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Thermal Transport in Porous Structures: Mechanisms, Modeling Approaches, and Future Directions

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Abstract: Understanding thermal transport phenomena in porous structures is of fundamental importance across diverse sectors, including energy systems, construction, electronics, and biomedical engineering. In contrast to conventional dense solids, porous materials exhibit distinct thermal behaviors due to the intrinsic discontinuity between solid phases, pore geometry, and interfacial interactions. In this review, current advances in the understanding of heat transfer mechanisms—namely conduction, convection, and radiation—within porous media were systematically analyzed, with particular emphasis on the influence of porosity, pore morphology, and material composition on effective thermal conductivity. Both open- and closed-cell architectures were examined, and their respective roles in thermal transport were clarified in relation to practical applications. The predictive capability of numerical models was shown to improve significantly through the incorporation of local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) models, as well as homogenization techniques. State-of-the-art experimental techniques employed for characterizing thermal transport in porous materials at micro- and nanoscales were also discussed, including steady-state and transient plane source (TPS) methods, along with high-resolution imaging techniques such as X-ray Computed Tomography (XCT) and electron microscopy. Emerging computational strategies, particularly the integration of reinforcement learning and machine learning (ML) algorithms into numerical and analytical models, were identified as promising tools for optimizing the thermal performance of porous structures. Furthermore, recent progress in the development of functional nanostructured and composite porous materials has enabled enhanced performance in applications such as thermal insulation, energy storage, and medical device design. Nonetheless, several critical challenges persist, particularly in experimental reproducibility, accurate model development, and the bridging of multi-scale effects. The strategic integration of artificial intelligence (AI) and data-driven design methodologies is anticipated to play a transformative role in advancing the next generation of porous materials for sustainable thermal management solutions. The findings underscore the necessity of porous structures in accelerating low-carbon technologies and achieving energy-efficient thermal transport systems.

Keywords: Porous materials; Heat transfer mechanisms; Effective thermal conductivity; Phase change materials; Nanostructured materials

1 Introduction

Examining thermal transport in porous materials has attracted a lot of interest because it plays a major role in energy, construction, and electronics. The special thermal qualities of porous materials differ from those of typical solid materials because porous materials consist of complex networks of pores. Such properties permit efficient transfer of heat from one place to another, making them suitable for successful thermal management.

As technology grows, more attention is given to the demand for high-performing thermal systems. As an illustration, electric vehicles (EVs) need good cooling methods to control the heat produced by their batteries and other electronic systems. If heat transport in porous materials can be improved, the performance and reliability of these devices can also be improved. In addition, using phase change materials (PCMs) with porous materials creates new possibilities for passive thermal management.

Many projects are focused on investigating how temperature and fluid motion work together inside such porous materials. This covers the study of porosity effects on the total conductivity of heat, along with seeing how material composition can increase or decrease the efficiency of managing temperature. Using advanced approaches to design models enables us to predict a variety of behaviors in porous media that can improve material design for particular purposes. Research on advanced fibers and textiles has shown superior ways to control heat movement both microscopically and nanoscopically. They add new capabilities to fabrics by helping maintain temperatures in smart devices, as well as to materials for better energy efficiency in buildings.

It can be concluded that research on heat transport in porous networks both tackles fundamental engineering issues and helps create a sustainable technology path. Serious improvements in porous materials mean that they can provide a variety of useful services suited to a wide range of needs in many different sectors, as well as meet new demands [1–4].

Although a lot of studies have investigated the thermal transport mechanism in porous materials, there is still a research gap concerning its changes over time within a practical environment. As an example, the effect of ageing or environmental degradation (e.g., high temperature or mechanical forces) on the thermal conductivity and performance of porous materials has not been studied sufficiently. This research gap suggests the necessity of future investigations concerning the long-term stability of porous structures in particular cases when the materials are applied in energy-storing systems, insulators, or thermal management devices. This gives a background to a more in-depth analysis of the underlying processes in heat transfer through a porous medium.

2 Overview of Heat Transfer Mechanisms

2.1 Heat Transfer Mechanisms

Three ways of heat transfer occur in porous structures: conduction, convection, and radiation. Conduction is what lets heat pass between objects, and the amount it does is largely determined by the thermal conductivity of the material. Porosity, the shape of the pores, and the composition of the material influence conductivity; in general, more air-filled spaces in the material lower thermal conductivity. Heat transfer by convection comes as fluids pass by the pores within the material. The relationship between heat transfer and fluid flow depends on the fluid's speed, temperature, and characteristics. Strong convection is achieved when the flow takes place in saturated porous media. When temperatures are high or the surface of a material is large, radiative heat transfer is more important, as seen in nanostructured porous materials. Radiation is the process of releasing energy in the form of electromagnetic waves, whose intensity and spectral characteristics vary depending on the material properties and surface geometry.

There are mainly three mechanisms of heat transfer in porous materials that include conduction, convection, and radiation. Thermal conductivity of the material influences the conduction process, and it is dependent on the pore structure, porosity, and composition of the material. Highly porous materials tend to have low thermal conductivity because of the elevated amount of air in them. Such mechanisms, especially conduction, form the basis of how porous materials regulate the heat transfer. When PCMs are present in porous structures, the energy stored during transitions is largely affected by the latent heat of the PCM. Since both solid conduction and fluid convection are present, the thermal systems formed are not simple, and precise modeling is necessary to make accurate predictions.

Using different models and calculations, researchers have discovered the impact of pore variations on heat conduction and used this to project temperature levels in a range of situations. Understanding these processes is important for getting the best from energy storage, cooling electronics, and insulation, as better thermal management increases an application's efficiency and performance [2, 5–7].

2.2 Governing Equations and Models

Predicting heat transfer in porous materials relies on key equations and models. According to Fourier's law, the rate of heat travel within solids and porous media refers to the temperature changes along the path. Because of these conservation principles, these models generate partial differential equations for both changes in transient and steady-state situations. Most studies in porous media have used either LTE or LTNE models. In the LTE model, it is assumed that there is a constant temperature link between the walls and the fluid at any point, which simplifies calculation but may disregard finer aspects in porous formations. Unlike LTE, LTNE is designed to address temperature changes, key for materials that heat or cool fast and for substances with a considerable thermal lag.

LTE presumes that the solid and fluid phases of a porous medium have even temperatures at every point. It is assumed that the solid matrix and the fluid phase can be placed in thermal equilibrium at the microscopic scale, i.e., they have the same temperature in any place. The model is generally used when the time scale of the thermal energy transfer between the solid and fluid phases is short compared with the thermal transport time in the medium. LTE can best be applied when the material possesses a low porosity level, high conductivity, and/or small pore size because it is presumed that the transfer of heat between the solid and fluid phases is very quick.

Like LTE, LTNE supposes that temperatures of the fluid and the solid phases can vary at every location within the porous medium. In this model, the heat transfer between the fluid and the solid matrix is not very clear, and as such, the thermal lag of the solid matrix on the fluid is considered. The LTNE model is applied in situations where heat transfer exists on a time scale, e.g., in porous media that have large pores or those with low thermal conductivity or a large porosity. LTNE has found applications in processes subject to large temperature variation between fluid and solid phases, being especially useful in PCMs, high-porosity materials, or other materials where thermal gradients are high.

LTE and LTNE models are applied widely, including the study of porous media, battery cooling systems, and energy storage systems. The LTE model has found broad applications in the research on porous media, wherein the solid framework governs the conduct of heat transfer. The LTNE system fits better on systems containing PCMs or large pores in the battery cooling systems. LTE is a thermodynamic model that is applied in materials, such as fibrous insulation, in which the solid phase and air can rapidly approach a common temperature. LTNE is applied in case of large thermal resistance between the liquid and solid phases, causing the temperature to vary between the two phases. It is commonly used when there is a difference by large difference between the solid matrix temperature and the fluid in systems such as geothermal energy storage or battery cooling. The process of switching between LTE and LTNE is also important because any change in material parameters, i.e., porosity or heat flux, might demand a switch between them. For example, when the pore size becomes large and the thermal conductivity is reduced, the system may change the state to LTNE. In a strongly porous substance where the pores are large, or the conductivity of the matter is low, the solid and fluid phases no longer efficiently exchange heat, which is considered thermal equilibrium. This causes a scenario whereby the fluid phase may not have the same temperature as the solid phase, necessitating the LTNE model. Actually, the LTE assumption fails in reality when the heat flux is high, the material is in phase change (e.g., in thermal energy storage systems or high-thermal-gradient battery systems), or the solid and fluid phases are interacting in a delayed fashion. Then, when this delayed thermal interaction is important, it is desired to use the LTNE model to consider it.

LTE and LTNE models are utilized in different application studies of porous media, battery cooling operations, and energy storage structures. The former is common in porous media analysis, whose heat transmission is characterized by a solid matrix. The latter is more suitable for systems containing PCMs or large pores. To make them easier to understand, the article gives examples of their real-life usage. The LTE model has been successfully used in the simulation of heat exchangers on metal foams since they have small pore sizes and high thermal conductivity, followed by the effective thermal interaction between the solid and fluid phases. The LTNE model has been used in geothermal energy storage systems to factor in the temperature variations between the solid rock and the circulating fluid, particularly in cases where the conditions of high porosity and low thermal conductivity are met. These instances give credible sources that can justify definitions and areas of application of these terms.

By using homogenization techniques, scientists can learn the useful thermal properties from various types of microstructures. By using Representative Volume Elements (RVEs), scientists can find typical thermophysical details that include the range of shapes seen in real rocks, thereby enhancing the model's ability to represent irregular or angular pore structures. With the Finite Element Method (FEM), analytical and mathematical solutions can be used to model difficult problems and complex shapes found in engineering. Methods used in Computational Fluid Dynamics (CFD) follow and detect changes in heat and mass transport in fluids. Because PCMs cause latent heat effects, the inclusion of them in porous materials makes thermal modeling more difficult. Modeling such materials with accuracy involves setting up methods for conductive and convective heat transfer of PCMs in porous materials. Thanks to this integration, confident thermal transport predictions are possible for a wide variety of applications [2, 8, 9].

Although most of the literature has considered porous structures as either homogeneous or uniform, there is a possibility of utilizing heterogeneous porous materials with non-homogeneous pore distributions as well as multi-scale porosity that may provide much more desirable thermal management features. The implication of this observation forces reconsideration of thermal modeling strategies, typically dependent on pore structure simplifications. The combination of a multi-scale modeling framework where both the micro- and macro-scale porosity distributions are considered may allow a more realistic prediction of thermal transport properties and introduce a new way to design a tailored thermal performance in complex materials such as composites or nano-porous structures.

Overall, heat transportation in porous media induces conduction, convection, and radiation, although the major process relies on porous materials and structures of pores. These basic mechanisms need to be clearly understood to enhance thermal properties in different applications. The subsequent chapter investigates how these heat transfer processes are dictated by the classification of the porous structures, especially in connection with the global pore connectivity and pore structure. After discussing the mechanism of heat transfer in porous media, the way the structure of porous materials affects the total thermal characteristics can be noted. Chapter 3 discusses the classification of porous structures with a particular focus on open- and closed-cell arrangements and the role that both play in thermal transport. In addition, Chapter 3 discusses how the basic heat transfer mechanisms are affected by the various porous shapes present in practice by discussing the nature of porous materials and how they affect the thermal transport.

3 Types of Porous Structures

3.1 Open- vs. Closed-Cell Structures

Based on the knowledge about the concepts of heat transfer in porous materials, this chapter concentrates on the types of porous structures. A thermal classification of these structures is essential to identify the dynamics of their thermal conductivity since the pore connectivity and geometry may have considerable effects on the thermal transport characteristics. The porous materials can be characterized into the so-called open- and closed-cell structures. The inter-linking pores of the open-cell materials facilitate the flow of heat through convection laws and conduction processes. Conversely, the closed-cell materials are isolated with pores, thereby limiting the convection and transferring heat mainly via conduction.

Different from open-cell structures, closed-cell structures have pores that do not let air or water move from one hole to another. The gas in each pore is solidly surrounded, preventing quick conduction since it cannot take part in convection. For this reason, the lesser thermal conductivity observed in closed cells is a result of heat mostly moving by conduction within their solid structure. As there are no flowing fluids, these materials rely completely on conduction for heat transport. That is why they are perfect for insulation. The distinct structures of these pores give rise to many thermal applications. In situations where it's important to dampen sound or make insulation light, open-cell structures are chosen, but for high standards of insulation and resistance to moisture, closed-cell structures are preferred.

Moreover, grasping the link between porosity and thermal conductivity is necessary to choose the right porous materials based on their uses. Thermal conductivity in both open- and closed-cells can be strongly affected by adjusting pore size and porosity, though the results vary when considering pore connections and shape. Both kinds of cell structures are important in moving forward with thermal management solutions found in the construction and biomedical industries [10–12].

3.2 Homogeneous vs. Heterogeneous Porosity

Porous materials are divided into two categories according to whether they are homogeneous or heterogeneous. Uniform thermal transport is achieved in homogeneous porosity, as all pores are similar in size, making it simple to create models. Knowing what to expect allows synthetic materials made for insulation or heat management to conduct heat efficiently from one place to another. As opposed to this, heterogeneous porosity involves pores of uneven structure and size, as is found in natural soils. Because it is not uniform, the material causes irregular temperature and flow patterns in thermal analysis. Such changes influence both large-scale movement and interactions at the scale of the pores.

Because the pores are not identical, tortuosity results, and the paths oil or gas travel are made longer. When systems are tortuous, they become more resistant to heat transfer and less efficient thermally. Besides, the many scales involved in porous media make it necessary to use sophisticated ways of modeling them. XCT allows researchers to learn about pore morphology, yet it shows that analyzing porous and complex materials requires advanced techniques. Because the link between fluids and heat transfer grows more complex, scientists must use advanced methods that join modern data-based approaches with conventional numerical modeling. Knowing the difference between homogeneous and heterogeneous porosity is very important in optimizing energy systems and insulation, because better designs result in better performance and lower amounts of waste caused by making things with complex forms [13–15].

The proposed novel classification system of porous materials is presented based on efficiency in thermal transportation and mechanical stability in order to have a better perception of the thermal transportation characteristics of the porous materials. Porous materials have been categorized in this system into four classes:

a) Skybox materials: Materials having high thermal conductivity but low stability under stress or at high temperatures (e.g., open-cell polymer-based foams).

b) High-stability, low-efficiency materials: Materials that offer high stability over a long period but are limited in thermal conductivity (examples are closed-cell ceramics, used as insulation materials).

c) Moderate-efficiency, moderate-stability materials: Materials that contribute to thermal efficiency and stability over a long period (e.g., metal foams or composite materials).

d) New hybrid materials: Materials with both PCMs and nanostructures to maximize the thermal management and mechanical performance (e.g., nano-composites that contain PCMs).

Such a structure may be helpful in choosing the materials depending upon the application needs (e.g., energy storage, construction, and biomedical applications) and the compromise between thermal performance and longevity of products. As the nature of the porous structure and the impact of such structures on the issue of thermal transport have been understood, the experimental characterization of the given materials is the next logical step.

The different arrangements of porous materials, as explained in Chapter 3, directly influence the thermal transfer mechanism in Chapter 2. The thermal conductivity of a material is not the only thing that determines the motion of heat through it, but also the shape and connectivity of the pores. Chapter 4 explains some experimental methods, such as the steady-state technique and transient technique, adopted to examine the thermal properties of porous media.

4 Experimental Techniques

4.1 Steady-State Methods

Stable methods are necessary to reliably study the thermal transport processes in materials with multiple pores. The sample is typically placed in a controlled temperature environment, and then the heat moving inside the structure is observed. Many scientists prefer to use the guarded hot plate technique because it helps them get precise results for thermal conductivity by cutting down on heat loss. Both plates, one heated and the other cool, are positioned with the sample between them so that heat transfer is easy to monitor during steady conditions. Many researchers have also used the TPS technique. The method is mainly transient, but it can become quasi-steady under certain conditions. It runs by setting a heat source into the material and measuring temperature over a period; after calibrating for steady-state situations, it delivers useful information about thermal properties and maintains parts of its transient function.

Both steady-state and transient experimental methods of measuring the thermal conductivity of porous materials exist. Accurate measurement of thermal conductivity can be obtained by the use of steady-state methods like the guarded hot plate technique. On the other hand, the transient method, such as TPS, can be more rapid in obtaining results with possibly lesser accuracy. Although the two methods possess unique strengths and weaknesses, they are complementary and can be employed jointly to gain fundamental insight into the thermal transport phenomenon. Applying advanced imaging methods in steady-state experiments makes it possible for researchers to view temperature distributions in porous media materials. As an example, infrared thermography shows current surface temperatures and helps spot spots or differences that might affect how well heat moves through the material.

Steady-state tests are great for studying entire materials, but they might miss important details that occur inside the pores of heterogeneous systems. As a result, if these methods are used with transient methods or numerical simulations, it would help better understand heat transfer inside different types of porous structures [14, 16].

4.2 Transient Methods

Studying thermal movements inside porous materials is made possible by using transient methods for analysis. Unlike models that focus on constant conditions, transient approaches watch how temperature and heat develop over time, finding out which thermal properties rely on different conditions. Laser Flash Analysis (LFA) shines a laser on a sample that rises in temperature on the other side, and time changes are measured as the material cools. With this approach, thermal diffusivity is measured quickly, and its value can be connected to conductivity and capacity. The use of TPS is an efficient transient approach. With this technique, an electric current created by a sensor builds heat in the two sections of the material. The changes in temperature are recorded with time so that thermal conductivity in the porous medium can be evaluated. TPS shows great accuracy for all materials and is particularly effective on heterogeneous surfaces.

Moreover, a technique such as infrared thermography is very useful for observing changes in surface temperature as a sample transit through different stages of its journey. Since this method does not damage the material, it is best for assessing a wide range of samples. Transient techniques serve different aims because they come with their own special advantages. That means LFA can evaluate materials quickly, but TPS looks in detail at certain heating qualities in controlled settings. Mixing the techniques commonly results in useful data that improves our understanding of how heat is transferred in porous materials. The method that is best depends on the material used, the shape of the part, and how accurately it needs to be made. Using both transient testing and numerical or mathematical models, scientists can gain a deeper insight into thermal behavior in porous materials [14–16].

Thermal conductivity of porous materials is usually measured by steady-state and transient methods. Although the steady-state techniques, including the guarded hot plate technique, give high-precision measurements, the technique is too labor-intensive, and it might not be effective in materials with low thermal diffusivity. Conversely, the transient methods, including TPS, can provide faster results but not necessarily precise ones in heterogeneous materials. On a comparative analysis of these methods, it is noted that steady-state methods are more accurate when high and precise measurements are required, and transient methods are more adequate in quick, large-scale evaluations. The difficulty in this is mainly having the right method when it comes to variables in the material and the use requirements. Besides, non-destructive imaging systems, including X-ray tomography, have recently demonstrated the possibility of operating both according to the steady-state and transient methods, which can lead to even more thorough and precise thermal measurements. The next steps of research should be to combine such methods with the computational models in order to increase the predictive value of thermal transport in porous media.

4.3 Advanced Imaging Techniques

Recent imaging equipment greatly helps us to study heat movement in porous materials at different scales. XCT is one of the most important non-destructive tools for producing 3D images with resolutions ranging from micrometers to nanometers. XCT makes it possible to examine detailed pore systems and compare experimental results to simulations. To achieve nanoscale imaging, Focused Ion Beam Scanning Electron Microscopy (FIB-SEM) is used because it can produce highly detailed pictures. Even though this method causes damage and is not easy to prepare, it makes it possible to check the details of pore tortuosity and connectivity. Tilt-series imaging in electron tomography helps visualize details about 3D pore structures and these insights are essential for knowing how the arrangement of microstructures can affect thermal transfer. Now, ML is being used with imaging to enhance how images are analyzed. These techniques segment the image automatically and make pores more visible, reducing the time needed for data analysis. Deep learning enables computers to improve scanned images, fixing some of the issues found in old methods.

Recent developments in ML applications, especially deep learning applications, have demonstrated the potential of improving the thermal transport model's efficiency in porous media. These algorithms make it possible to process huge amounts of data quickly and determine the patterns that cannot be observed in conventional models. Nevertheless, there are still some problems in the realization of their potential. The need to have high-quality labeled data can be considered as one of the main constraints of the ML models. Such datasets are often available in limited amounts or not at all in the case of complex materials and new configurations. In addition, although ML models can provide predictions very quickly, they might not be physically interpretable compared with traditional models, and as such, one might not be in a position to verify outcomes. Thus, the combination of ML and physical models or a hybrid method may provide the solution at the balance between the powers of both techniques. Various real-time monitoring systems, including laboratory micro-computed tomography, can observe fluid or chemical activity in pores with just a few seconds of delay. The recent progress in this field explains transient heat transfers with greater accuracy and connects experimental data to theoretical models, helping many disciplines predict and implement new ideas [14, 17–19].

In the attempt to narrow the divide separating numerical modeling and experimentation, the use of an integrated approach, combining ML and advanced imaging techniques with multi-scale modeling, is suggested. The model would entail:

a) Data acquisition: Applying modern data imaging techniques (e.g., X-ray tomography and electron microscopy) to obtain multi-scale data of a porous structure.

b) Data processing: Using ML algorithms to analyze large and complex data and extract features that affect thermal properties (e.g., pore size distribution and material composition).

c) Simulation integration: Incorporation of the extracted features as inputs of multi-scale modelling (e.g., finite element modeling) in order to estimate thermal conductivity with different levels (micro to macro).

d) Validation and feedback loop: The results of the simulation process and corresponding data of experimental observations are compared with each other in order to make models more accurate over time.

Such a framework may result in a more wholesome and dynamic roadmap to the study of porous materials that can help in real-time tracking and performance optimization of porous materials in realistic engineering settings. In addition to this, as has been observed, correct experimental methods play a major role in defining thermal transport. The following chapter dwells upon how computational methods in the form of models and simulations supplement such experimental techniques.

5 Modeling and Simulation Approaches

5.1 Analytical Models

The analysis of thermal transport is made easier with the use of analytical models in porous systems. They allow scientists to estimate the heat transfer rate in different materials based on their physical properties during design and analysis. A useful approach, known as the Rule of Mixtures, combines the thermal conductivities of parts depending on their volumes. Although it is beneficial for early identification, it fails to detect complex features within the material. Better predictions have been made possible with Effective Medium Theory (EMT), which recognizes that certain microstructural aspects, such as the shape and placement of particles, strongly influence the thermal conductivity value. EMT teaches that shifts in a circuit's construction affect how heat travels and the devices' resistance.

Another productive way, known as homogenization, is great for dealing with periodic porous materials. The model uses the average of the field variables in an RVE to determine effective properties, thereby working through any complex shape and predicting heat transfer processes. These new models also capture nonlinear features and phase changes in PCMs. Detailed geometries may be tackled with FEM, something that traditional approaches cannot do.

AI-based techniques are now being used, along with ML, to better predict results and choose materials more efficiently based on a lot of data. The combination of physics and design software allows for a more thorough investigation of the design domain. Overall, it is necessary to use analytical models to precisely represent thermal conduction in many materials and applications [16, 20]. Figure 1 represents the schematic diagram of modeling methodologies to forecast heat transfer in composite materials at both different sizes and time scales. The figure emphasizes various numerical techniques (e.g., finite element modeling and homogenization techniques) and how they could be used on composite materials that have complicated pore structures. The models indicate the accuracy of predicting effective thermal conductivity using parameters of the material that include porosity and pore size distribution.

The inverse dependence between porosity and thermal conductivity manifests itself, as shown in Figure 2, where a plot of thermal conductivity against porosity of various porous materials is seen. As can be seen in the graph, the lower the porosity, the higher the heat conductivity of the material. This is of great concern owing to the insulating feature of such materials as open-cell foams or thermal insulation materials, whose design specification entails high porosity to reduce thermal conductivity. The approaches reflect different advantages, based on how large and intricate the problem is.

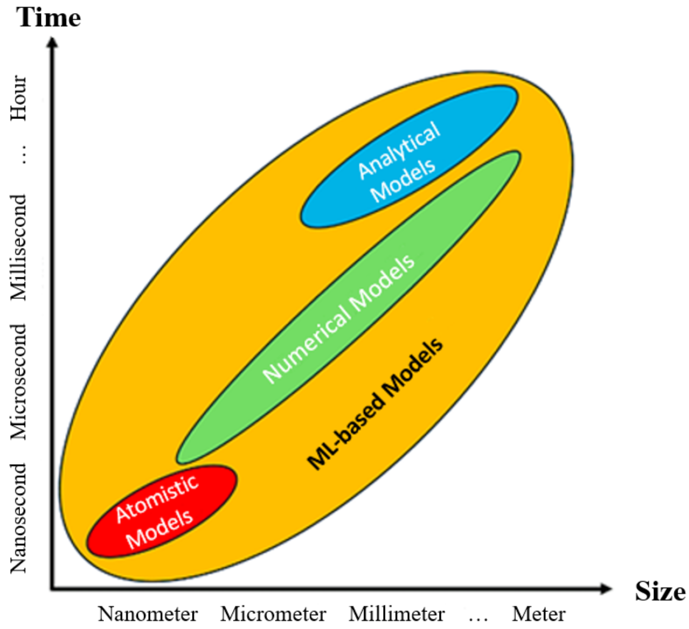

Figure 1. Portrayal of the ability of possible modeling procedures to predict heat transfer in composite materials at a range of sizes and periods [16]

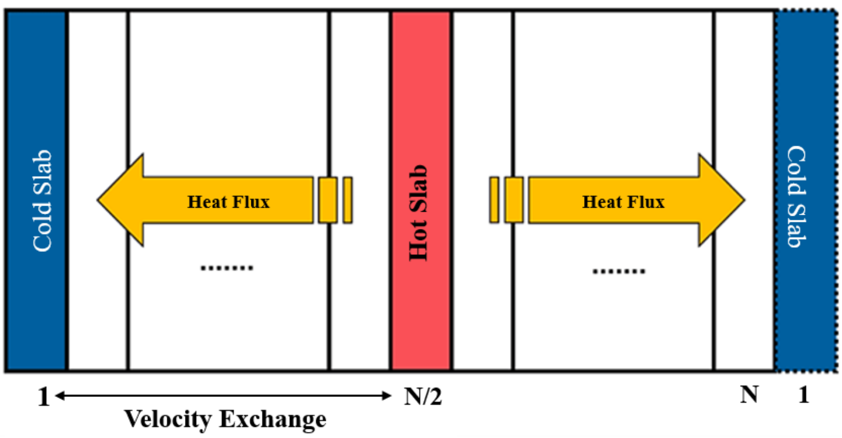

Figure 2. Thermal conductivity measurement using NEMD [16]

Figure 2 shows how non-equilibrium molecular dynamics (NEMD) can be used to measure thermal conductivity. The way this approach works is, first, heat flux is forced onto the system in the simulation, and the temperature difference generated is then the result, going against the normal cause-and-effect link. The use of this method makes everything easier, including meeting the requirements of periodic boundary conditions, energy conservation, momentum conservation, and accurately sampling the time-dependent temperature gradient at a temperature difference [16].

5.2 Numerical Simulations

In porous structures, investigating how thermal energy flows requires numerical calculations that enable researchers to explore effects that hardware experiments might miss. FEM, Finite Volume Method (FVM) and Lattice Boltzmann Method (LBM) each differ in their strengths for using numerical simulations. In terms of heat conduction, FEM stands out when dealing with challenging forms and limitations, whereas FVM conserves mass and energy well when used for coupled situations involving both heat transfer and fluid dynamics. LBM excels in simulating how heat moves in porous media because it captures the details of the flow inside each pore, informing us about how changes to the pore shape can change heat transport. Today, researchers are increasing the forecast accuracy of models by blending both ML and numerical methods. Using input variations, deep learning algorithms can optimize their parameters and design systems to reduce the time it takes to run simulations, with support from extensive data from earlier experiments or tests to find repeating designs in thermal performance.

Researchers can learn more about thermal properties and produce new kinds of materials with desired features by using Generative Adversarial Networks (GANs) with simulations to make synthetic porous materials. Both experiment and mathematical modeling are used to validate and improve fluid flow and heat transfer models so that applications like energy storage and improved insulation can be made with better designs [7, 14, 16, 17, 19, 21–23].

A combination between ML and an existing numerical technique has also been suggested to increase the reliability of thermo transport prediction in porous materials, including FEM. Although this mixed model has potential, there are serious difficulties in the context of practical implementations. As an example, the efficiency of ML models greatly depends on the quality and quantity of training data. This is problematic, especially in the case of porous materials, since the results of experimental measurements at different scales (micro to macro) do not always correlate with each other. Besides, training such models is computationally very costly, and the models must be finely tuned to suit a particular application, restricting their applicability. Another challenge, especially in practical engineering applications, is the complexity of combining these highly advanced techniques and existing systems, as in the case of setting up building thermal management systems or energy storage mechanisms. These difficulties invite future investigations into the concept of data-driven approaches that are more flexible and functional to address the ever-changing and technically different input of real-life materials.

5.3 CFD Approaches

CFD is now essential for understanding thermal transport in porous materials. With numerical techniques for simulating fluid motion and heat, CFD handles issues related to different material qualities and changing conditions at the boundaries. Its value comes from offering precise data on temperature patterns, how the flow is distributed, and how heat is shared between different fluids. Commonly, CFD models depend on the Navier-Stokes equations to model fluid flow in porous media and use the Brinkman equation to include the contribution from the solid part when describing fluid viscosity. This supports the accurate modelling of flows at different sizes and of all kinds, laminar and turbulent.

Advanced computer tools allow for a detailed study of heat transfer methods so that simulations can detect changes in heat conduction and convection due to changes in porosity. It has been found that multiphase flow research examines how the phases heat or cool the porous material as they interact. The improvement of computer power allows CFD simulations to pay close attention to how thermal effects interact with a structure's mechanical motion. It provides significant value for energy systems and aerospace components where predicting heat accurately is key. To solve the equations, numerical approaches like FVM are used on a grid. Therefore, the model can track both temperature variations and different flow rates. Introducing ML into CFD simulations is a new trend that boosts their accuracy and efficiency. Improvements in CFD techniques greatly help increase our knowledge of heat transfer in porous materials [13, 14, 16, 24].

The measurements of the thermal conductivity of different porous materials are shown in Figure 3 as the results of experiments. The graphs, which are the results of the guarded hot plate method, represent a definite pattern that materials with smaller pores have a greater level of thermal conductivity than materials with larger ones. The findings of Materials A and B prove the results of Peters et al. [24], who found the same patterns in the investigation of the effects of pore size on thermal conductivity. The figure also provides an emphasis on the role of the geometry of the pore in the prediction of heat transfer in the porous media.

Figure 3 shows how a multi-scale framework is used in both material designing and flight testing. Both modeling and testing use length scales that vary by several orders of magnitude. Early experimental models help plan and check the outcomes of much larger experiments [24].

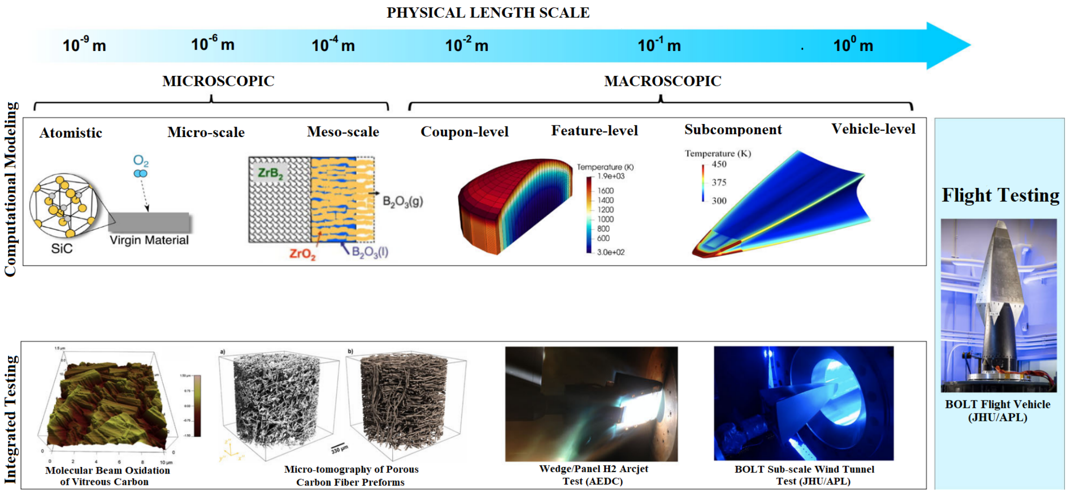

Figure 3. Use of a multi-scale framework in both material designing and flight testing [24]

6 Influence of Material Properties and Porosity on Thermal Transport

6.1 Thermal Conductivity Variations with Porosity

The way porous materials conduct heat is largely affected by their porosity, which shows the amount of void space to the overall size of the material. With higher porosity, insulation in a porous material may be better. The reason for this is that gases show less thermal conductivity than solids. In most cases, materials with larger pore fractions struggle more to transfer heat quickly. Additionally, the size and form of the pores greatly determine the differences in thermal conductivity in different porous materials. Because the solid–gas interface is larger in tiny pores, heat moves more slowly. Therefore, the material is better at retaining heat. It can actually improve the insulation of the area. Having larger pores may actually harm the insulation performance by allowing heat to move efficiently.

The structure of the pores—whether they are the same everywhere or not—plays an important role in thermal efficiency. A good spread of fibers allows heat to dissipate consistently, but a bad arrangement causes some areas to feel hot and can lower the performance of the insulation. Strongly connected pores improve the transfer of heat and help raise the overall thermal conductivity of the material. The kind of material consists of matter too; its different conductivities can change the behavior of the rock, depending on the way its pores are structured. If nanostructures are blended into structures, the barrier to gas transport can increase, which reduces the thermal conductivity up to 330 times more than when air is in motion through the material.

Different pore shapes and the physical properties of the material play a role in affecting thermal transport. Many new techniques have been used to model these interactions and better plan material designs, leading to increased performance. Having this understanding is important for energy storage and insulation materials, as making sure the pores are arranged well can greatly increase their performance [5, 10, 25, 26].

6.2 Impact of Material Composition on Heat Transfer Performance

Structural elements of the materials in porous structures greatly influence how easily heat can move within them. The way heat spreads is affected by the content of the key substance and any necessary additives. Incorporating $\mathrm{Al_2O_3}$ and $\mathrm{Zr_2O_3}$ oxides in porous ceramics makes them better at conserving heat energy because their conductivity is lower than known materials. Depending on how the components combine and bond, heat transfer can be either faster or slower. Using additives allows copper to conduct heat better; $\mathrm{La(Fe, Si)_{13}}$ within a copper matrix is an example, improving thermal conductivity via strong particle interactions in the microstructure. Adding either nanoparticles or fibers to high-performance composites helps them conduct heat while remaining light.

Pore structure features play a key role in deciding how the composition changes thermal transport. When porosity is increased, the density comes down and insulation improves, but it needs to be controlled so that strength is maintained. Although smaller pores increase the area for quick heat conduction, they might also keep air inside and thus slow the process. On the other hand, big pores, while promoting heat conduction from the walls, might let much convective heat leave, weakening the insulation ability.

Because of the way materials are built, connected pores help the overall heat management of the fabric. Great architectural designs need to make sure that buildings keep cool in the summer and are still strong in the winter. With the use of 3D printing, it is possible to manage the size and placement of pores precisely, allowing customizations that improve the mechanical and heat management properties of the material [22, 27].

7 Advances in Functional Porous Materials for Enhanced Thermal Transport

7.1 Nanostructured Materials

The use of nanostructures greatly increases thermal transport in porous systems and improves their ability to transfer heat. They make use of frameworks in which the nanoscale parts work to increase thermal conductivity and give control over properties such as porosity and surface area. Metal-organic frameworks (MOFs), made from metal ions and organic molecules, are one instance of this new approach. Because of their molecular structure, they can offer both a large surface for reactions and different pore sizes, which improves how quickly phonons travel in their material.

Heat conduction is enhanced by covalent organic frameworks (COFs) as well as mesoporous silica and polymeric aerogels. Because of their unusual pore shapes, these materials are less resistant to heat, which allows for special modifications that improve their usefulness in energy storage and insulation. Making nanostructured materials is now simpler thanks to improvements in 3D printing and other manufacturing processes. Thanks to this technology, heat transfer channels can be properly designed, aiding both electronic coolers and insulation in buildings. Researchers are paying more attention to improving heat transfer across surfaces in composite structures. The objective of this work is to achieve systems that mix the properties of nanotechnology and large-scale technology. It is expected that nanotechnology will be used with renewable energy technologies to drive better heat movement and assist in reaching sustainability. New advancements in manufacturing and characterization help take these materials further in thermal management for different industries [10, 27–30].

The nanostructured materials have been identified as one of the promising fields in the enhancement of thermal conductivity in porous structures due to the fact that nanostructured materials can maximize heat transfer at the nano level. Nevertheless, they are yet to be used in practice, and challenges of scale-up, price, and long-term durability persist. Although such experiments are very promising at a laboratory scale, the dynamics of these materials at a larger scale remain unknown. Further study ought to be devoted to the jurisprudence of mass-producing fabrication of nanostructured materials by techniques that do not interfere with thermal characteristics. In addition, the compatibility of these materials with various environmental conditions should be carefully evaluated since the materials may degrade with time and hence lose much performance here. Additionally, future developments should also involve a hybrid use of materials where the advantage of nanostructures is added to other promising materials, like PCMs, to improve not only thermal management but also energy storage.

7.2 Composite Materials with Tailored Properties

Improved thermal conductivity in composite materials signifies a big step forward for thermal management technology. When different materials are used, the resulting composites can have designed thermal behavior for use in aerospace, automotive, and electronics. Generally, a lot of carbon nanotubes or graphene are added to the polymer to improve how heat is transferred inside the matrix.

Most fiber reinforcements are anisotropic. Therefore, heat transfer is better along their axis than across their width. The material must be designed carefully so that its qualities meet the requirements of the product's use. Recently, a new type of composite material has been created by combining organic and inorganic substances, which makes it easier to tweak mechanical and thermal features. With the use of additive manufacturing, engineers control the layout and direction of filler materials that, in turn, help produce designs that make the product more efficient with thermal energy. Electrospinning and other technologies increase heat transfer capability at the nanometer scale.

New developments in self-healing composites and adaptive thermal conductivity allow the material to be more durable in changing temperatures. Working with materials whose temperature can be adjusted by stimuli demonstrates the major advantages composites have for different purposes. Adding PCMs to designs allows modern technology to handle heat more effectively. Researchers have discovered that there is a shift underway in managing thermal problems across many industries [16]. The simulation results between the LTE and LTNE models to predict the thermal conductivity of a porous medium are shown in Figure 4. The simulations indicate that at increased porosities, the LTE model underpredicts the thermal conductivity as a large thermal lag exists between the solid and fluid phases. On the contrary, the LTNE model can yield a more precise prediction under such conditions, and this fact reaffirms the need to use a properly selected model that takes into account the properties of the material.

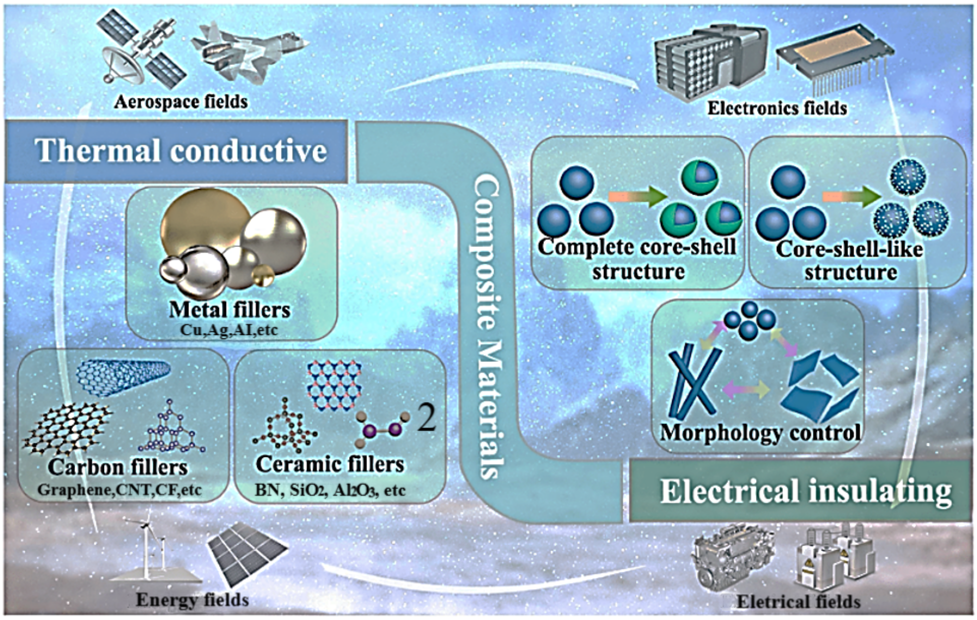

Figure 4. Composite materials created to improve the balance between thermal efficiency and high insulation against electricity, which behave as desired in managing temperature [16]

8 Applications of Thermal Transport in Porous Structures

8.1 Energy Storage Systems

Porous architectures in energy storage are being noticed for their improvements in both thermoregulation and energy effectiveness. Porous materials help heat transfer and energy storage thanks to their large and connected pore networks. In solar thermal systems, these units trap extra heat in bright sunlight and then distribute it when there is less sunlight. Adding PCMs into porous materials greatly enhances the way energy can be stored. By transferring and storing heat through their phase shifts and using highly thermally conductive porous materials, PCMs can achieve improved energy storage and better heat transfer. Using this approach, indoor temperatures are kept constant and power use is decreased across the building.

Lately, studies have shown that porous materials can make EV batteries work better. The use of PCMs in battery cooling systems holds down charging temperatures, helps batteries last longer, and increases overall efficiency. Because of computational modeling, researchers are able to predict the heat flow within these composites, resulting in better solutions for improved cooling and structure. In addition, ML is used to optimize the design settings for porous media and PCMs. They are able to uncover the best operating parameters for improved thermal efficiency across different applications, including local district heating and industrial uses. Overall, adding porous materials to energy storage systems helps move toward sustainability in renewable and thermal energy [2, 3, 23, 31].

8.2 Insulation Materials in the Construction Industry

In construction, insulating materials are very significant, as they are needed for a building to be comfortable and to reduce energy use. Such products stop heat from passing inside or outside, permitting comfortable indoor temperatures at a lower expense for heating and cooling. Heat flow resistance provided by insulation depends mainly on how porous and structured the material is. Micro- or nano-porous materials have become the best insulation materials on the market. The materials cut down on thermal conductivQity by effectively capturing air or gases that insulate the system. The effect is especially apparent in porous ceramics and new composite materials produced with advanced methods like 3D printing. The precise pore size and arrangement made possible by these improvements increase the thermal performance of the material for specific purposes.

The combination of metal oxides (Al_2O_3 and ZrO_2) into insulation designs has raised the thermal performance and durability of the products. It has been demonstrated that carefully creating pores in these ceramics both improves how they work at high temperatures and preserves their structure. Furthermore, using composite materials allows us to bring together various advantages useful for various building envelope applications. Not only do porous insulation materials help build walls and roofs, but they are now added to passive solar systems and refrigerators to help increase energy savings. Further progress in computational modeling enables architects and engineers to apply heat transfer simulations to porous materials and predict their behavior more accurately. Even so, there are still difficulties in making the process consistent and scaling up new porous insulation products. It is important that the construction industry accept new materials if production processes can meet demand without lowering their quality [25, 30].

8.3 Biomedical Applications

Porous structures are becoming more important in medicine because they have unique heat flow properties that can be set to different values, useful in drug delivery, engineering tissues, and temperature control of medical equipment. A breakthrough is the rise of porous scaffolds meant to copy the natural extracellular matrix. They aid cell adhesion and promote growth, also making it easier for them to get the nutrients they need. Being able to adjust the pores and have a high surface area lets these materials efficiently move heat, an essential part of keeping cellular activities warm or cold as needed. Porous materials are important in drug delivery because they release drugs as needed and can control the heat that forms during body reactions or stimulation. With thermoresponsive hydrogels and porous structures, it becomes possible to deliver drugs directly as temperatures rise. The strategy relies on the thermal features of these materials to develop devices that can change as needed for local infections or long-term ailments.

In addition, the advances made in 3D printing now allow us to manufacture individualized porous implants for each patient. They provide both support and useful features to regulate the temperature around the sites where surgery or an injury has occurred. Biosensing techniques make significant use of porous materials. Since they move heat much better than other materials, they are perfect for creating biosensors that detect small levels of biomolecules. Thanks to their design flexibility, sensors can detect nature's changes in the body and are crucial for diagnosing diseases or checking how well treatment is working. Adding functional porous materials to biomedical use supports their ability to be varied, leading to better outcomes by managing body temperature and interacting safely with biological systems. Many ongoing studies are looking for improved ways to use these systems in healthcare [25, 30].

9 Challenges and Limitations in Current Research

9.1 Measurement Difficulties

Analyzing thermal transport in porous materials is made difficult by certain measurement issues. Because of the irregular shapes and patterns in porous media, assessing thermal properties is very challenging. Conventional experiments are not effective, as they miss important details within the microstructure needed to explain heat transfer. The high price of using advanced imaging tools makes it difficult to use them for studying pore structures. It takes a lot of time to use these methods, and samples must be carefully prepared so that any mistakes will not affect the results. Besides, because of a lack of resolution, identifying finer parts of clay or cement-based compounds can be difficult, and tiny deviations from the real state can lead to misunderstandings of how transport occurs within those materials.

Modifications to pore structures during the life or aging of materials add further complexity to measurements. Modifications to the structure can happen from chemical reactions, being subjected to excessive force, or due to biological processes that make the pores less permeable over time. For this reason, creating tools that respond quickly to changes in porous media requires special experimental systems that can handle different surroundings while still recording accurately. In addition, because there are variations between average properties found in large-scale tests and those in small pores, some conclusions about transport may be wrong. Generally, the speed measures from bulk tests are not reliable for single porous sites because of extra mass transfer difficulties at those scales.

Adopting machine-learning approaches with experimental methods may offer appealing answers to these problems because the predictions consider the uncertain aspects involved in porous media characterization. By combining data analysis tools with common laboratory experiments, this research can support both greater accuracy in measurements and increased insight into heat flow in complex porous environments [14, 16, 18, 23].

Figure 5 reveals how thermal fillers such as carbon nanotubes (CNTs), graphene, and boron nitride enhance thermal conductivity of the porous composites. Directions of thermal conduction are improved by uniformity of dispersions and by alignment in the heat flow direction. Such methods as chemical functionalization, surface roughening, and interfacial bridging layers minimize interface resistance and lead to enhanced continuity of heat flow. Special processes such as roll-to-roll regulations, 3D printing, or spray foaming need to be applied to scale the fabrication to the industrial level. Materials in thermal management must be durable/and or thermally stable and this can be achieved by choosing thermally stable crosslinked matrices, thermally stable fillers, and thermally stable architecture to provide durability. The innovations in thermal porous materials should accommodate a variety of fields, such as Electric vehicles (EV) batteries, biomedical devices, aerospace insulation, and builds. It is also necessary to integrate the computational and experimental methods, apply predictive thermal modeling and machine learning, and make use of sustainable and environmentally friendly materials.

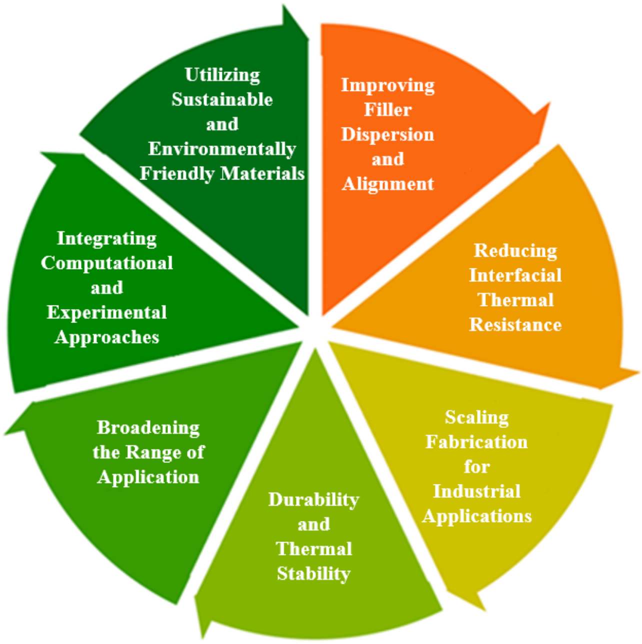

Figure 5. An outline of the main problems and the route the field should take in heat transport management of composites [16]

9.2 Scale-Up Issues

Transporting heat through porous structures is very challenging when transferring from studies in the lab to use in industry. Key problems include that traits in microstructures vary among scales, making it hard to match experiments done on a small scale with outcomes on a large scale. How heat moves through pores in complex structures adds to the problem of understanding heat transfer. When material fabrics vary widely in their build, porous features tend to change both in size and in how well connected they are. This can cause major differences in thermal conductivity as larger structures are made. Such absorption changes not only reduce what an absorbent material can do but also complicate the process of checking item quality.

Imaging at a high resolution to measure thermal properties is difficult for large samples because the precision can decrease, possibly increasing the uncertainty in any models. In other words, increasing the size of an experimental setup can introduce previously unconsidered boundary conditions. Because many porous materials can alter over time due to different influences, their endurance significantly affects both their thermal qualities and dependability in real-life situations. It is essential to ensure that these materials maintain their basic features under stress. Adding novel porous materials with new properties into existing systems brings challenges related to their compatibility with production and supply. It is important for aerospace and energy storage to produce these materials efficiently and at a reasonable cost, considering how well they perform. Aside from this, ensuring compliance with safety and environmental regulations increases the complexity of testing, which further lengthens the development period [14, 32].

10 Future Perspectives and Research Directions

10.1 Emerging Technologies in Material Development

New discoveries are helping transform material engineering for heat conductivity, mainly for porous systems. New approaches for better material design and improved thermal efficiency have come about thanks to combining AI and ML. Through predictive modeling, ML algorithms can study wide sets of data and precisely estimate the thermal features of different materials. Convolutional Neural Networks (CNNs) have demonstrated strong results in calculating thermal conductivity values in composite materials compared to routine methods. Generative models, especially GANs and Variational Autoencoders (VAEs), have made it possible to digitally visualize porous structures in 2D and 3D that reflect the geometry of many real materials taken from large sources of data. With this, scientists can design materials to perform certain functions while lowering both time and cost spent in experiments.

ML helps to rebuild the structure of porous media, tying the properties of those structures to measures of permeability and thermal conductivity. Thanks to advanced algorithms, systems for energy storage and insulation can work well due to their heat transfer properties being customized. Using deep learning, it is now possible to predict thermal conductance under various conditions with much less simulation work. Examining big data helps us understand the way microstructures affect the movement of heat. However, using these technologies on a large scale in industry is still difficult because of not enough data, demanding hardware and clear models. Continued development in generative modeling is expected to sharpen how specialized porous media are made so that the collaboration among material scientists, engineers and data experts accelerates [7, 15, 16, 21].

Combining AI and modeling of thermal transport may transform the sphere of human activity with more precise, data-based forecasting. Nonetheless, this is not a smooth process. AI models obviously need large training datasets, and in the thermal transport fields, those are intrinsically challenging to produce, both in general and especially in new materials or complex multi-phase systems. Furthermore, although AI is more efficient in modeling, in many cases, it may act as a black box, and it is hard to understand the physical law of heat transfer. To make AI more commonly used in the engineering field, some effort must go into attempts to integrate ML with physical models, leading to hybrid tools that would improve not only the accuracy of predictions but also the understanding of the process that underlies them. In addition, the latest technologies such as new imaging systems and AI would be able to monitor/control the thermal transport processes in real time, which would enable smart materials to change thermal characteristics according to the environment. The blending of these technologies might lead to the production of the next-generation thermal management systems.

Measurement of long-term degradation of porous materials in an environmental condition is one of the fundamental issues to deal with in the future. There has been extensive research on the thermal performance of these materials at their instantaneous behavior but the effects of ageing and stress on the fatigue properties of materials on the thermal performance of materials are unexplored. The long-term commercial viability of porous materials in practical applications to treat buildings to make them more energy efficient or as an energy storage device requires the development of reproducible experimental environments and even models that consider these factors.

10.2 Integration with Renewable Energy Systems

Attaching porous structures together with renewable energy technologies can help increase both refining and protecting the environment. Since porous materials have abundant surface and respond differently to heat, they are useful in improving new developments in energy. For example, solar thermal collectors use them to boost both heat absorption and holding, leading to better energy use. Thermal energy storage from solar is well matched to the discontinuous output of solar panels. In geothermal applications, porous media allow fluids to move, improving how heat is transferred from one part to another. Combining PCMs with porous structures is an effective method for controlling temperature fluctuations in renewable energy systems and improving overall function.

Advances in modeling and ML are now being used to perfect the layout and structure of integrated systems. Through simulations, researchers can see which combos of materials and designs can improve thermal efficiency while costing less. Using this method, innovators can quickly see how their designs would be used for real-world solutions.

By using nanostructured porous materials, the thermal transport ability of compounds can be improved by reducing the effects at the interface and employing phenomena that happen at the nanoscale. Such changes make both systems more efficient and allow them to produce less carbon, encouraging the use of renewables. In future studies, researchers should design solutions using different porous materials and new technologies to make multifunctional systems that make use of renewable energy, manage temperatures well, and produce breakthroughs [2, 14, 21, 25, 33, 34].

11 Conclusion

Porous material systems can help us uncover how factors in material science, engineering and environmental safety are related. Since effective thermal management is needed in many industries, the continual development of porous materials is becoming very relevant. Thanks to improvements in manufacturing methods related to 3D printing, the precise modulation of porosity and pore structures is now possible which helps improve a building's thermal insulation and energy efficiency. When looking into better materials, scientists should pay attention to how these materials affect the environment both when they are made and after they are disposed of. Using sustainable materials and helping products decompose or recycling them is the best approach for maintaining sustainability. Integrating renewable energy into these products can bring many benefits; for instance, textiles using solar or wind power may become more functional.

Leading the transformation are new fibers and materials that adjust users' body temperatures in many ways, including with PCMs and by absorbing and releasing different energies with heat and light exposure. The new developments can be used in wearable tech, as well as in advanced insulation systems built for construction and defense. A clear understanding of how heat transfers through conduction, convection, and radiation still shapes the development of advanced porous structures needed now. Researchers from multiple areas need to come together to address the measurement challenges and drive growth for this field. Understanding these subtle heat transfer processes in porous materials helps us identify new areas where these can be used to improve thermal management, conserve energy, and assist the environment. With the ongoing progress of construction efforts, both technical requirements and the environment should always be taken into account. Looking ahead, it is expected that many smart materials will be used to increase how fast heat is transferred in various settings—from factories to commercial products.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declare no conflict of interest.

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