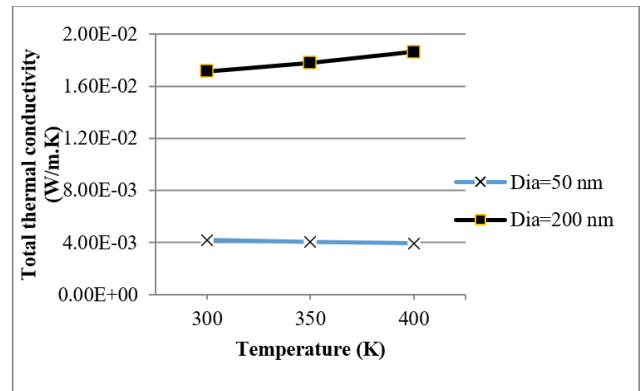


Figure 30. Total thermal conductivity at different temperatures (Polyurethane with CO₂ inside)

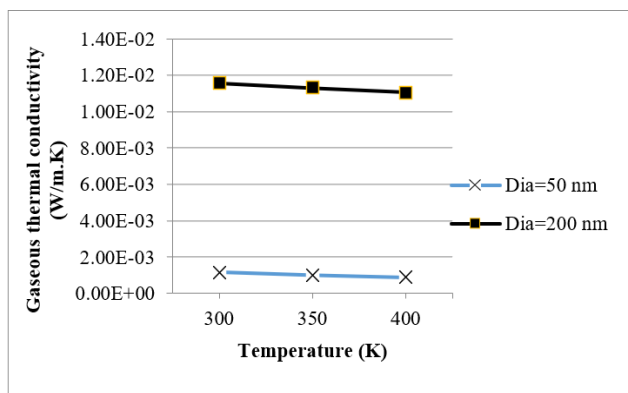


Figure 28. Gaseous thermal conductivity at different temperatures (Polyurethane with CO₂ inside)

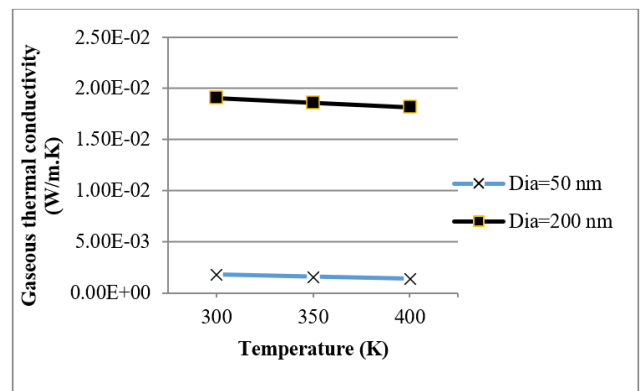


Figure 31. Gaseous thermal conductivity at different temperatures (Expanded Polystyrene with air inside)

Figure 26 shows the radiative thermal conductivity with a range of air temperatures inside the PU foam pores. The radiative k-value has increased by raising the temperature from the standard level (300 K) to a higher one (400 K), where the increase was more than 80%. This is attributed to the increase in MFP, which increases the k-value in the formula related to radiation. However, Zhou et al. [42] referred to an increase in radiation by temperature rise more than others (gaseous or solid). Figure 27 shows the total thermal conductivity with a range of air temperatures inside the PU foam pores. Since there is a decrease in the gaseous k-value and an increase in the radiative k-value, as well as in the solid part k-value, the total k-value has increased as a result. It depends on which of these terms has the bigger influence. However, this increase does not exceed 10%.

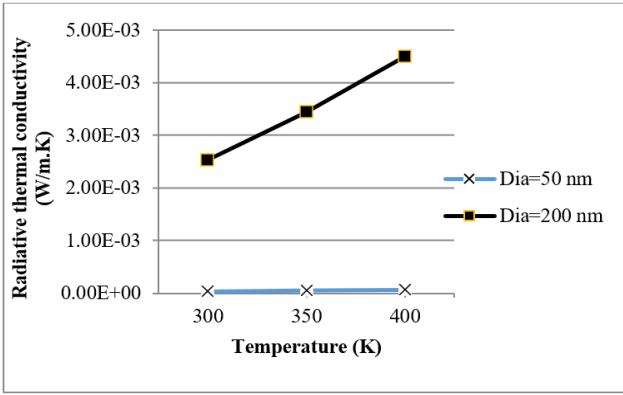


Figure 32. Radiative thermal conductivity at different temperatures (Expanded Polystyrene with air inside)

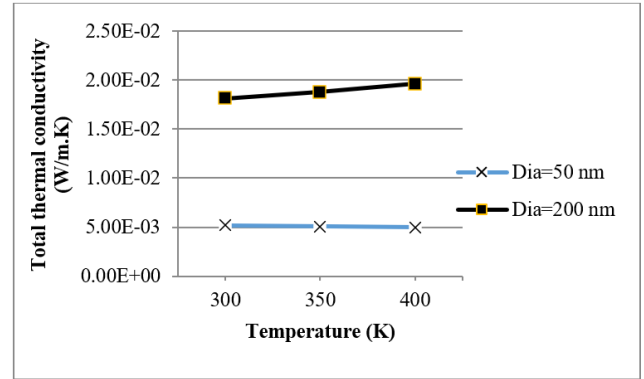


Figure 36. Total thermal conductivity at different temperatures (Expanded Polystyrene with CO₂ inside)

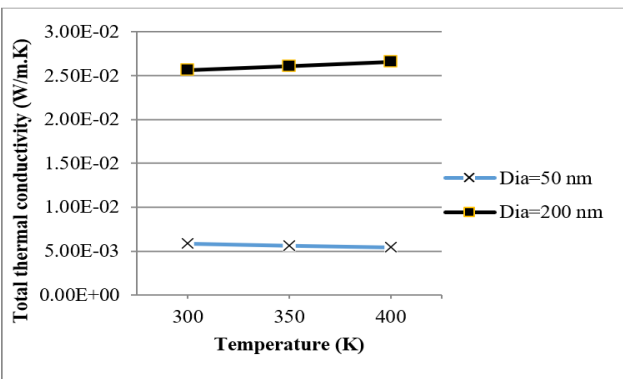


Figure 33. Total thermal conductivity at different temperatures (Expanded Polystyrene with air inside)

The study expanded by replacing the air inside the pores with CO₂. The corresponding results are shown in Figures 28, 29, and 30 for gaseous, radiative, and total thermal conductivity values, respectively. The results show similar behavior to that of pores containing air, but with lower values in general due to the lower thermal conductivity of CO₂ compared to air. Figures 31-36 show the results in the case of using EPS in place of the PU. The results show higher thermal conductivities due to the higher k-value of EPS (solid part) compared to the PU.

3.5 Thermal performance

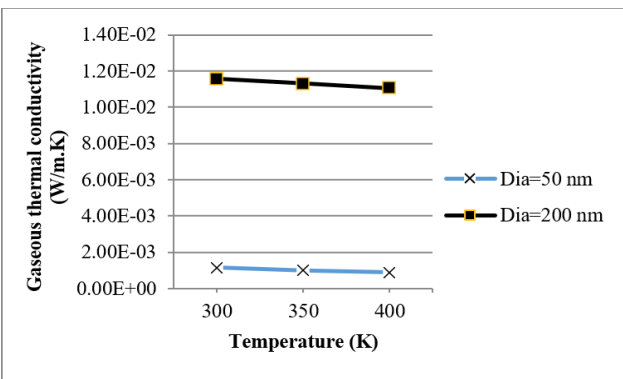


Figure 34. Gaseous thermal conductivity at different temperatures (Expanded Polystyrene with CO₂ inside)

The analysis of the effective k-value of the nano-foamed product has shown some important parameters: material for the rigid walls, gas inside the pores, pore size, porosity, pressure, and temperature inside the pores. It can be noticed that the optimum choice is using PU foam with CO₂ gas inside. The porosity between 0.8 and 0.9 is preferable with pore sizes between 50 and 100 nm. To evaluate the thermal performance of the nano-insulation foam, a set of panels has been suggested with several thicknesses, different conditions, and for various compositions, as shown in Table 2.

In Iraq, the main construction material for walls is the common brick (adobe made by baking of rammed earth soil). The wall has a thickness of 24 cm with a k-value of 0.48 W/(m·K) [45]. Since the reference thermal resistance of traditional 10 cm PU foam is 3.33 m²·K/W; thus U-value of a wall composed of 24 cm adobe brick with traditional PU foam is 0.26 W/(m²·K). Also, the reference thermal resistance of traditional 10 cm EPS foam is 2.50 m²·K/W; hence, the U-value of a wall composed of 24 cm adobe brick with this EPS foam is 0.33 W/(m²·K).

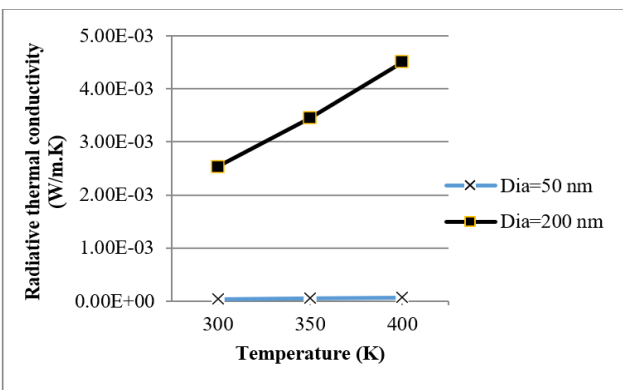


Figure 35. Radiative thermal conductivity at different temperatures (Expanded Polystyrene with CO₂ inside)

Table 2. Specification of nano-insulation panels under consideration

Features	Details
Composition	- PU with air inside pores - PU with CO ₂ inside pores - EPS with air inside pores - EPS with CO ₂ inside pores
Foam	Thickness of 10 cm Porosity of 0.9 Pore diameter of 50 nm
Condition	Inside pressure of 10, 50, and 100 kPa Ambient temperature of 300, 350, and 400 K

Note: PU: Polyurethane; EPS: Expanded Polystyrene.

Figure 37 shows the thermal resistance (R-value) for a set of suggested insulation layers at different pressures. The thermal resistance values related to the PU-CO₂ layers were between 24 and 32 m²·K/W. The obtained results revealed that the R-value has increased by decreasing the pressure inside the pores. On average, the increase was 40%. Figure 38 shows the thermal resistance for a set of suggested insulation layers at different temperatures. The R-value has increased slightly by increasing the ambient temperature (5% in average). Figure 39 shows the heat transfer coefficient (U-value) for a set of suggested insulation layers at different pressures. The lowest U-values were related to the PU-CO₂ layers (between 0.03-0.04 W/m²·K). The obtained results revealed that the U-value has decreased by decreasing the pressure inside the pores. Averagely the reduction was 25%. Figure 40 shows the U-value for a set of suggested insulation layers at different temperatures. The U-value has decreased slightly by increasing the ambient temperature (10% in average). In general, lowering the U-value using nano insulating materials has a direct effect on decreasing the air-conditioning load for a typical building up to 30% comparing to a conventional insulated one [46, 47].

Since the study assumed the omission of convection in nano-pores, larger pores can create stronger internal convective loops, which increase effective conductivity. However, very fine nano-pores have limited convection [48]. Moreover, recent studies revealed that the neglect of coupling terms in thermal analysis makes the calculation of effective thermal conductivity less accurate [49].

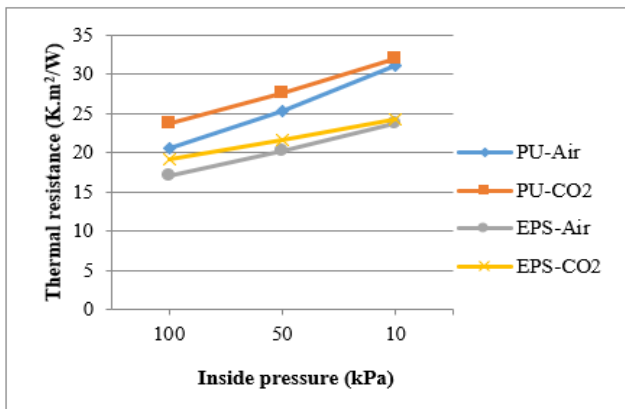


Figure 37. Thermal resistance of the insulation layer at different pressures

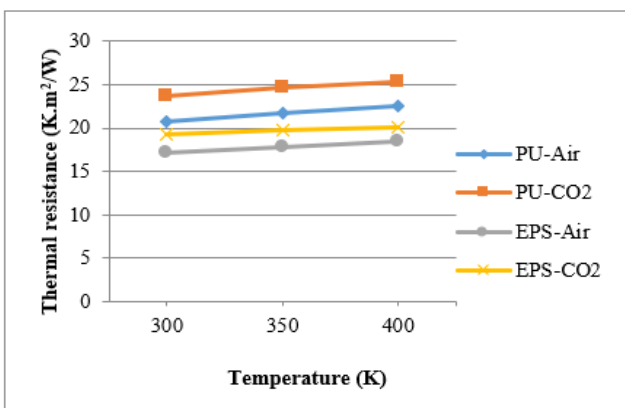


Figure 38. Thermal resistance of the insulation layer at different temperatures

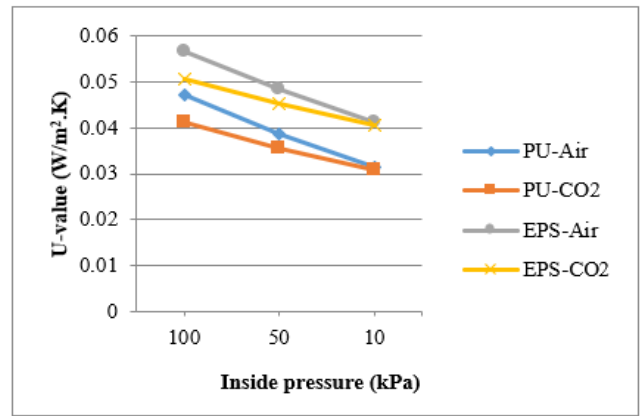


Figure 39. U-value of the insulated wall at different pressures

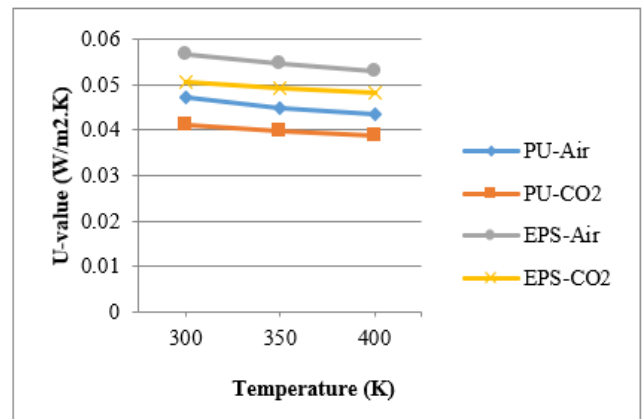


Figure 40. U-value of the insulated wall at different temperatures

The feasibility of maintaining low pressure or CO₂ in the pores within the foam in a real building can be achieved in the same way of implementing VIP. Where the panel is closed which maintains its pressure and gas.

4. CONCLUSIONS

The study presents a theoretical study to determine the thermal performance of nano-foamed insulation for buildings. Multiple cases are considered under different operating conditions, boundary constraints, and parameter ranges. The main goal is to analyze the heat transfer across a limited thickness of the nano-foamed thermal insulation for a building in hot regions. The study also determines the effective thermal conductivity of the material. The obtained results support the following conclusions:

- The diameter of the pores and their quantity significantly influence the thermal conductivity value. Smaller pores decrease gas-phase conduction, which decreases the k-value.
- By increasing the porosity more than 0.8, the k-value of the gas-phase has increased by 20–25% .
- It is recommended not to exceed a pore diameter of 100 nm to satisfy a low range of k-values for the gas-phase conduction (below 10 mW/(m·K)).
- By increasing the pore diameter and porosity, the radiative k-value has increased by 30–35%.

However, the contribution of the radiation part is still ineffective on the total thermal conductivity value due to the low ranges (less than 2 mW/(m·K)).

- Among all, the solid part contributes by 50% to the total k-value. The gas-phase contribution is around 40%, and the radiation part is less than 10% .
- The decrease in total k-value was extremely high at higher porosities and lower diameters .
- The results show similar behavior of foam with CO₂ to that containing air, but with lower values of gaseous thermal conductivity in general by 30–40%.
- The results show similar behavior of EPS foam compared to PU foam, but with higher thermal conductivity in general by 10%.
- Decreasing the pressure of the gas inside the pores leads to a decrease in the k-value, which is observed more at higher pore diameter rather than at a smaller size. Reducing the gaseous k-value was between 60–80%, reducing the radiative k-value was about 90%, and reducing the total k-value was about 50%.
- Increasing the temperature of the gas inside the pores leads to a decrease in the corresponding k-value by 10–20%. On the other side, the radiative k-value has increased by 80%, as well as an increase in the solid part k-value. Therefore, the total k-value tends to increase by 10%.
- The optimum thermal resistance values in the current study were related to the PU-CO₂ layers (between 24 and 32 m²·K/W). These values have increased 40% by decreasing the pressure inside the pores below the standard pressure. The values have increased 5% by increasing the temperature above the standard temperature.
- The lowest U-values were related to the PU-CO₂ layers (between 0.03 and 0.04 W/m²·K). The U-value decreased 25% by decreasing the pressure inside the pores, and decreased 10% by increasing the ambient temperature.

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