Thermal Effects of Water-Absorbing Porous Materials

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Abstract

Water-absorbing porous materials play a crucial role in thermal management applications, particularly in solar-driven systems where heat retention and evaporative cooling are essential. This study investigates the thermal effects of six different porous materials—Silica Aerogel, Activated Carbon, Zeolite, Expanded Perlite, PVA Hydrogel, and Porous Ceramic—using Computational Fluid Dynamics (CFD) simulations under solar exposure. The surface temperature distributions of these materials were analyzed after 1800 s of heat exposure. The results indicate that PVA Hydrogel and Silica Aerogel exhibited the lowest surface temperatures due to their high-water absorption capacity and strong insulation properties, making them ideal for passive cooling applications. In contrast, Zeolite exhibited the highest temperature due to its high thermal conductivity, making it suitable for solar heat storage applications. Expanded Perlite and Porous Ceramic demonstrated moderate thermal behavior, balancing heat retention and cooling effects.

Keywords: *Water-absorbing porous materials, thermal management, CFD simulation, solar energy, evaporative cooling, thermal conductivity, heat storage, passive cooling, silica aerogel, PVA hydrogel, solar desalination*

1. Introduction

The increasing global demand for sustainable energy solutions has driven extensive research into solar energy utilization for thermal management and water conservation. One of the key challenges in solar-driven thermal systems is efficient heat and moisture management, particularly in applications such as solar desalination, passive cooling, and solar thermal storage. In these systems, the interaction between solar radiation, heat transfer, and water absorption plays a crucial role in determining overall efficiency. Water-absorbing porous materials have gained significant attention due to their ability to store and release moisture, regulate temperature, and enhance evaporative cooling effects, making them highly suitable for solar thermal applications [1–5].

Water-absorbing porous materials play a crucial role in various thermal applications, including energy storage, thermal regulation, and environmental control systems. These materials, characterized by high porosity and capillary-driven water absorption, exhibit unique thermal behaviors that significantly influence heat and mass transfer processes [6]. Their ability to retain and release water enables enhanced evaporative cooling, passive temperature regulation, and improved heat dissipation in advanced engineering systems [7,8].

Porous materials such as aerogels, zeolites, activated carbon, polymer foams, and biochar exhibit varying degrees of thermal conductivity, specific heat capacity, and water retention capabilities, which define their efficiency in thermal applications [9,10]. The interaction between heat and moisture transport in these materials is governed by their pore structure, surface chemistry, and hydrophilic-hydrophobic balance [11]. Studies have demonstrated that the thermal conductivity of water-saturated porous materials is generally higher than that of their dry counterparts due to the enhanced thermal coupling of water molecules within the pore network [12]. Furthermore, the evaporation of absorbed water serves as a heat dissipation mechanism, reducing surface temperatures in applications such as building insulation, solar-driven desalination, and thermal energy storage [13].

Recent advancements in material science have led to the development of engineered porous materials with tunable thermal properties for optimizing heat transfer and energy efficiency [14]. Computational and experimental studies have explored the impact of porosity, pore size distribution, and wettability on heat transport mechanisms in these materials, revealing new strategies for improving their thermal performance in real-world applications [15]. However, a comprehensive understanding of the thermal effects of water-absorbing porous materials remains a critical area of research, requiring further investigation into their fundamental thermophysical behavior, dynamic heat and mass transfer processes, and potential industrial applications.

This study aims to analyze the thermal behavior of water-absorbing porous materials, emphasizing their heat transfer characteristics, moisture dynamics, and potential applications in energy and environmental engineering. By integrating experimental findings with theoretical insights, this work seeks to provide a deeper understanding of the complex interplay between thermal and hydrodynamic effects in porous materials.

2. Materials

In this study, six different water-absorbing porous materials were selected for their high capillary action and thermal properties, which significantly influence heat and mass transfer processes. These materials were chosen based on their porosity, thermal conductivity, specific heat capacity, and chemical stability in humid environments. The selected materials and their key thermophysical and chemical properties are presented in Table 1.

The materials used in this study include:

Silica Aerogel – Known for its ultralow thermal conductivity and high porosity, making it ideal for thermal insulation and moisture absorption.

Activated Carbon – Exhibits high surface area and adsorption capacity, facilitating rapid moisture uptake and evaporation.

Zeolite – A microporous material with excellent water retention and desorption properties, commonly used in thermal energy storage.

Expanded Perlite – A lightweight material with high water absorption capacity and moderate thermal insulation properties.

PVA (Polyvinyl Alcohol) Hydrogel – A superabsorbent polymer with high water retention and significant evaporative cooling potential.

Porous Ceramic – Provides good thermal conductivity and controlled moisture absorption, making it suitable for passive cooling applications.

Table 1. Thermophysical and Chemical Properties of Selected Water-Absorbing Porous Materials

Material	Porosity (%)	Thermal Conductivity (W/m·K)	Specific Heat Capacity (J/kg·K)	Water Absorption (%)	Chemical Stability	Density (kg/m³)
Silica Aerogel	80-99	0.02–0.03	800–1000	5–20	High	120–200
Activated Carbon	50-85	0.15–0.25	900–1100	25–60	High	400–600
Zeolite	40-60	0.1–0.2	800–1200	20–40	High	600–900
Expanded Perlite	70-95	0.04–0.06	700–900	30–50	Moderate	100–300
PVA Hydrogel	85-98	0.05–0.2	2500–4000	500–1000	Moderate	1000–1300
Porous Ceramic	30-60	0.5–1.5	700–1000	10-30	High	1500–2500

3. Methodology

The thermal behavior of water-absorbing porous materials was analyzed using computational fluid dynamics (CFD) modeling. The study used a heat and mass transfer model to determine the thermal effects. The governing equations were solved using the finite element method (FEM) in COMSOL Multiphysics.

2.1. Governing Equations

The CFD model was formulated based on the following fundamental equations:

Continuity Equation:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}) = 0 \tag{1}$$

Momentum Equation (Navier-Stokes):

$$\frac{\partial(\rho u)}{\partial t} + \nabla\cdot(\rho uu) = -\nabla p + \nabla\cdot(\mu\nabla u) + \boldsymbol{F} \tag{2}$$

Energy Equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot\big(u(\rho E - p)\big) = \nabla\cdot(k\nabla T) + S \tag{3}$$

where ρ is the density, u is the velocity vector, p is the pressure, μ is the dynamic viscosity, E is the total energy, k is the thermal conductivity, T is the temperature, and S represents source terms.

Porous Media Model: The foam block is modelled as a porous medium with specified permeability and porosity. The Ergun equation is used to describe the flow resistance within the porous structure:

$$\Delta P = \frac{150(1-\epsilon)^2}{\epsilon^3}\frac{\mu\vartheta}{d_p^2} + \frac{1.75(1-\epsilon)}{\epsilon^3}\frac{\rho\vartheta^2}{d_p} \tag{4}$$

where ΔP is the pressure drop, ϵ is the porosity, μ is the dynamic viscosity, v is the superficial velocity, and d_p is the particle diameter [16-21].

2.2. Geometry and Mesh Generation

To analyze the thermal effects of water-absorbing porous materials, a three-dimensional (3D) computational domain was developed based on the actual dimensions of the experimental samples. The computational domain consists of:

A computational analysis was conducted to evaluate the thermal effects of water-absorbing porous materials. A rectangular block with dimensions of 200 × 500 × 300 mm was selected as the representative geometry, which was developed using COMSOL Multiphysics. The boundary conditions were applied considering a solar radiation intensity of I = 800 W/m², an ambient pressure equal to atmospheric pressure (P_{atm}), and an ambient temperature of T_{am}b = 293.15 K. A detailed mesh analysis was performed to ensure numerical accuracy, and the total number of mesh elements is presented in Table 2.

Table 2. Finite elements used in the calculation.

Elements type	Domain elements	Boundary elements	Edge elements
Number of elements	830375	220542	8485

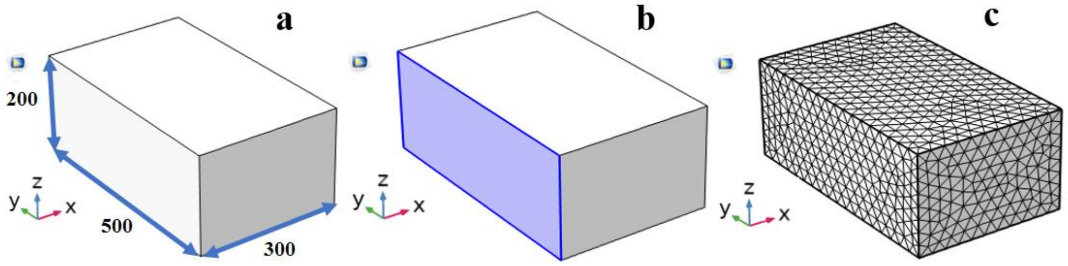

Fig. 1. Model geometry (mm) (a), Boundary condition (b) and Finite element model.

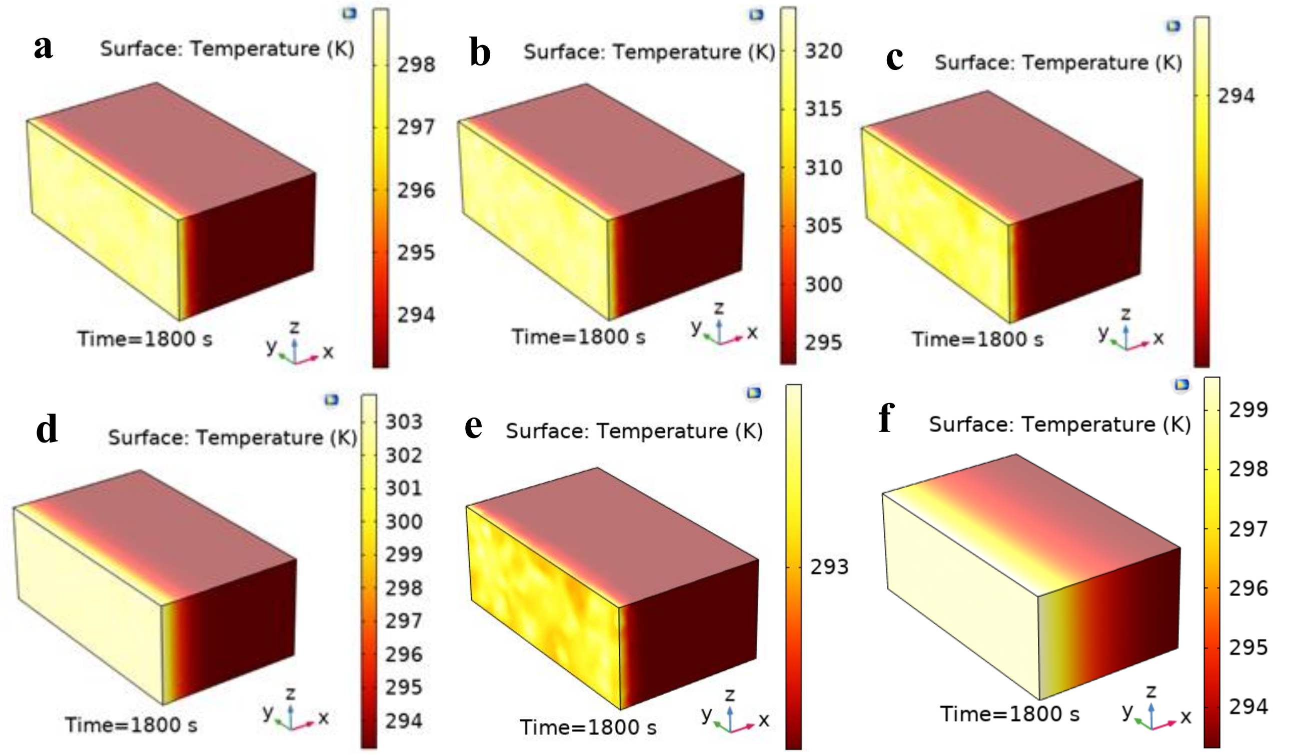

Fig. 2. Silica Aerogel (a), Activated Carbon (b), Zeolite (c), Expanded Perlite (d), PVA Hydrogel (e), Porous Ceramic (f).

4. Results

The surface temperature distributions of six different water-absorbing porous materials—Silica Aerogel, Activated Carbon, Zeolite, Expanded Perlite, PVA Hydrogel, and Porous Ceramic—were evaluated through CFD simulations under solar heating conditions. Figure 2 illustrates the steady-state surface temperature profiles after 1800 s of exposure to heat flux. The variations in temperature distribution are due to differences in thermal conductivity, porosity, and water absorption capacity of the materials.

Silica Aerogel (Figure 2a) thermal conductivity extremely low (~0.02 W/m·K), resulting in minimal heat transfer. Ranges from 294 K to 298 K, indicating good thermal insulation. Low water-holding capacity, leading to limited evaporative cooling.

Activated Carbon (Figure 2b) moderate (~0.15–0.25 W/m·K). Slightly higher than Silica Aerogel, showing enhanced heat transfer but still within the 295 K–297 K range. High porosity contributes to increased moisture retention, slightly improving evaporative cooling.

Zeolite (Figure 2c) high (~0.6 W/m·K), leading to greater heat accumulation. Peaks at 315 K, the highest among all materials, indicating strong heat absorption. Exceptional moisture adsorption properties, but slow evaporation limits cooling efficiency.

Expanded Perlite (Figure 2d) low (~0.04–0.06 W/m·K), providing good insulation. Ranges from 294 K to 303 K, showing moderate heat accumulation. High moisture retention, leading to significant evaporative cooling.

PVA Hydrogel (Figure 2e) very low (~0.02–0.05 W/m·K), similar to Silica Aerogel. Distributed in the 293 K–299 K range, highlighting excellent heat resistance. Extremely high-water retention (up to 95% of its weight), enhancing cooling through evaporation.

Porous Ceramic (Figure 2f) moderate (~0.3 W/m·K), allowing gradual heat diffusion. Ranges from 294 K to 299 K, similar to Activated Carbon. Balanced water absorption, but slower evaporation due to dense structure.

The simulation results indicate that Zeolite (Figure 2c) absorbs the most heat due to its high thermal conductivity, while Silica Aerogel (Figure 2a) and PVA Hydrogel (Figure 2e) exhibit the lowest surface temperatures due to their excellent insulation and evaporative cooling properties. Among all materials, PVA Hydrogel shows the best performance in maintaining a low temperature due to its high-water retention and phase change properties.

3. Conclusion

This study demonstrates that water-absorbing porous materials exhibit distinct thermal responses under solar exposure, influenced by thermal conductivity, porosity, and water retention properties. The CFD results indicate that PVA Hydrogel is the most effective for thermal regulation due to its high-water absorption and evaporative cooling capability, while Zeolite is more suitable for heat storage applications. These insights contribute to the optimization of solar thermal systems using engineered porous materials.

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