

Article

Enhancing the Insulation Property of Polypropylene Through a 3D-Printed Multi-Hollow Structured Board: A Numerical Investigation

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Abstract

This study aims to develop polypropylene (PP) as an insulation material by engineering it into a multi-hollow structured board using 3D printing technology. A previous experimental study determined the effective thermal conductivity of the porous PP board using a hot box test, yielding a value of 0.0033 W/mK, which represents a significant improvement over conventional building insulators like rock wool and cellulose. To validate the experimental results, a numerical simulation using COMSOL Multiphysics 6.2 software was conducted to model the heat transfer process within the porous PP board. The simulation employed an appropriate methodology, including parameter definition, geometry creation, material definition, steady-state porous heat transfer module, initial and boundary conditions, meshing, and analysis. The numerical analysis focused on determining the indoor surface temperature, evaluating the total heat flux, and calculating the effective thermal conductivity of the porous PP board. The simulation results revealed an effective thermal conductivity of 0.0036 W/mK, closely matching the experimentally obtained value from the hot box test. The agreement between the experimental and numerical results validates the numerical study and demonstrates the potential of combining 3D printing technology with materials like polypropylene to develop highly efficient insulation solutions for building applications.

Keywords: polypropylene; 3D printing; multi-hollow structure; insulation; thermal conductivity; COMSOL Multiphysics; numerical simulation

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1. Introduction

Building energy efficiency is a critical area of research as the world seeks to reduce building energy consumption and greenhouse gas emissions and combat climate change. In the United States, buildings account for 36% of primary energy consumption, with heating and cooling loads representing a significant portion of this energy use [1]. Improving building insulation is one of the most effective strategies for reducing these loads and achieving energy savings. While conventional insulation materials like fiberglass and polyurethane foam are widely used, they have limitations in terms of environmental safety, installation complexity, and thermal performance. 3D printing technologies, also

known as additive manufacturing, offer a promising solution to these challenges by enabling the creation of complex, optimized geometries not feasible with traditional manufacturing methods [2]. Recent advances in additive manufacturing have expanded the development of 3D-printed thermal insulating materials and porous polymer composites, enriching the design space for thermal management. Emerging 3D printing technologies enable the fabrication of complex, customizable insulation structures with improved performance and sustainability [3]. Notably, hybrid fluid-filled lattice architectures have been explored for multifunctional capabilities, offering enhanced flexibility, thermal conductivity, and mechanical cushioning, thus broadening application potential beyond traditional insulators [4]. Furthermore, the anisotropic thermal behavior inherent to 3D-printed composites, arising from filament orientation and microstructural alignment, significantly affects heat transfer and must be carefully considered in both design and simulation [5]. Together, this body of work situates the present study within an evolving landscape where material innovation, structural complexity, and anisotropic effects converge to optimize thermal insulation performance through additive manufacturing. Polypropylene (PP) is a promising material for 3D-printed insulation due to its low thermal conductivity, recyclability, low density, high strength-to-weight ratio, and excellent chemical resistance [6,7]. Designing a hollow structure into the solid polypropylene improves its insulation properties and allows it to compete with conventional building insulators, like fiberglass, cellulose, or polyurethane. Materials with strategically designed hollow structures have emerged as a promising solution for thermal insulation applications due to their unique ability to disrupt heat transfer pathways [8–15]. Gaseous voids within these hollow-structured materials (HSMs) significantly reduce their effective thermal conductivity by introducing a high density of low-conductivity regions that impede the continuity of heat conduction networks. Polypropylene was developed into a hollow-structured material to improve its thermal insulation by reducing the PP's effective thermal conductivity. Osaze and Khanna [16] conducted an experimental investigation of a 3D-printed HSM model made of PP, utilizing a hot box test, which measures the heat flux through the porous PP, to determine its effective thermal conductivity. Their results demonstrated that the HSM PP model achieved a remarkably low thermal conductivity of 0.0033 W/mK, highlighting the potential of this approach for creating highly insulating building materials.

To further validate the experimental findings of Osaze and Khanna [16] and provide a deeper understanding of the heat transfer mechanisms within the HSM PP model, the study presents a numerical investigation of 3D-printed multi-hollow structured polypropylene (PP) as a thermal insulation material. This work distinguishes itself by focusing on the design and simulation of multi-hollow geometries in PP, advancing beyond prior research that primarily explored conventional lattice structures, such as gyroids or spacer materials printed with different polymers [17,18]. By employing advanced computational techniques, such as finite element analysis (FEA), the thermal behavior of the HSM PP model will be simulated and analyzed in detail. The numerical results will be compared with the experimental data to assess the congruency between simulation and practice, thereby validating the experimental research conducted by Osaze and Khanna [16].

Numerical simulation and numerical analysis are fundamental tools in various fields of science and engineering, enabling the study and prediction of complex physical, chemical, and biological phenomena. These techniques involve the use of mathematical models and computational algorithms to approximate the behavior of real-world systems and processes. It encompasses a wide range of techniques, including root-find methods, interpolation, numerical integration, numerical differentiation, and finite element methods, among others [19]. Numerical analysis is essential for solving problems that cannot be solved analytically, or for which analytical solutions are impractical or too complex to derive. The accuracy and reliability of numerical simulation and analysis depend on the

quality of the mathematical models, the discretization techniques, the numerical algorithms, and the computational resources available. Careful validation and verification of the numerical results against experimental data or analytical solutions are essential to ensure the credibility of the simulation outcomes [20]. The computing software package used for our analysis is COMSOL Multiphysics 6.2.

COMSOL Multiphysics is a robust Finite Element Method (FEM) Partial Differential Equation (PDE) solution engine for deriving numerical solutions for complex problems [21]. Researchers and engineers have extensively used COMSOL Multiphysics to analyze heat transfer in solid blocks with various boundary conditions and material properties. Suarez et al. [22] used COMSOL to study the heat transfer of an isotropic solid excited by a periodic laser beam on the front of the material. They validated their COMSOL model with experimental results from an Infrared Photothermal Radiometry method and found a matching agreement. Similarly, Maharajan et al. [23] employed COMSOL to predict the temperature distribution of a 3D solid with a discontinuous profile at high temperature in combination with Python software. COMSOL Multiphysics can also be deployed to solve complex problems in structural and fluid mechanics. The key advantage of using COMSOL Multiphysics for heat transfer analysis in a block is its ability to seamlessly integrate the finite element formulation with the underlying physics and boundary conditions. This allows researchers and engineers to quickly set up and solve complex heat transfer problems, including those involving multiple materials, heat sources, and boundary conditions. Additionally, COMSOL's user-friendly interface and powerful visualization tools make it easier to interpret the simulation results and optimize the design of the thermal system [24]

2. Method

2.1. Surface Temperature Distribution on the Room Side of the HSM Polypropylene Block

Roy [25] asserted that one successful approach to achieve a low thermal conductivity in ceramics is to introduce a large amount of porosity. Thermal simulation can be used to track the thermal behavior and insulation performance of hollow structured polypropylene blocks. A 3D model of the polypropylene block was done in COMSOL Multiphysics 6.2 software with a multi-hollow structure of diameter 4 mm and volume of $0.1 \text{ m} \times 0.1 \text{ m} \times 0.1 \text{ m}$, shown in Figure 1. For our analysis and to save simulation and time costs, a 2D model was employed to capture the heat flow gradient. As 3D printing usually distorts the material property of polypropylene into three orthotropic directions due to the effect of anisotropy, care must be taken to tensorize the bulk thermal conductivity to capture the anisotropic behavior of the 3D printed HSM polypropylene block.

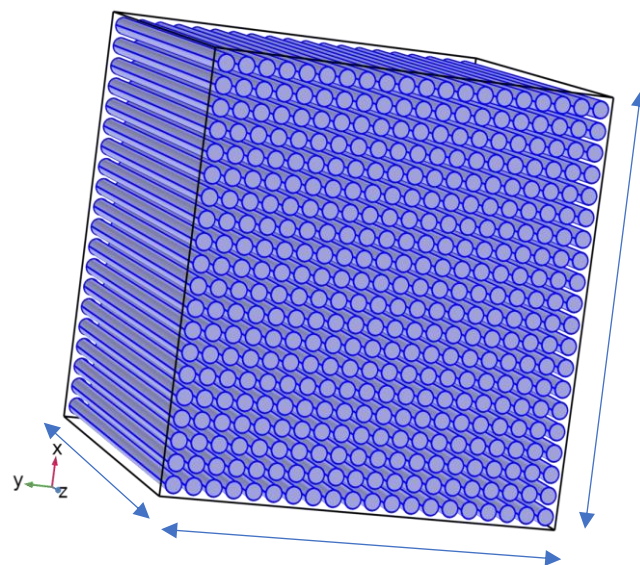


Figure 1. 3D cross-section model of polypropylene block (4 mm hole) and volume $0.1 \text{ m} \times 0.1 \text{ m} \times 0.1 \text{ m}$.

2.2. Anisotropic Behavior of 3D-Printed Polypropylene

Anisotropy refers to a material's tendency to display differences in its mechanical, electrical, thermal, optical properties, etc., along different axes' direction being observed [26]. The behavior is most commonly observed in crystalline materials where atoms, ions, or molecules of the materials are arranged in an orderly fashion. Polypropylene, being a semi-crystalline solid, shows anisotropic characteristics when it is extruded or undergoes 3D printing, which can cause some distortion in the molecular arrangement of the material. This distortion can affect thermal conductivity and modulus of elasticity problems in heat transfer and structural mechanics problems, respectively, if care is not taken to pay attention to the axes characterizing values. In general, 3D-printed plastics exhibit anisotropic thermal conductivity due to the layered nature of the printing process, which results in different thermal properties in different directions. For a 3D-printed PP, the thermal conductivity tensor can be represented as a 3×3 diagonal matrix:

$$\begin{bmatrix} xx & xy & xz \\ yz & yy & yz \\ zx & zy & zz \end{bmatrix}$$

The xx , yy , and zz are the thermal conductivities along the principal axes (x , y , and z). The off-diagonal terms are usually zeros for orthotropic material, which is conferred on PP when 3D printed. The specific values of the thermal conductivity tensor components depend on the printing material and the printing process parameters, i.e., layer height, infill density, printing speed, etc., and the post-processing technique employed, i.e., annealing. Anisotropy is typical for FDM-printed parts due to the deposited layer-structure resulting from the printing process that introduces directional dependence in thermal properties. For our 3D-printed polypropylene (PP) using Fused Deposition Modeling (FDM), the specific values of the thermal conductivity tensor components are:

$$\begin{bmatrix} 0.29 & 0 & 0 \\ 0 & 0.29 & 0 \\ 0 & 0 & 0.14 \end{bmatrix} \text{ W/mK}$$

The thermal conductivity in the x and y directions (in-plane) is approximately twice the thermal conductivity in the z direction (through-plane) from the data-specific values obtained from the material supplier, Sculpteo. The in-plane direction represents thermal conductivity values along the printed layers, while the through-plane direction represents

thermal conductivity across printed layers. The lower thermal conductivity value in the through-plane direction arises from weaker interlayer bonding and the presence of inter-layer voids, which act as barriers to heat transfer. For a 2D model, the through-plane thermal conductivity effect must be captured to show the true behavior of the PP under simulation. This is achieved by averaging in-plane and through-plane conductivities. The effective 2D thermal conductivity matrix, $k_{\text{eff},2D}$, becomes:

$$k_{\text{eff},2D} = \begin{bmatrix} k_{\text{eff},xx} & 0 \\ 0 & k_{\text{eff},yy} \end{bmatrix} = \begin{bmatrix} \frac{k_{xx} + k_{zz}}{2} & 0 \\ 0 & \frac{k_{yy} + k_{zz}}{2} \end{bmatrix} \text{ W/mK}$$

where $k_{\text{eff},xx}$ and $k_{\text{eff},yy}$ are effective thermal conductivities in the x and y -direction, respectively, which are equal. k_{xx} , k_{yy} and k_{zz} are thermal conductivities in the x , y , and z -directions, respectively.

This approach enables the simulation to predict spatial temperature distributions and heat flux pathways realistically. Studies have shown that anisotropic conductivity in printed polymers can vary by factors of 2 to 6, depending on direction, and neglecting this can lead to under- or overestimation of thermal resistance and peak temperatures [27].

2.3. Polypropylene Block Porosity

Porosity is a measure of void spaces in a material. It is defined as the ratio of the volume of the void spaces (pores) to the total volume of the material [28]. Porosity is a dimensionless quantity and is usually expressed as a fraction or a percentage.

Mathematically, porosity (ε_p) [29] is defined in Equation (1):

$$\varepsilon_p = \frac{\theta_f}{\theta_t} \quad (1)$$

where

θ_f is the volume of the void spaces (m^3)

θ_t is the total volume of the material (m^3).

Porosity can range from 0 to 1 (or 0% to 100%). A porosity of 0 means the material is completely solid with no void spaces, while a porosity of 1 indicates that the material is entirely composed of void spaces [30].

The porosity of a material can significantly affect its effective thermal conductivity properties. The presence of pores filled with air, or another fluid, reduces the effective thermal conductivity of the material [31]. The effective thermal conductivity depends on the porosity, the thermal conductivities of the solid matrix and the fluid in the pores, and the pore structure [32].

When modeling heat transfer in porous materials, it is essential to consider the effects of porosity on the relevant heat transfer mechanisms and to use appropriate effective properties, such as effective thermal conductivity, which account for the presence of pores.

In COMSOL Multiphysics, you can define the porosity of a material in the “Heat Transfer in Porous Media” interface by specifying the porosity value in the “Fluid and Matrix Properties” section. The software will then take into account the effects of porosity on heat transfer when solving the model [24].

For our model, the porosity ε_p with a hole size of radius r , and the total model volume of length l , breadth b and height h is given by:

$$\varepsilon_p = \frac{400 * \pi r^2 h}{lbh}$$

$$\varepsilon_p = 0.502$$

2.4. Simulation Set Up

The 3D model of the PP block for the numerical simulation measures 0.1 m by 0.1 m by 0.1 m, shown in Figure 1. We present the simulation setup in Figure 2. The 3D cross-section forms a wall that separates two air envelopes. The left side of the block is the room-side air envelope. The right-side air envelope is the outside air. Awbi [33] determined the heat transfer coefficients of room surfaces for natural convection to be between 3 and 4 W/m²K. The room air temperature is supplied at 20 °C with a natural convective heat coefficient of 3 W/m²K. The outside air temperature varies from a very cold weather temperature of −20 °C to a very hot weather temperature of 40 °C. The natural convective heat transfer coefficient for the outside air stream is 5 W/m²K, which is documented in ASHRAE [34], Incropera et al. [35] and Churchill and Chu [36]. The material properties of polypropylene and air that were used to carry out the simulation are tabulated in Table 1.

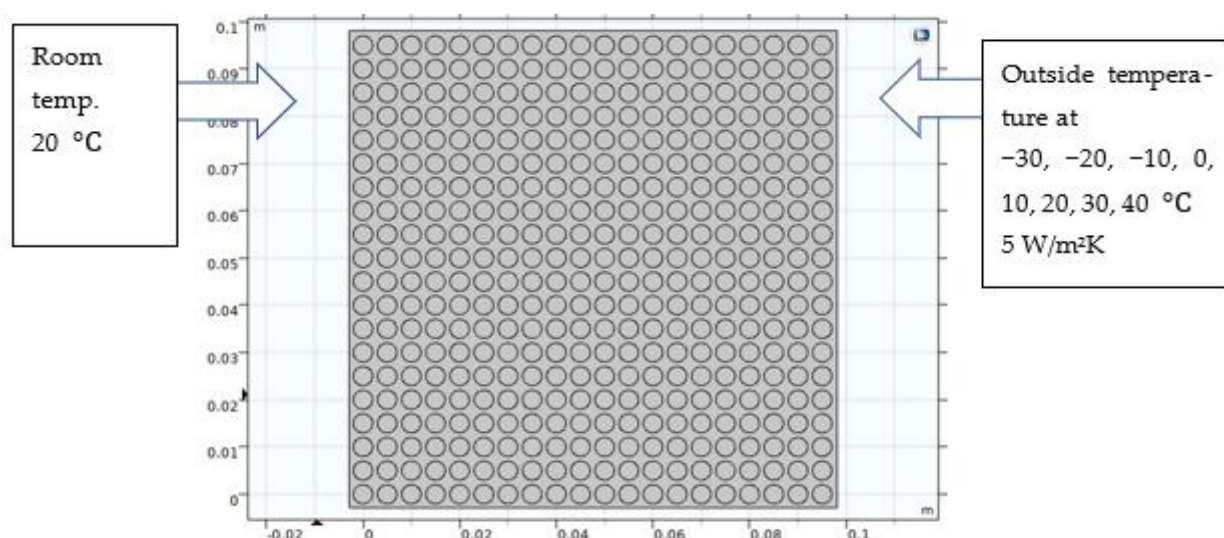


Figure 2. Simulation setup.

Table 1. Material properties for polypropylene and air.

Material Properties	Polypropylene	Air
Thermal conductivity K	$\begin{bmatrix} 0.29 & 0 & 0 \\ 0 & 0.29 & 0 \\ 0 & 0 & 0.14 \end{bmatrix}$ W/mK	0.025 W/mk
Specific heat C_p	1.9 KJ/KgK	1 KJ/KgK
Density ρ	900 kg/m ³	1.204 kg/m ³

2.5. Boundary Conditions for the Heat Transfer Interfaces

COMSOL Multiphysics supports various boundary condition principles that can be applied to different physics interfaces and models. The choice of boundary conditions depends on the specific problem, the governing equations, and the modeled physical phenomena. The heat equation accepts two basic types of boundary conditions—Dirichlet and Neumann boundary conditions. A Dirichlet boundary condition, named after the German mathematician Johann Peter Gustav Lejeune Dirichlet [37] specifies the value of a temperature on a domain's boundary. In the context of partial differential equations (PDEs), Dirichlet boundary conditions are used to specify the values of the solution on the boundaries of the computational domain. It provides a direct constraint on the solution and is often used to model physical situations where the value of a quantity is known or controlled at the boundary [38]. A Neumann boundary condition, named after the German mathematician Carl Gottfried Neumann [37], specifies the normal derivative (flux) of a

dependent variable, such as temperature in this instance, on a domain's boundary. In the context of partial differential equations (PDEs), Neumann boundary conditions specify the flux or rate of change in the solution across the boundaries of the computational domain. It provides a constraint on the gradient of the solution and is often used to model physical situations where the flux of a quantity is known or controlled at the boundary [38]. In our work, the Dirichlet boundary condition given by Equation (2) specifies the temperature at the solid-fluid interface:

$$T = T_0 \quad (2)$$

where T_0 is the inside or outside air temperature.

The Neumann boundary condition specifies the known value of the natural convective heat transfer impinging on the polypropylene wall. Convective heat transfer takes place when an object is hotter or colder than the neighboring fluid. Convective heat flux on the polypropylene wall, that is, the solid-fluid interface, is given by Equations (3) and (4):

$$q = q_o \quad (3)$$

$$q_o = h \cdot (T_{\text{ext}} - T) \quad (4)$$

where h denotes the convective heat transfer coefficient, which depends on the ambient air movement or whether an external force aiding the convective fluid flow is present, and where T_{ext} is the external temperature. For natural convection, a value of $3 - 10 \text{ W/m}^2\text{K}$ is adequate to represent the free air condition. The external temperature T_{ext} is reliant on the ambient flow conditions. In this work, two external temperatures exist—the inside surface temperature T_{ext} is at 20°C room temperature while the outside surface temperature, T_{ext} of the polypropylene block is at -20°C cold air temperature.

A convective heat flux boundary condition is also set up at the inside hole fluid interface to depict natural convection. From the thermal continuity condition [39], a no-temperature-jump condition exists between the solid-fluid interfaces, which makes the temperatures of the solid-fluid interface equal according to the principle of energy conservation. i.e.,

$$T_s = T_f$$

where T_s and T_f are the temperatures of the solid and fluid, respectively, at the various interfaces.

Lastly, a symmetry boundary condition is applied to two boundaries of the HSM PP block to simplify the modeling and computational effort required for the geometric and loading symmetry. By applying symmetry boundary conditions on a small portion of our PP block, it becomes representative of the behavior of the entire wall from which the PP block was taken. Figure 3 highlights the application of symmetry boundary conditions on the model. The symmetry boundary condition acts like a homogeneous Neumann boundary condition, a unique case of the Neumann boundary condition where the normal derivative (flux) of the dependent variable is set to zero on a boundary of a domain [40]. The interface heat flux here, in Equation (5), is equivalent to zero.

$$-n \cdot q = 0 \quad (5)$$

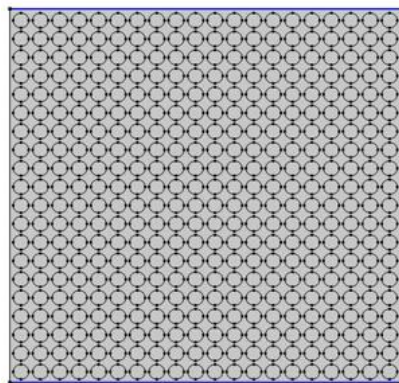


Figure 3. Adding a symmetry boundary condition to the HSM Polypropylene.

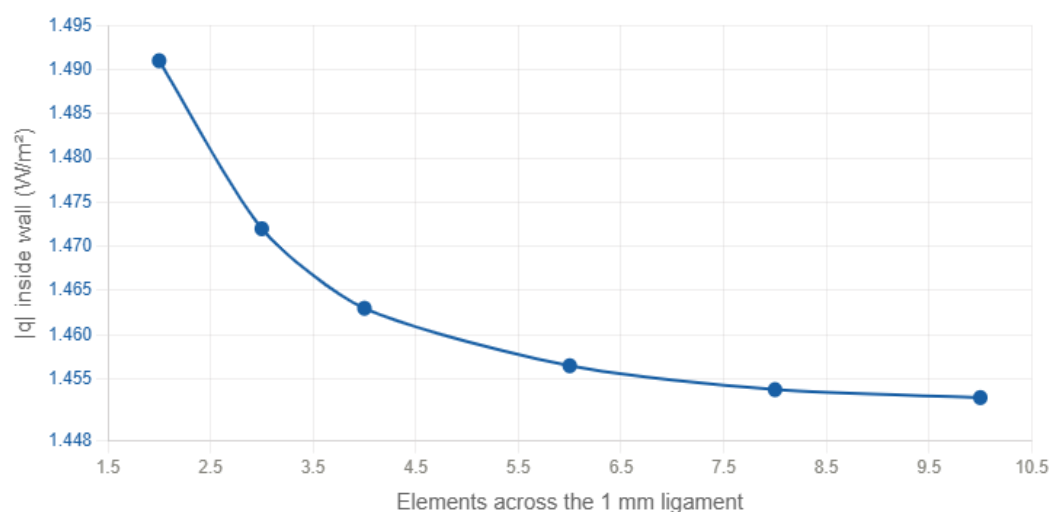
The boundary conditions employed in this numerical investigation were carefully selected to realistically replicate the thermal environment of the 3D-printed polypropylene multi-hollow structures. Dirichlet boundary conditions (prescribed temperatures) were applied to surfaces with controlled thermal inputs or sinks, providing fixed temperature references consistent with experimental setups. Neumann boundary conditions (prescribed heat flux or insulation) were imposed on insulated or convective surfaces to accurately model heat loss or barrier effects. This combination ensures the capture of both conduction-dominated and convective heat transfer phenomena within the structure. The adopted boundary conditions are consistent with prior validated numerical investigations and provide a rigorous framework to simulate the heat transfer modeling of additive manufacturing and porous media. For example, studies on porous intumescent coatings utilize combined conduction and radiation models with carefully defined thermal boundaries approximating experimental calorimeter conditions [41]. Similarly, investigations into spacer materials in cold environments and hierarchical porous ceramics employ Dirichlet and Neumann conditions to mirror realistic heating and insulation scenarios [18,42].

2.6. Meshing

Mesh generation is another critical step in the simulation process, as it discretizes the computational domain into smaller elements [43]. COMSOL Multiphysics offers various meshing techniques, such as free tetrahedral, swept, and boundary layer meshes, which can be adapted to the insulator's geometry [44]. A fine mesh is typically required near the cavity walls and in regions with high-temperature gradients to capture the heat transfer accurately [45]. Solving the simulation model employs the physics-controlled adaptive tetrahedral element type for the meshing process, which has the ability to adapt to the external and internal surfaces of the model for accurate thermal solving. The goal of mesh generation is to increase the speed and accuracy of numerical calculations. However, there is a trade-off between speed and accuracy in the finite element method, as one may limit the other. There exists a balance point where a sufficient number of meshing nodes on the model is adequate to effect quality numerical solutions. The default meshing sequence available in the COMSOL Multiphysics software was utilized to efficiently justify the meshing requirement, reducing the computer memory space and providing accurate results. The material, HSM polypropylene, takes the coarser adaptive triangular element meshing. Table 2 describes the mesh statistics. The average element quality is 79.4%. A mesh analysis of the hollow section of the model converges to the total heat transfer rate through the block after six iterations of the mesh element across the solid 1 mm ligament of the solid polypropylene dimension. The percent change curve drops to less than 0.5% by 6 elements. Figure 4 shows the mesh convergence plot.

Table 2. Mesh statistics.

Description	Value
Status	Complete mesh
Mesh vertices	20,610
Triangles	31,324
Edge elements	9894
Vertex elements	3204
Number of elements	31,324
Minimum element quality	0.3154
Average element quality	0.7945
Element area ratio	0.092891
Mesh area	10,200 mm ²

**Figure 4.** Mesh convergence plot.

3. Theory of Heat Transfer

We start with the conservation of energy principle, which states that the rate of change in energy in a system is equal to the sum of the rate of heat added and the rate of work done on the system. In this case, we consider a small fluid element in a two-dimensional flow field.

The energy balance equation for the fluid element can be written as Equation (6)

$$\rho c_p \left(\frac{\partial T}{\partial t} \right) = - \left(\frac{\partial q_x}{\partial x} \right) - \left(\frac{\partial q_y}{\partial y} \right) + \dot{q} \quad (6)$$

where

ρ is the fluid density

c_p is the specific heat capacity of the fluid

T is the temperature

t is time

q_x and q_y are the heat fluxes in the x and y directions, respectively

$\dot{q}$ is the heat generation rate per unit volume

The heat fluxes can be expressed using Fourier's law of heat conduction, given by Equations (7) and (8):

$$q_x = -k \left(\frac{\partial T}{\partial x} \right) \quad (7)$$

$$q_y = -k \left(\frac{\partial T}{\partial y} \right) \quad (8)$$

where k is the thermal conductivity of the fluid.

Substituting the heat flux expressions into the energy balance equation, we get Equation (9):

$$\rho c_p \left(\frac{\partial T}{\partial t} \right) = \left(\frac{\partial}{\partial x} \right) \left[k \left(\frac{\partial T}{\partial x} \right) \right] + \left(\frac{\partial}{\partial y} \right) \left[k \left(\frac{\partial T}{\partial y} \right) \right] + \dot{q} \quad (9)$$

To account for convection, we introduce the fluid velocity components u and v in the x and y directions, respectively. The convective terms can be added to the energy balance equation using the material derivative given by Equation (10):

$$\rho c_p \left[\frac{\partial T}{\partial t} + u \left(\frac{\partial T}{\partial x} \right) + v \left(\frac{\partial T}{\partial y} \right) \right] = \left(\frac{\partial}{\partial x} \right) \left[k \left(\frac{\partial T}{\partial x} \right) \right] + \left(\frac{\partial}{\partial y} \right) \left[k \left(\frac{\partial T}{\partial y} \right) \right] + \dot{q} \quad (10)$$

Assuming constant thermal conductivity and rearranging the terms, we obtain the final form of the thermal Equation (11) for two-dimensional flow with convection and conduction:

$$\rho c_p \left[\frac{\partial T}{\partial t} + u \left(\frac{\partial T}{\partial x} \right) + v \left(\frac{\partial T}{\partial y} \right) \right] = k \left[\left(\frac{\partial^2 T}{\partial x^2} \right) + \left(\frac{\partial^2 T}{\partial y^2} \right) \right] + \dot{q} \quad (11)$$

This equation, along with appropriate initial and boundary conditions, can be solved numerically using various methods, such as the finite difference method or the finite element method, to obtain the temperature distribution in the two-dimensional flow field.

Considering the effect of porosity, the governing heat transfer equation becomes Equation (12):

$$\begin{aligned} (1 - \varepsilon_p) \rho_s c_{ps} \left(\frac{\partial T}{\partial t} \right) + \varepsilon_p \rho_f c_{pf} \left[\frac{\partial T}{\partial t} + u \left(\frac{\partial T}{\partial x} \right) + v \left(\frac{\partial T}{\partial y} \right) \right] \\ = \left(\frac{\partial}{\partial x} \right) \left[k_e \left(\frac{\partial T}{\partial x} \right) \right] + \left(\frac{\partial}{\partial y} \right) \left[k_e \left(\frac{\partial T}{\partial y} \right) \right] + (1 - \varepsilon_p) \dot{q}_s + \varepsilon_p \dot{q}_f \end{aligned} \quad (12)$$

where

ε_p is the porosity of the medium (dimensionless)

ρ_s and ρ_f are the densities of the solid and fluid phases, respectively (kg/m^3)

c_{ps} and c_{pf} are the specific heat capacities of the solid and fluid phases, respectively ($\text{J}/(\text{kg}\cdot\text{K})$)

T is the temperature (K)

t is time (s)

u and v are the fluid velocity components in the x and y directions, respectively (m/s)

k_e is the effective thermal conductivity of the porous medium ($\text{W}/(\text{m}\cdot\text{K})$)

$\dot{q}_s$ and $\dot{q}_f$ are the heat generation rates per unit volume in the solid and fluid phases, respectively (W/m^3).

In this equation, the terms are modified to account for the presence of both solid and fluid phases in the porous medium:

The energy storage term is split into two parts: one for the solid phase $(1 - \varepsilon_p) \rho_s c_{ps} \left(\frac{\partial T}{\partial t} \right)$ and one for the fluid phase $\varepsilon_p \rho_f c_{pf} \left(\frac{\partial T}{\partial t} \right)$

The convective term $\varepsilon_p \rho_f c_{pf} \left[u \left(\frac{\partial T}{\partial x} \right) + v \left(\frac{\partial T}{\partial y} \right) \right]$ only applies to the fluid phase, as the solid phase is stationary.

The conductive heat transfer term uses the effective thermal conductivity k_e instead of the fluid thermal conductivity k . The effective thermal conductivity depends on the thermal conductivities of the solid and fluid phases, as well as the porosity and pore structure of the medium.

The heat generation term is split into two parts: one for the solid phase $(1 - \varepsilon_p) \dot{q}_s$ and one for the fluid phase $\varepsilon_p \dot{q}_f$.

The principle is applied in the COMSOL Multiphysics 6.2 heat transfer through porous media physics, which is reproduced below in Equation (13):

$$(\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t} + \rho_f C_{p,f} u \cdot \nabla T + \nabla \cdot q = Q + Q_p + Q_{\text{vd}} + Q_{\text{geo}} \quad (13)$$

$$q = -k_{\text{eff}} \nabla T$$

$$(\rho C_p)_{\text{eff}} = \varepsilon_p \rho_f C_{p,f} + \theta_s \rho_s C_{p,s} + \theta_{\text{imf}} \rho_{\text{imf}} C_{p,\text{imf}}$$

$$k_{\text{eff}} = \varepsilon_p k_f + \theta_s k_s + \theta_{\text{imf}} k_{\text{imf}} + k_{\text{disp}}$$

eff, vd, geo, imf, dis subscripts are standard notation for effective, viscous dissipation, geothermal, immobile fluid and dispersion terms respectively. To solve this equation using COMSOL, we specified the appropriate initial and boundary conditions and the porosity of the PP.

4. Results and Discussion

A steady-state heat transfer module was employed in the simulation, as the temperature distribution within the system does not change over time. It is typical to apply steady-state analysis in building envelopes, including walls, roofs, and windows. COMSOL Multiphysics software was able to solve the physics equation under computational time of 13 s (see Figure 5). The temperature profile that is highlighted in Figure 6 for a 4 mm HSM PP board with an inside wall surface at room temperature (20 °C) and an outside wall cold surface at −20 °C. The shape of the temperature profile is a non-linear temperature profile curve, showing that HSM PP is an insulator [46,47]. In contrast, conductors have a linear temperature profile curve with a more uniform temperature gradient throughout the material [29]. The room side of the HSM PP remains at room temperature and is able to provide thermal comfort for dwellers. Figure 7 and Figure 8 show the same surface temperature and temperature profile, respectively, as before, except for the outside temperature being a hotter 40 °C. The shape of the temperature profile remains non-symmetrical, demonstrating that SHM PP is a good insulator in hot temperature environments. Figure 9 shows the temperature profile of various outside surface temperature conditions and the room surface temperature after simulations. The funnel shape profiles show that there is a significant resistance to heat flow from outside temperature conditions to indoor temperature conditions. The profile allows the room to be kept at room temperature.

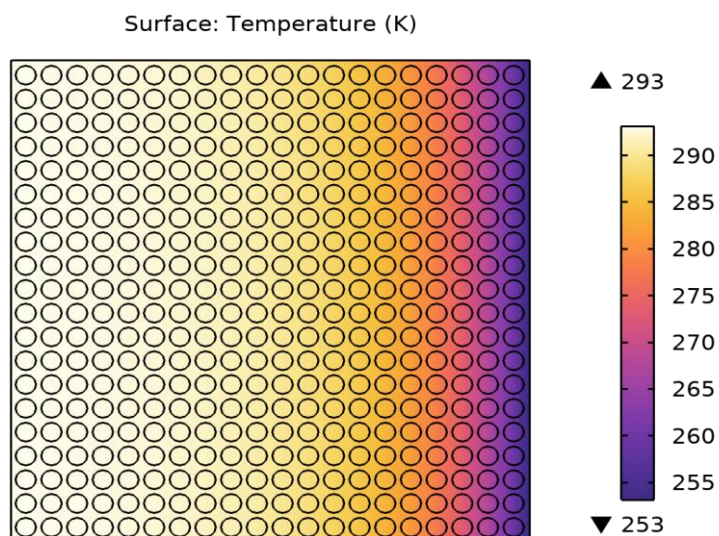


Figure 5. Surface temperature profile—outside temperature at $-20\text{ }^{\circ}\text{C}$.

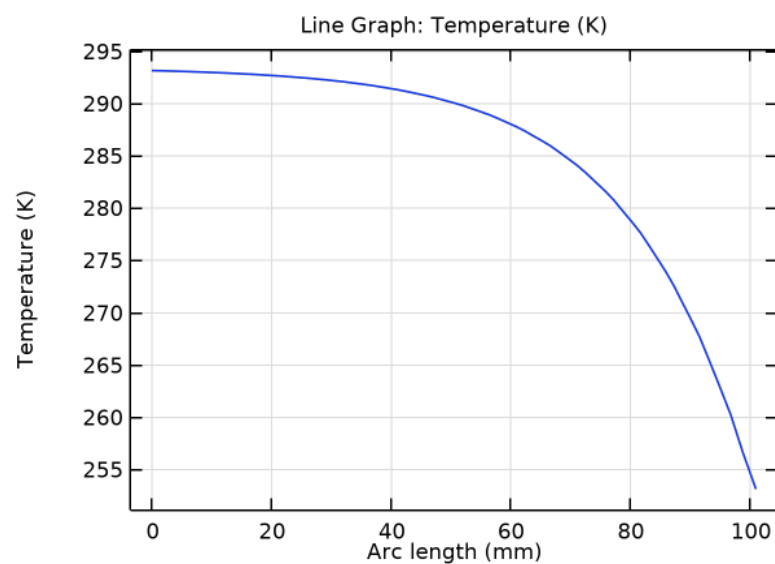


Figure 6. Temperature profile—outside temperature at $-20\text{ }^{\circ}\text{C}$.

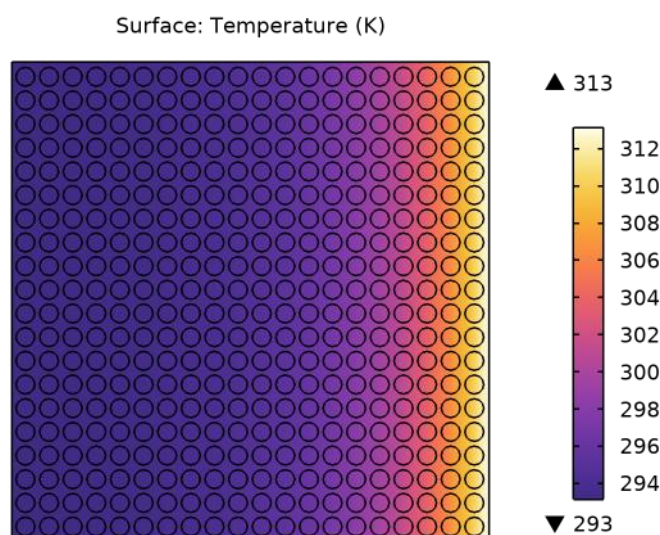
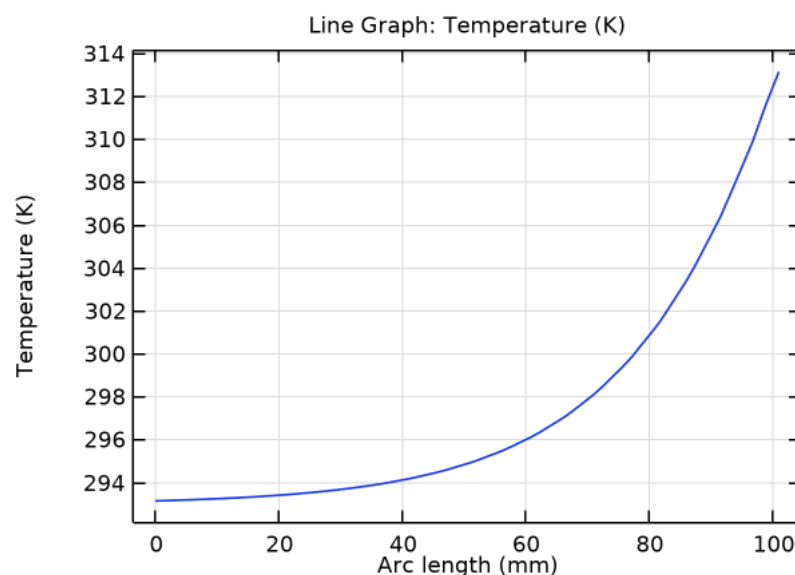
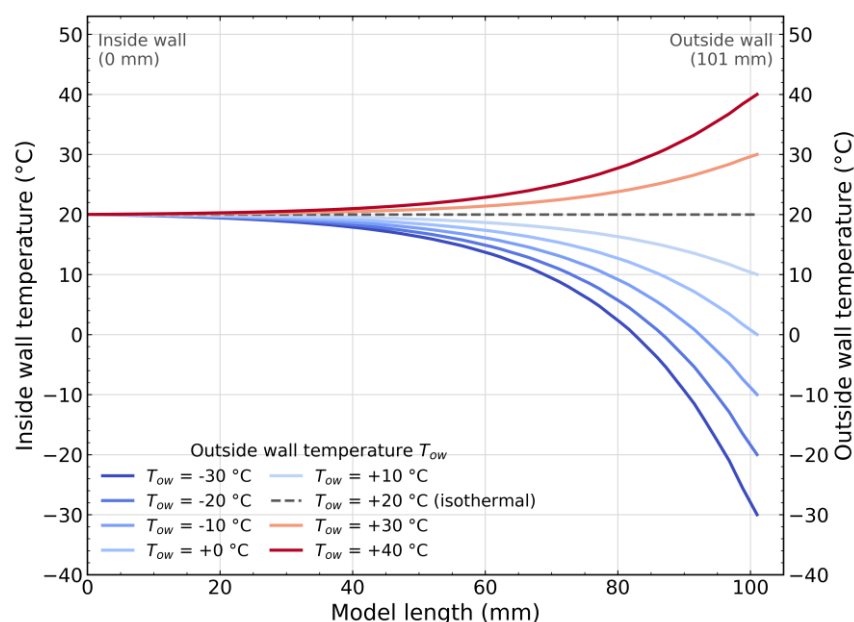


Figure 7. Surface temperature profile—outside temperature at 40 °C.**Figure 8.** Temperature profile—outside temperature at 40 °C.**Figure 9.** Inside and outside wall temperature distribution after simulation under various outside wall temperatures.

Effective Thermal Conductivity Determination of Porous PP Using COMSOL Simulation

Model validation is needed for assessing the accuracy and reliability of the simulation results [20]. Numerical analysis can be validated using experimental and analytical methods. We employ the heat flux and temperature gradient method to determine the effective thermal conductivity of the hollow structure PP and compare it with the experimental effective thermal conductivity of the same material using the hot box. The method follows:

- Compute the average heat flux q through a specific cross-section or boundary of the model.

- Evaluate the average temperature T_{av} across the same boundary and another parallel boundary at a distance L from the first boundary.
- Evaluate the temperature gradient ∇T which is given by:

$$\nabla T = (T_{av2} - T_{av1})/L$$

- Use Fourier's law, Equation (14), to calculate the effective thermal conductivity k_e

$$k_e = q/\nabla T \quad (14)$$

The inside wall surface normal total heat flux was evaluated from COMSOL Multiphysics to be -1.4529 W/m^2 when the inside wall temperature was 20°C and the outside wall temperature was -20°C . The negative sign shows heat is flowing in the opposite direction. The input on the COMSOL setting expression to get the normal heat flux is "ht.ntflux".

$$q = -1.4529 \text{ W/m}^2$$

$$\nabla T = (293.13 - 253.13)\text{K}/0.1$$

$$k_e = \frac{-1.4529}{400} \text{ K}$$

Therefore,

$$k_e = 0.0036 \text{ W/mK}$$

Table 3 presents a table of heat fluxes through porous PP at different outside wall temperatures compared to the inside wall temperature of 20°C . The average of the effective thermal conductivity in the different simulation setups is taken to arrive at an approximate effective thermal conductivity of porous PP of 0.00363 W/mK .

Table 3. Average effective thermal conductivity of different simulation temperatures

Inside Wall Temperature ($^\circ\text{C}$)	Outside Wall Temperature ($^\circ\text{C}$)	Heat Flux (W/m^2)	Temperature Gradient (K/m)	Effective Thermal Conductivity (W/mK)	Average Effective Thermal Conductivity (W/mK)
20	-30	-1.8161	500	0.00363	0.00363
20	-20	-1.4529	400	0.00363	
20	-10	-1.0895	300	0.00363	
20	0	-0.7264	200	0.00363	
20	10	-0.3629	100	0.00363	
20	30	0.3632	100	0.00363	
20	40	0.7265	200	0.00363	
20	50	1.0896	300	0.00363	

The numerically determined effective thermal conductivity of Porous PP closely matches the experimentally determined effective thermal conductivity of porous PP from Osaze and Khanna [16], which was $k_e = 0.0033 \text{ W/mK}$, thus validating the experimental method of the thermal conductivity values obtained from the hot box test. The slight difference between experimental and numerical results can be due to a number of factors, including simplification and assumption of the model, uncertainty in material properties, inaccurate or insufficient boundary conditions, measurement uncertainties, and sensor errors, etc.

The HSM polypropylene board experiences a high-temperature gradient over a short distance, which is typical of insulators. Bergman et al. [46] inferred that this rapid temper-

ature change over a short distance, in the range ± 50 K/m or higher, characterizes insulators. The presence of enclosed air pores with low velocity in the HSM PP confers a conjugate 2-dimensional heat transfer mechanism by convection through air pores and conduction through the PP solid. The total heat transfer is the sum of the heat transfer by convection and conduction in HSM PP. The low thermal conductivity property of the material offers resistance to heat flow, which keeps the room temperature unchanged.

A numerical analysis of the experimental hot box test conducted by Osaze and Khanna [16] to evaluate the thermal conductivity of a 3D-printed HSM polypropylene has been simulated in the COMSOL Multiphysics software to validate the experimental result. Model validation is crucial for assessing the accuracy and reliability of simulation results. Numerical analysis can be validated using experimental and analytical methods. In this study, we employ the heat flux and temperature gradient method to determine the effective thermal conductivity of the hollow structure polypropylene (PP) and compare it with the experimental effective thermal conductivity of the same material obtained using the hot box method [1]. The numerically determined effective thermal conductivity of porous PP (0.0036 W/mK) closely matches the experimentally determined effective thermal conductivity of porous PP from Osaze and Khanna [16], which was 0.0033 W/mK. This agreement validates the experimental method and the thermal conductivity value obtained from the hot box test. The result confirmed the enhanced insulation properties of multi-hollow structured PP board and its applicability in building insulation. Liang's [13] experiment to determine the effective thermal conductivity of polypropylene/hollow beads composite provided evidence that the effective thermal conductivity decreases with the increase in the volume size of air in the polymer. For convective heat transfer to play a crucial role in the overall heat transfer through the medium, a choice of 4 mm hole was considered, such that a critical Rayleigh number for the fluid medium is surpassed [16,48–51]. The significance here is that with proper hollow polypropylene material design and minimal material usage, there is a higher gain in insulation property compared to a solid polypropylene block.

5. Conclusions

Thermal simulation of a hollow structured polypropylene can be used to determine its suitability for building insulation. The hollow-structured materials, HSM PP model, offer resistance to heat flow in the HSM material, which lowered the thermal conductivity of the PP model to 0.0033 W/Mk. The constant room surface temperature distribution demonstrated that hollow-structured polypropylene material can be applied to building insulation to maintain room thermal comfort. Future research is needed to determine the optimum air volume in the hollow structure of polypropylene that can confer the optimum insulation property. The numerical investigation will focus on several key aspects of the HSM PP model, including the influence of void size, shape and distribution, and connectivity of pores on the effective thermal conductivity. Parametric studies should be performed to identify the optimal hollow structure design that maximizes thermal insulation performance while maintaining the necessary mechanical properties. The insights gained from this numerical analysis will contribute to the development of advanced HSMs with precisely controlled hollow architectures, paving the way for the creation of high-performance, lightweight, and sustainable thermal insulation solutions.

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