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Porous materials in building energy technologies—A review of the applications, modelling and experiments

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ABSTRACT

Improving energy efficiency in buildings is central to achieving the goals set by Paris agreement in 2015, as it reduces the energy consumption and consequently the emission of greenhouse gases without jeopardising human comfort. The literature includes a large number of articles on energy performance of the residential and commercial buildings. Many researchers have examined porous materials as affordable and promising means of improving the energy efficiency of buildings. Further, some of the natural media involved in building energy technologies are porous. However, currently, there is no review article exclusively focused on the porous media pertinent to the building energy technologies. Accordingly, this article performs a review of literature on the applications, modelling and experimental studies about the materials containing macro, micro, and nano-porous media and their advantages and limitations in different building energy technologies. These include roof cooling, ground-source heat pumps and heat exchangers, insulations, and thermal energy storage systems. The progress made and the remaining challenges in each technology are discussed and some conclusions and suggestions are made for the future research.

1. Introduction

Energy consumptions in buildings are constantly ramping up due to the increase in human population and rapid growth of building construction in urban areas. As an example, residential buildings consume 21.7% of the total energy produced in the United States [32]. As another example, currently, heat accounts for nearly half of the energy consumption in the United Kingdom and about a third of the carbon emissions in this country [62]. Around 80% of heat is used in houses and other buildings, and the remaining 20% is used in various industrial sectors in the UK [62]. The energy issues associated with thermal management of buildings directly affect the environment, economy, and living standards. These problems are tangled with the ongoing worldwide crises including the high cost of energy and the urgent needs to decrease the emissions of greenhouse gases. Consequently, many researchers have focused on improving the energy efficiency in buildings as an essential priority. Many active and passive techniques have been developed in this regard. Amongst these, using porous materials has received significant attention. This is because of the fact that these materials have a relatively low cost and a great potential to improve the energy efficiency of buildings.

Recently, De Boeck et al. [12] performed a review on improving the energy performance of residential buildings. They did not consider non-residential buildings in their review. This review revealed that most existing investigations have been focused on European buildings and the Asian buildings have received much smaller attention. Considering the significant population and rapid urban growth in Asia, this finding highlighted the importance of extension of research to Asian buildings. In this research, the attention of the authors was on the works about energy optimisation in residential buildings. Omrany et al. [92] reviewed the potentials of passive wall systems for improving the energy performance in buildings. They identified the Trombe walls as a suitable system capable of reducing the energy consumption of building. This work was exclusively focused on the types of walls used in buildings. Other parts of buildings such as roofs, floors, and windows were not covered by these authors. Ruparathna et al. [104] performed a review on the approaches used to improve the energy yield of operating commercial and institutional buildings. They stated that some important factors such as design, safety risks, installation, and regulatory barriers along with new technologies must be investigated before they are applied in practice. Authors in this article reviewed a number of new technologies such as installing sensors, automated lighting

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controls, enthalpy exchangers, changing building fenestration geometry, upgrading chillers, etc. to improve energy yield in buildings. Valladares-Rendón et al. [122] recommended the effective passive solutions to reduce insolation and to enhance energy savings for solar cooling systems used in buildings. Façade self-shading, shading devices, window-to-wall-ratio, and building orientation were the four factors investigated in this article. Asdrubali et al. [4] conducted a review on structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. They recommended wooden materials with excellent strength-to-weight ratios, thermal insulating, and acoustical properties that can be used for various applications in building.

Porous materials are of significant scientific and technological interests for energy conversion and storage [68]. These materials include a solid matrix with inter connected pores. Based on the physical properties of these materials, they may be utilized for various purposes in energy systems. These include adsorption systems, thermal energy saving systems, insulation systems, evaporation systems, and geothermal systems [121].

The fundamental characteristics of these materials especially the fundamental transport phenomena in porous media are discussed in monographs and handbooks in this area (e.g. [56,88,121]). The applications of porous materials in different energy systems have already been reviewed. Rashidi et al. [100] investigated the applications of porous materials in solar energy systems in a review article. Applications of porous materials in solar chimneys, collectors, heat exchangers/heaters, ponds, stills, and the thermal energy saving units used in solar systems were reviewed in this work. Kasaeian et al. [55] reviewed the nanofluid flow and heat transfer in porous media. They stated that the thermal efficiency of ducts improve by creating high surface area contact porous materials.

Usually, buildings have a poor energy performance [103]. Accordingly, it is important to improve this energy performance by reasonable and affordable techniques. One of these techniques is through using porous materials for different targets in building energy systems. There are a large number of articles about building energy efficiency. Many researchers have used porous materials to improve the efficiency of energy in buildings. Further, some of the natural media involved in building energy technologies are porous. However, currently, there is no review article specifically focused on the porous media pertinent to the building energy technologies. The objective of this work is to review the applications of porous materials in building energy systems. These systems are roof cooling, ground-source heat pumps and heat exchangers, insulation and thermal storage systems.

Applications of the porous materials in these systems are presented as follows.

- Ground heat pumps extract energy from the ground using borehole heat exchangers. Indeed, boreholes are surrounded by the porous soil/rock. The soil temperature distribution, soil humidity content, thermal properties of the soil, groundwater movement, and possible freezing and melting of the water content in the soil as a porous material are some parameters that affect directly the performance of ground heat pumps. Thus, analysis of the characteristics of soil as a porous material is important for designing these devices.
- Usually, insulation materials have porous fibres or foam natures. These materials should have the lowest possible heat conductivity, while at the same time they have to be structurally stable. Selecting porous material with lower thermal conductivity and high structural stability is important for insulation purposes.
- Using humid porous materials on the surface of the roof results in cooling effects caused by the passive water evaporation. When heat transfer occurs between the upper surface of the roof and atmosphere, liquid water diffuses from the internal substrates to the surface and evaporates in there and therefore generates a cooling effect. Accordingly, evaporative cooling through using porous materials is recognised as an efficient technique for roof cooling targets.
- An interesting possibility in building application is the impregnation of phase change materials into porous construction materials used in buildings (e.g. gypsum, concrete, plasterboard, etc.) to enhance thermal mass. Note that saving thermal energy by phase change material plays an important role in cooling and heating of buildings.
- Porous materials such as screens, shelters, filters, porous ceramic and porous baffles can be used for controlling the thermal energy of building.

2. Mathematical modelling of transport phenomena in porous media

The governing equations for simulating the flow and heat transfer in porous media are presented in this section [88]:

2.1. Continuity equation

By volume averaging of the general continuity equation over a porous medium, the continuity equation can be presented in the following form:

$$\varepsilon\frac{\partial \rho_f}{\partial t} + \nabla.(\rho_f V) = 0 \tag{1}$$

where ρ_f, ε, t, and V are density of fluid, porosity, time, and velocity of flow, respectively. It is recalled that the porosity of a porous medium is defined as the ratio of void space volume to the total volume of the porous medium.

2.2. Momentum equation

There is a general model, known as Brinkman-Forchheimer-extended Darcy model, for simulating fluid flow through porous media which considers both the inertial and boundary influences, and the quadratic drag. This model can be presented in the following form:

$$\underbrace{\rho_f\left[\frac{1}{\varepsilon}\frac{\partial V}{\partial t} + \frac{1}{\varepsilon}\nabla\left(\frac{V.V}{\varepsilon}\right)\right]}_{\text{Convective development effect}} = -\nabla p + \underbrace{\frac{\mu}{\varepsilon\rho_f}\nabla^2 V}_{\text{Brinkman effect}} - \underbrace{\frac{\mu}{K}V}_{\text{Darcy effect}} - \underbrace{\frac{C_F\rho_f}{K^{\frac{1}{2}}}|V|V}_{\text{Forchheimer effect}}, \tag{2}$$

where p, K, and C_F are pressure, permeability, and Forchheimer coefficient, respectively. This equation is obtained through local volume averaging and matched asymptotic expansions. Moreover, the volume-averaged fluid velocity, $\vec{V}$, inside the porous layer with porosity ε is related to the Darcy velocity $\vec{v}$ through Dupuit-Forchheimer relationship, as $\vec{v} = \varepsilon\vec{V}$. Forchheimer coefficient, C_F, is given by the following relation:

$$C_F = \frac{1.75}{\sqrt{150\varepsilon^3}}. \tag{3}$$

2.3. Energy equation

Heat transfer through a porous medium can be simulated using energy equation. This equation can be presented for two conditions including local thermal equilibrium and non-local thermal equilibrium. For local thermal equilibrium, the temperature gradient at any location between the two phases in the porous media is assumed to be negligible

$$(\rho c)_m\frac{\partial T}{\partial t} + (\rho c)_f V.\nabla T = \nabla.(k_m\nabla T), \tag{4}$$

where $(\rho c)_m$ and k_m are the total heat capacity per volume and the thermal conductivity of the porous medium, respectively. These