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

Saman Rashidi[a], Javad Abolfazli Esfahani[b], Nader Karimi[c,d,*]

[a] Department of Mechanical Engineering, Semnan Branch, Islamic Azad University, Semnan, Iran
[b] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 91775-1111, Iran
[c] School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[d] School of Computing and Engineering, University of Missouri-Kansas City, Kansas City, MO 64110, United States

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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

* Corresponding author at: School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom.
*E-mail address:* Nader.Karimi@glasgow.ac.uk (N. Karimi).

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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 $\rho_f$, $\varepsilon$, 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:

$$\underbrace{\rho_f\left[\frac{1}{\varepsilon}\frac{\partial V}{\partial t} + \frac{1}{\varepsilon}\nabla\left(\frac{V.V}{\varepsilon}\right)\right]}_{\text{Convectivedevelopmenteffect}} = -\nabla p + \underbrace{\frac{\mu}{\varepsilon\rho_f}\nabla^2 V}_{\text{Brinkmaneffect}} - \underbrace{\frac{\mu}{K}V}_{\text{Darcyeffect}} - \underbrace{\frac{C_F\rho_f}{K^{\frac{1}{2}}}|V|V}_{\text{Forchheimereffect}}, \tag{2}$$

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 $\varepsilon$ 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 parameters can be calculated by:

$$(\rho c)_m = (1-\varepsilon)(\rho c)_s + \varepsilon(\rho c_p)_f, \tag{5}$$

$$k_m = (1-\varepsilon)k_s + \varepsilon(k)_f, \tag{6}$$

where subscripts s and f denote the solid and fluid phases, respectively. For non-local thermal equilibrium, there is a considerable temperature difference between fluid and solid phases in the porous medium. Hence, a separate energy equation should be written for each phase. For solid phase, the energy equation can be written in the following form:

$$(1-\varepsilon)(\rho c)_s\frac{\partial T_s}{\partial t} = (1-\varepsilon)\nabla.\,(K_s\nabla T_s) + h(T_f - T_s). \tag{7}$$

Further, this equation for fluid phase takes the form of

$$\varepsilon(\rho c_p)_f\frac{\partial T_f}{\partial t} + (\rho c_p)_f V.\,\nabla T_f = \varepsilon\nabla.\,(K_f\nabla T_f) + h(T_s - T_f), \tag{8}$$

where c and $c_p$ are the heat capacities of solid and fluid phases, respectively. The heat transfer coefficient, h, can be calculated by

$$h = \frac{6(1-\varepsilon)}{d_p}h^*. \tag{9}$$

An empirical equation can be used to calculate $h^*$ as follows:

$$h^* = \frac{d_p}{Nu_{fs}k_f} + \frac{d_p}{\beta ks}, \tag{10}$$

where β and dp are a constant and particle size, respectively. The value of β is equal to 10 in the case of spherical particles. Finally, the following equation can be used to calculate $Nu_{fs}$:

$$Nu_{fs} = \frac{0.255}{\varepsilon}pr^{\frac{1}{3}}\,\mathrm{Re}_p^{\frac{2}{3}}. \tag{10'}$$

The above equation is valid for $\mathrm{Re}_p < 10$. However, for smaller $\mathrm{Re}_p$, $\mathrm{Nu}_{fs}$ can be estimated in the range of 0.1–12.4.

## 3. Applications of the porous materials in building energy systems

### 3.1. Ground heat pumps

Ground heat pumps have been widely developed as heater and air-conditioner in commercial, institutional, and residential buildings [7]. These systems largely utilize the solar energy that has been stored in the shallow depth (around between 50 m and 400 m) of the ground and only a small part of their energy comes from a truly geothermal source [7]. Generally, ground heat pumps extract energy from the ground using borehole heat exchangers that can be placed in the ground horizontally or vertically [125,7]. Borehole heat exchangers include a number of boreholes in the form of a U-shape pipe. A heat transfer liquid is circulated in the pipe and exchanges heat with the ground. Usually, vertical boreholes are preferred in comparison with the horizontal ones as less ground areas are needed in this configuration [30]. Fig. 1 shows a vertical, borehole ground heat exchanger. Regardless of the configuration of the boreholes, the main purpose of their utilisation is to exchange heat with the ground, which is a natural porous medium.

Boreholes are grouted with materials that make a thermal contact between the pipes in the boreholes and the surrounding porous soil/rock. There are many factors affecting the performance of this system and therefore should be closely considered in the design and optimisation stage. These include the soil temperature distribution, humidity content, thermal properties, groundwater movement, and possible freezing and melting of water amount in the soil as a porous material. In reality, the boreholes in depth of 400 m may penetrate several geologic substrates containing unsaturated, semi saturated or fully saturated layers. Generally, the subsurface above the water table is an unsaturated zone in which pore includes both air and water. Below the water table, soil is saturated and there is groundwater that moves

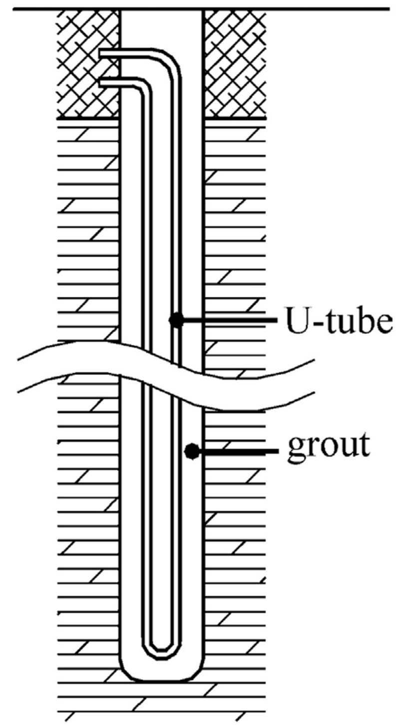


**Fig. 1.** Vertical borehole ground heat exchanger (Reprinted from Diao et al. [30] with permission from the publisher).

between the grains of geologic formations in response to hydraulic gradients. The characteristics of an unsaturated porous medium are very different to those of a fully saturated one. In a saturated zone, heat transfer is due to a coupled process of heat conduction in the solid matrix of soil and water in its voids and heat advection by motion of groundwater. However, there is no heat advection in an unsaturated porous medium. In the followings, an overview is given on the investigations done on saturated and unsaturated soil as apply to ground heat pumps.

#### 3.1.1. Experimental studies

Chen et al. [22] investigated experimentally heat and humidity transfers in an unsaturated soil during soil heat charging for a solar-soil source heat pump system. They concluded that the humidity transfer and the required time for reaching soil temperature stability are under the influence of the initial volumetric water content. Gao et al. [36] improved the thermal efficiency of a horizontal ground heat exchanger by using rainwater harvested in an unsaturated soil. The thermal conductivity of soil enhances by enhancing the level of humidity. Increasing the thermal conductivity is useful to improve the heat transfer and thermal efficiency of ground heat exchangers.

#### 3.1.2. Numerical/theoretical studies

Some researchers considered the ground as a saturated porous medium. Diao et al. [30] investigated analytically the effects of groundwater flow on the performance of geothermal heat exchangers used in ground heat pumps. They considered advection of groundwater in a saturated soil as a porous medium. It is noted that the heat transfer in aquifers may be considered as a coupled process of heat conductive through the solid zone and liquid in the pores and heat advection by flowing groundwater [30]. They found that liquid advection in the porous material may change considerably the temperature field [30]. Shang et al. [112] developed a numerical model to investigate the geo-temperature change in operation and recovery periods of ground-source heat pumps. They used the classical theory of transport in porous media in their model and considered the porous material as a saturated medium. Shang et al. [112] concluded that soil porosity, thermal conductivity, and backfill materials can significantly affect the thermal recovery of soil. It was observed that the process of soil temperature recovery accelerates as the soil thermal conductivity increases and the soil porosity decreases [112]. Given that the performance of the unit is heavily dependent upon the soil temperature recovery, this was an important finding. In a numerical work, Bottarelli et al. [13] coupled the phase change materials and ground heat exchangers on the basis of a drainage trench. The trench dug was filled with encapsulated phase change materials. Ground was modelled as a porous medium (saturated soil) in the numerical simulations. They showed that phase change materials offer more suitable and stable values of the working liquid temperature in comparison to the cases without this material. Lous et al. [74] investigated numerically flow and heat transport for a profound borehole heat exchanger in a synthetic aquifer system. They used a saturated porous medium with variable thermal conductivity. They performed a sensitivity analysis to specify the parameters affecting the transport phenomena and thermal performance of this system. They found that in borehole heat exchangers, porosity, geothermal flux, and thermal conductivities of the solid and the grout have the significant influences on the heat exchange process between the heat exchanger and the surrounding soil. However, the factors related to convection heat transfer including specific flux and thermal dispersion have only minor influences on borehole heat exchangers for small groundwater velocity ($< 10^{-7}\ \mathrm{m\,s^{-1}}$) typical of sedimentary aquifer system [74]. Erol et al. [33] investigated analytically the temperature distribution in the ground (saturated soil and rocks) for single and multi-boreholes heat exchangers. They considered discontinuous heat extraction, thermal advection, conduction, and dispersion in porous material, while in earlier investigations the problem had been solved only under continuous heat loads. Erol et al. [33] took Green's function approach to solve thermal advection, conduction, and dispersion equations in porous media. These authors observed a linear relation between thermal conductivity of the soil and the rate of heat extraction for multi-borehole heat exchangers [33]. Yang et al. [131] investigated numerically the influences of soil freezing on temperature distributions of soil near the ground heat exchangers. Under saturated condition, they found that the soil temperature with freezing is higher in comparison to unfreezing one and accordingly, freezing increases the heat transfer efficiency of ground heat exchanger. As a result, the soil freezing should be taken into account in the design of ground heat exchangers for cold regions. Chen et al. [23] investigated the heat transfer of a vertical ground heat exchanger in a saturated soil by numerical modelling and a multiple regression approach. They presented nine equations by regression model with the effects of nine parameters. These included thermal conductivity, volumetric heat capacity, input flow, input water temperature, soil porosity, Darcy's speed, and borehole profundity. Chen et al. observed that the efficiency of a ground heat exchanger is mainly affected by input water temperature, input flow, Darcy's speed, and borehole profundity. Nonetheless, the volumetric heat capacity and soil porosity have negligible effects on the efficiency of a ground heat exchanger.

Unsaturated porous media have been also investigated by modellers of ground-source heat pumps. Gopalakrishnan and Manik [38] used finite difference method to predict the isothermal soil moisture profiles and the motion of soil moisture above the ground water table. Evangelides et al. [34] estimated analytically the unsaturated soil humidity profile and obtained soil water diffusivity by using this profile. They found that the accuracy of the results is extremely dependent upon the soil humidity profile length and infiltration measurements. Wang et al. [126] investigated mathematically the effects of heat and humidity transports on the specifications of the ground heat pump systems operating in unsaturated soil. They considered sand, loam, and clay as porous materials. Wang et al. [126] found that heat diffusion in sand is superior to loam and clay while, the humidity diffusions of sand and clay are superior to loam. Most recently, Shang et al. [111] repeated the analysis of Shang et al. [112] for an unsaturated medium. They reported that the unsaturated porous model has a greater agreement with the experimental results in comparison with the saturated one [111]. Moreover, these authors found that the soil temperature reduces by an increase in the infiltration impact factor in shallow soil. It should be noted that the infiltration process in soil humidity causes the horizontal or vertical flows of humidity inside the soil under influences of irrigation or rainfall. However, irrigation and rainfall are significant drivers of the soil–liquid motion [111].

#### 3.1.3. Combined experimental and numerical studies

Zhao et al. [132] investigated experimentally and theoretically the heat transfer of saturated soil around a coaxial ground heat exchanger. They used theoretical models to mitigate the limitations of their experimental device. These authors observed that in winter days, thermal conductivity of the soil near the coaxial ground heat exchanger increases with enhancing moisture amount. However, an opposing behaviour was observed on summer days. Vasilyev et al. [124] investigated the thermal influence of ground humidity condensation/evaporation on heat transfer in the unsaturated sand out of a borehole. They found that the ground pore humidity condensation has a considerable effect on the efficiency of ground heat pumps. It should be stated that the pore humidity condensation or evaporation leads to a quick reduction in the ground heat conduction and obstructing the heat flow to the borehole. This, subsequently, affects the efficiency of ground heat pumps.

#### 3.1.4. Methods for determining thermal conductivity and thermal resistance of soil

Thermal conductivity and thermal resistance of soil as a porous material are major factors in the sustainable and technical fabrication of groundsource heat pumps [125]. A commonly used technique to measure these parameters is the thermal response test (TRT). Generally, a TRT system contains a borehole, circulation pump, pipe system, a cooler or heater with fixed power rate, and continuous recording of the input and output temperatures of the water [125]. The information of TRT (i.e. temperature distribution in the borehole at a certain energy extraction or injection) can be used to measure the effective thermal conductivity of the soil and the thermal resistance of the borehole. Wagner et al. [125] performed a numerical sensitivity analysis on the thermal response tests to investigate the primitive influences. They studied the effects of different parameters on the effective thermal conductivity and the borehole resistance. These parameters included the location of the U-shaped pipes of borehole heat exchangers, primary thermal distribution, and thermal dispersion. They reported that the influences of shank spacing and the primary non-uniform thermal distribution upon the effective thermal conductivity and the borehole resistance are negligible. Yet, the influences of thermal dispersion were shown to be rather significant. Raymond et al. [101] developed a numerical model to analyse a ground heat exchanger with the groundwater flow and employed the numerical simulator HydroGeoSphere to manage thermal response tests. They used saturated porous material with solid thermal conductivity of $3.57\ \mathrm{W\,m^{-1}\ k^{-1}}$. These authors applied the Kelvin line-source equation to describe conductive heat transfer in porous medium. Compared to that offered by the line source equation, Raymond et al. [101] improved the representation of the physical processes available in TRT, without any noticeable enhancement in the computational time. Choi and Ooka [24] investigated the influences of natural convection on the thermal response test performed in a saturated porous medium. They performed a comparison between gravel-backfilled and cement-grouted borehole heat exchangers. It was concluded that the thermal resistances of borehole for the gravel-backfilled and cement-grouted borehole heat exchangers reduce by about 9.8% and 8.7%, respectively through doubling the heat injection rate.

#### 3.1.5. Reviews of literature

Carotenuto et al. [17] reviewed the numerical models presented for simulating the thermo-fluid phenomena occurring in low enthalpy geothermal energy systems. The results of this modelling provide the data for estimating the ground thermo-physical properties from the analysis of thermal response tests. Moreover, these results can be used to predict hour by hour (or short term) responses of the ground to continuously changing energy loads. Their review showed that the research activities on the numerical study of convective phenomena involving ground water filled boreholes are limited and need more attentions. Li and Lai [69] reviewed analytical methods to model heat transfer from vertical ground heat exchangers by considering the space and time scales. They discussed the analytical methods to model heat and humidity transports inside the ground (soil) that can be considered as a porous medium. These authors concluded that all available analytical models feature limitations of time scales for determining the temperature response of a big matrix of ground heat exchangers.

#### 3.1.6. Summary

As a concluding remark to this section, it is emphasised that ground-source heat pumps as renewable systems have a significant potential to use in building energy systems [69]. This is due to their energy saving and environment friendly characteristics [69]. The soil temperature directly affects the performance of these systems and hence modelling heat transfer in soil medium is an essential step in design of these systems. Table 1 summarizes the research articles published on the applications of porous materials in ground heat pump systems. It is worth mentioning that despite the advantages of geothermal systems such as high efficiency, remarkable energy conservation, and low operating cost, currently geothermal energy has a contribution less than 1% of the total primary energy generated worldwide [48]. This shows the requirement of more activities in this field. In mathematical modelling, most of the existing works are concentred with constant thermal properties for soil. Investigations of the influence of varying soil thermal properties on the characteristics of the ground heat pumps are rather seldom. Variable soil thermal properties are more realistic [74] and hence this point should be considered in future investigations. Regarding this issue, Huang [45] investigated the effects of different parameters including thermal conductivities of soil and grout material and pipe length on the efficiency of the ground heat exchanger. They reported that a larger value of soil thermal conductivity causes better heat transfer performance of the ground, and subsequently amplifies of capability of the system for delivering the heat into the soil. Márquez et al. [77] suggested a simple and inexpensive approach to measure the thermal diffusivity of a given soil by using its temperature. Further, the influence of phase changes in the ground pore moisture on the efficiency of ground heat pumps is important for designing adaptable systems. Consideration of evaporation and moisture migration in soil is an important issue in the modelling of ground-source heat pumps. For example, it has been shown that the pore moisture evaporation leads to a quick reduction in the ground heat conduction and blocks the heat flow to the borehole [124]. It is therefore recommended to include this point for future studies in this field.

### 3.2. Insulation systems

Thermal energy is lost from buildings with various rates related to the shape and structure of the building. About 80% of the total energy expense in buildings is related to water and space heating (http://www.qualibuild.ie/heat-lost-building/). These heat losses degrade comfort levels and impose additional costs during the life time of the building. Heat losses in buildings occur through convection, conduction, and radiation. Fig. 2 shows the area of energy losses in a typical building. As shown in this figure, the main losses occur through the floor, roof, walls, and windows.

Most of thermal energy is lost through un-insulated components of a building. Choosing the right material for insulating the components of building reduces the energy consumption in building. 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. Some researchers have evaluated the potentials of this material to insulate the components of a building. The relevant experimental and numerical studies are presented here in two separate sections.

#### 3.2.1. Experimental studies

Levinson et al. [63] obtained the relationship between air-velocity and the thermal conductivity of fiberglass (a porous material) insulation in an internally insulated duct by obtaining the inlet-to-outlet temperature drop of warmed air passing inside the duct. They found that the measured conductivity of a flexible channel low density inner fiberglass-blanket insulation is intensified by about 140% as the duct air velocity increases from 0 to 15 m/s. Dimoudi et al. [29] conducted experiments on a wall fabricated by two main sub-layers containing the dynamic insulation and ventilated outer envelope sub-layers. The dynamic insulation sub-layer included substrates of porous materials that guide the air into the room. Their results indicated that the conduction heat losses through the wall decreases with an enhancement of the applied pressure difference between the internal and external sections of the room. Peuhkuri et al. [98] investigated experimentally moisture transfer inside insulation porous materials. Some non-hygroscopic materials such as rockwool and very hygroscopic materials such as cellulose insulation were investigated in this study. Peuhkuri et al. concluded that the temperature gradient in porous material leads to drive the humidity from the warm side towards the cold one. Mozumder and Singh [82] demonstrated experimentally that the solar heat flux on roof could be decreased by applying a porous insulation substrate. Insulation substrate was made by fly ash pieces. They further introduced fly ash as a great insulation material with decent structural stability. Zhang et al. [134] introduced a novel type of porous thermal insulation material through applying coal fly ash to insulate the walls of a building. They built this material by slip casting and foaming technique. The thermal conductivity of the proposed material was as low as $0.0511\ W\,m^{-1}\ K^{-1}$. Zhang et al. [134] recommended coal fly as an environment-friendly material, proper for wall application for the purpose of thermal insulation of walls. Buratti et al. [16] investigated the thermal efficiencies of novel basalt fibre insulation layers used in buildings. They measured the thermal conductivity of this material and reported that in the range of $0.030–0.034\ W\,m^{-1}\,K^{-1}$. Further, through using this material, the heat transfer in walls decreases between 20% and 40%. Li et al. [70] investigated the thermophysical characteristics of fibre/powder hybrid core materials as vacuum insulation panel (VIP). Fibre/powder hybrid core materials have a great porous nature with a large porosity (80–90%) and a fine average pore size in the range of 19.0–181.1 nm. The corresponding VIP of these materials has a low density in the range of $170–298\ kg\,m^{-3}$. They nominated fibre/powder hybrid core materials for vacuum insulation panels in building section. It is noted that vacuum insulation panels have low thermal conductivity (less than 50% of still air) and also a very thin width, which is supernatural appropriate for space constrained demands [11,86]. Fig. 3 compares the thermal conductivity and insulation width for the thermal resistance of some porous materials at a fixed thermal resistance ($5\ m^2\ KW^{-1}$). As shown in this figure, the width of vacuum insulation panel is about six to ten times lower than other insulation materials for a fixed thermal resistance ($5\ m^2\ KW^{-1}$).

Marangoni et al. [76] used a porous layer with low thermal conductivity on ceramic tiles to reduce penetration of heat into the building. This layer further decreases the thermal conductivity of the tile, which already has thermal insulation properties for building applications. The porous layer was made by $Si_3N_4$ and gypsum. Marangoni et al. [76] reported that the porosity of the layer should be tailored in order to have both adequate mechanical strength and low

**Table 1**
Research on the applications of porous materials in ground heat pumps.

| Authors | Type of research | Type of porous material | Spatial dimensions | Main results |
|---|---|---|---|---|
| Diao et al. [30] | Analytically | Saturated soil | 2D | The temperature field in the porous material may be changed considerably by liquid advection. |
| Gopalakrishnan and Manik [38] | Numerically | Saturated soil | 1D | They predicted the isothermal soil moisture profiles and the motion of soil moisture above the ground water table. These information are necessary for designing ground heat exchangers. |
| Zhao et al. [132] | Experimentally/ Theoretically | Saturated soil | 2D | In winter days, thermal conductivity of the soil near the coaxial ground heat exchanger increases with enhancing moisture amount. However, an opposing behaviour was observed on summer days. |
| Evangelides et al. [34] | Analytically | Unsaturated soil | 1D | They estimated analytically the unsaturated soil humidity profile and obtained soil water diffusivity by using this profile.<br>These information are necessary for designing ground heat exchangers. |
| Shang et al. [112] | Numerically | Saturated soil | 3D | The soil porosity, thermal conductivity, and backfill materials can significantly affect the thermal recovery of soil.<br>The process of soil temperature recovery accelerates as the soil thermal conductivity increases and the soil porosity decreases. |
| Raymond et al. [101] | Numerically | Saturated porous material with solids thermal conductivity of 3.57 $W\,m^{-1}\,k^{-1}$ | 2D | They developed a numerical model to analyse a ground heat exchanger with the groundwater flow.<br>They improved the representation of the physical processes available in TRT, without any noticeable enhancement in the computational time. |
| Vasilyev et al. [124] | Theoretical/ Experimental | Unsaturated sand soil | 3D | The ground pore humidity condensation has a considerable effect on the efficiency of ground heat pumps.<br>The pore humidity condensation or evaporation causes a quick reduction in the ground heat conduction and obstructing the heat flow to the borehole. |
| Chen et al. [22] | Experimentally | Unsaturated soil | – | The humidity transfer is under the influence of the initial volumetric water content. |
| Yang et al. [131] | Numerically | Saturated sandstone, sand, and clay | 2D | Under saturated condition, it was found that the soil temperature with freezing is higher in comparison to unfreezing one and accordingly, freezing increases the heat transfer efficiency of ground heat exchanger. |
| Erol et al. [33] | Analytically | Saturated soil and rocks | 3D | They determined analytically the temperature distribution in the ground (saturated soil and rocks) for single and multi-boreholes heat exchangers. They observed a linear relation between thermal conductivity of the soil and the rate of heat extraction for multi-borehole heat exchangers. |
| Bottarelli et al. [13] | Numerically | Saturated soil | 2D | They coupled the phase change materials and ground heat exchangers on the basis of a drainage trench.<br>Phase change materials offer more suitable and stable values of the working liquid temperature in comparison to the cases without this material. |
| Lous et al. [74] | Numerically | Saturated porous medium with variable thermal conductivity | 3D | The factors related to convection heat transfer including specific flux and thermal dispersion have only minor influences on borehole heat exchangers for small groundwater velocity ($< 10^{-7}$ $m\,s^{-1}$). |
| Chen et al. [23] | Numerically | Saturated soil | 3D | The efficiency of a ground heat exchanger is mainly affected by input water temperature, input flow, Darcy's speed, and borehole profundity.<br>The volumetric heat capacity and soil porosity have negligible effects on the efficiency of a ground heat exchanger. |
| Wang et al. [126] | Mathematically | Unsaturated sand, loam, and clay | 3D | Heat diffusion in sand is superior to loam and clay while, the humidity diffusions of sand and clay are superior to loam. |
| Gao et al. [36] | Experimentally | Unsaturated sandy soil | – | The thermal conductivity of soil enhances by enhancing the level of humidity. |
| Choi and Ooka [24] | Experimentally | Saturated gravel and cement | – | The thermal resistances of borehole for the gravel-backfilled and cement-grouted borehole heat exchangers reduce by about 9.8% and 8.7%, respectively through doubling the heat injection rate. |
| Shang et al. [111] | Numerically | Unsaturated soil | 3D | The soil temperature reduces by an increase in the infiltration impact factor in shallow soil.<br>The infiltration process in soil humidity causes the horizontal or vertical flows of humidity inside the soil under influences of irrigation or rainfall. |

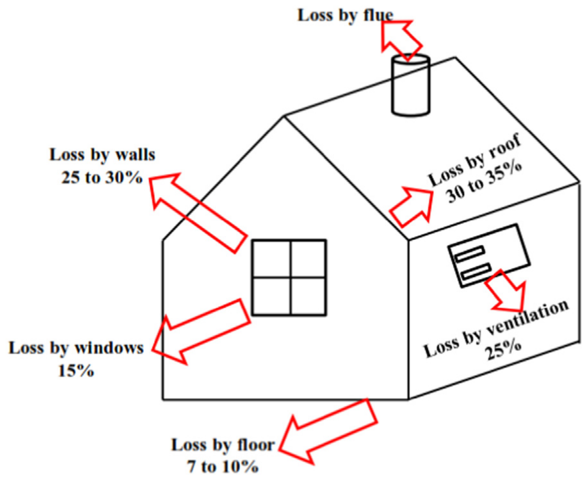


**Fig. 2.** Area of energy losses in building.

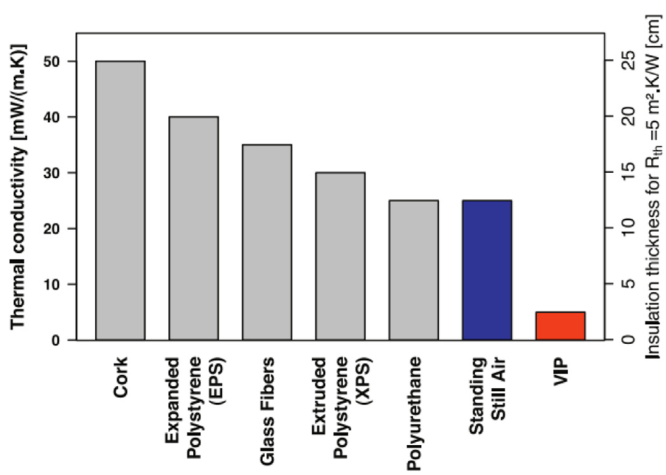


**Fig. 3.** Thermal efficiency of insulation materials: thermal conductivity and insulation width for a fixed thermal resistance of 5 $m^2$ $KW^{-1}$ (Reprinted from Bouquerel et al. [14] with permission from the publisher).

value of thermal conductivity. Zhang et al. [135] measured the moisture amount in a porous insulation material using a hot wire probe. It is important to note that the acquired humidity can lead to the deduction of insulation efficiency. Accordingly, it is important to monitor the humidity amount in porous insulation materials with high accuracy. The results of Zhang et al. [135] showed that the hot-wire method is able to measure both the water and the ice amounts with an appropriate accuracy. It is worth mentioning that hot wire technique is a well-established dynamic measurement method. It is based on the measurement of the temperature growth in a special distance from a hot wire as linear heat source placed in the experiment material [40]. Usually, this method is used to measure the thermal conductivity of porous materials [40]. It is assumed that the hot-wire have a constant and uniform output along the length of experiment material. Accordingly, the thermal conductivity may be obtained directly from the resulting change in the temperature over a special time interval. Zhang et al. [136] measured the humidity amount based on the relationship between thermal conductivity and humidity amount. Aside from hot wire technique, Lian et al. [71] measured the thermal conductivity of porous insulation material by laser flash technique. Their results showed that this technique is a reliable and quick measurement method to measure the performance of low thermal conductivity materials.

#### 3.2.2. Numerical/theoretical studies

Alongi and Mazzarella [3] investigated numerically the heat transfer between an air flow and the solid matrix at microscopic scale of a porous material as a dynamic insulation in building envelopes. They found that the contribution of thermal dispersion on the energy balance is negligible for the low values of Peclet number. It should be clarified that a dynamic insulation systems have been developed on the basis of integration between ventilation plant and building structures [3]. In such systems, instead of being delivered or extracted through ducts or openings, ventilation air is forced to go slowly through dedicated building envelope porous walls, which consequently act as heat exchangers [47]. Hao et al. [41] optimized porosity distribution of insulation materials by employing variational technique. They used this method to determine the optimum distribution of porosity in porous media.

#### 3.2.3. Combined experimental and numerical studies

Jim and Tsang [51] evaluated experimentally and theoretically, the influences of soil, rockwool, and drainage layers on a roof as insulating materials in the moist-tropical area. They used a theoretical model to investigate heat diffusion procedure of these materials. These authors introduced the plastic drainage sheet with abundant inner air spaces as a greatly efficient thermal insulation substrate. Hoseini et al. [44] investigated the deformation and thermal resistance of aerogel blanket insulation material subject to a uniaxial compression. They showed that aerogel blankets retain the effective thermal insulation characteristics under compression. Aerogel materials have a porous structure with high surface area and pore volume. They have a small density and large porosity (more than 90%), which introduce them as a great thermal insulators [1]. Some researchers have investigated the thermal properties of this material. Table 2 presents a summary of the available research articles on aerogel composites and some obtained results.

#### 3.2.4. Reviews of literature

Vacuum insulation panel is composed of an open porous core of fumed silica covered by multiple metallized polymer sheeted substrates. This panel has a thermal conductivity in the range of 3–4 $mW\,m^{-1}\,K^{-1}$ and can be used as an insulation material in buildings [49]. Alam et al. [2] conducted a review on the vacuum insulation panels for building construction industry. For more information about these panels, readers are referred to this article. It should be stated that a closed-porous material can be used as possible vacuum insulation material [95]. Closed-porous material has a closed-porosity structure and therefore in this material, it is no longer required to use a panel envelope to maintain an inner vacuum. This type of insulation material is basically homogenous and achieves its high performance thermal insulating qualities due to vacuum technology in its closed-porous structure (See Fig. 4).

Bouquerel et al. [14] performed a comprehensive review on heat transfer simulations in vacuum insulation panels consisting of nanoporous silicas, granular aerogels, monolithic aerogel, and nanoporous powders. It is worth mentioning that nanoporous silica has a low thermal conductivity, at atmospheric pressure, and a much lower conductivity subject to primitive vacuum. Hence, it is strongly recommended for the use in buildings as vacuum insulation panels [115]. Fig. 5 shows the application of nanoporous core material in a vacuum insulation panel.

#### 3.2.5. Summary

Table 3 summarizes the existing investigations performed on the applications of porous insulation materials in buildings. It is emphasised here that the use of new technologies such as solar photovoltaics or wind energy is far less cost-effective than insulation retrofit for buildings [78]. Thermal resistance, thermal conductivity, and insulation layer thickness are the main factors affecting the performance of insulation materials [15]. The insulation thickness is a limiting factor in urban regions where the living space is limited [15]. Most of insulation materials are composite. Determining the relationship between

**Table 2**
A summary of available research on aerogel composites (Reprinted from Hoseini et al. [44] with permission from the publisher).

| Researcher(s) | Points |
|---|---|
| Cuce et al. [28] | 1. Determined optimum width of aerogel blanket insulation to achieve the maximum energy storage and thermal comfort<br>2. Obtained relation between annual energy apply and insulation width |
| Gupta and Ricci [39] | 1. Prepared aerogel/epoxy composites<br>2. Investigated the composites with density of 980 and 1070 $kg\,m^{-3}$ under pressing loads of 0–120 MPa<br>3. Detected some cracks without strength loss at 25% pressing strain |
| Bardy et al. [8] | 1. Examined samples of prototype and product-line aerogel insulating blankets for thermal conductivity and pressing strain at additive loads about 1.2 MPa<br>2. Concluded that the prototype sample has better resistance under pressing and recovers to its original width upon decompression |
| Shi et al. [113] | 1. Prepared ceramic-fibre- reinforced $SiO_2$ aerogel<br>2. Studied the composite characteristics under pressing about 1.5 MPa for in-plane and 16 MPa for out-of-plane pressing at large temperatures about 900 °C<br>3. Concluded that in-plane Young's modulus enhances with temperature, while out-of plane modulus reduces with temperature |
| Wu et al. [128] | 1. Prepared multilayer fibre-reinforced aerogel composites applying $SiO_2$ aerogel and glass fibre<br>2. Applied unit cell method to simulate the conduction in the composite<br>3. Enhanced the mechanical strengths of the aerogel composites by incorporating multi-substrate aligned fibres and aerogels<br>4. Investigated the influence of fibre alignments on thermal conductivity and pressing and bending strengths of the composites |
| Neugebauer [87] | 1. Decreased the thermal conductivity of a bed of granular aerogels under pressing<br>2. Recommended thermal resistance can be increased by controlling the load on the beds of granular aerogels |
| Joly et al. [52] | 1. Presented the aerogel-based composite material with high performance and low cost.<br>2. Determined the thermal conductivity, the pressing stress and the tensile strength.<br>3. Recommended this material for the European insulation market.<br>4. Reported that the thermal conductivity of this material was below 0.016 W/(m K). |
| Muthuraj et al. [83] | 1. Used elium acrylic resin/cellulose nanofiber based composite aerogels.<br>2. Investigated mechanical and thermal insulation characteristics of this material.<br>3. Reported this material has a good mechanical, thermal stability, and thermal insulation characteristics. |
| Jia et al. [50] | 1. Prepared aerogel/expanded perlite composite as building thermal insulation material.<br>2. Concluded that aerogel can distributed within porous structure of expanded perlite to has good characteristics of the thermal insulation efficiency and pore structure of expanded perlite.<br>3. Concluded that the thermal conductivity of aerogel/expanded perlite composite is under the influence of particle diameter. |
| Fan et al. [35] | 1. Prepared polyimide/carbon nanotube composite aerogels<br>2. This material has the controllable porous structures.<br>3. Recommended this material with good characteristics including small density of 0.1 $g\,cm^{-3}$, enhanced compression modulus of 33.5 MPa, and high thermal stability of 580 °C. |

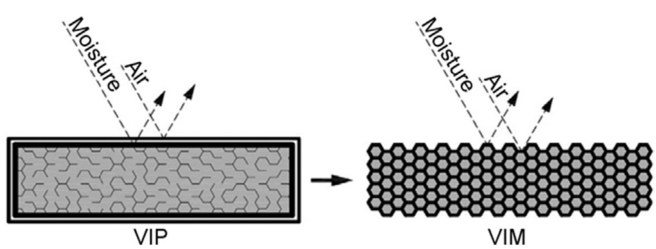


**Fig. 4.** Closed-porous materials as vacuum insulation material (VIM) (Reprinted from Baetens et al. [5] with permission from the publisher).

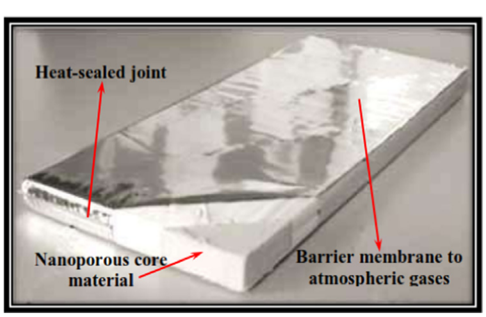


**Fig. 5.** Application of nanoporous core material in a vacuum insulation panel [120].

compression, deformation, thickness, and thermal performance of these materials is important as it has direct influences upon the thermal performance of the building. However, this point has not been investigated in enough depth in the previous studies. Hence, application of porous materials in dynamic insulation system used in buildings has significant potentials for future investigations. Nano-porous heat insulation materials are excellent candidate to save energy in buildings due to their great heat-insulating characteristics and light weigh. Finally, further studies on inorganic porous insulation materials such as geopolymer foam are strongly recommended due to their environmentally friendly characteristics.

### 3.3. Roof cooling

Buildings are exposed to solar heat fluxes. Due to their footprint, they may receive large amounts of solar radiation, which is subsequently converted to heat and penetrates into the building. Traditionally, roofs are made of materials with moderate to high absorption coefficients such as asphalt, clay, tar, etc. in some mid and high latitude regions [114]. These materials are cheap and easy to install but they absorbs much of the input solar radiation and transport the resultant heat to the buildings. As an example, asphalt shingles have solar reflectivity in the range of 0.05–0.2, which can enhance the temperature of roof surface by about 27 ℃ [61]. This can conveniently cause an air conditioning problem. In order to fix these problems, a substrate of humid porous material such as humid sand substrate can be laid on the roof. This is to balance the heating of solar radiation and outdoor air temperature, which has passive cooling influence. Using humid porous materials on the surface of the roof results in cooling influences caused by the passive water evaporation. When heat transfer occurs between upper surface of the roof and atmosphere, humidity diffuses from the internal substrates to the surface and evaporates in there and therefore generates a cooling effect. Fig. 6 shows the cooling mechanism of a porous roof. In this roof, rainwater penetrates and is stored within the porous substrate. This water evaporates through exposure to sunlight during the day. When evaporation occurs, the surface temperature of the porous substrate reduces due to the latent heat being released. Moreover, when the roof is exposed to considerable humidity during night time or on cloudy days, the porous substrate adsorbs

**Table 3**
Research on the applications of porous insulation materials in buildings.

| Authors | Type of research | Type of porous material | Spatial dimensions | Main results |
|---|---|---|---|---|
| Levinson et al. [63] | Experimentally | Fiberglass | – | The measured conductivity of a flexible channel low density inner fiberglass-blanket insulation is intensified by about 140% as the duct air velocity increases from 0 to 15 m/s. |
| Dimoudi et al. [29] | Experimentally | Breathing materials | – | The conduction heat losses through the insulated wall decreases with an enhancement of the applied pressure difference between the internal and external sections of the room. |
| Peuhkuri et al. [98] | Experimentally | Non-hygroscopic materials (e.g. rock wool) and very hygroscopic materials (e.g. cellulose insulation) | – | The temperature gradient in porous material leads to drive the humidity from the warm side towards the cold one. |
| Jim and Tsang [51] | Experimentally/ theoretically | Soil, rockwool and drainage layers | 1D | The plastic drainage sheet with abundant inner air spaces is a greatly efficient thermal insulation substrate. |
| Mozumder and Singh [82] | Experimentally | Fly ash pieces | – | The solar heat flux on roof could be decreased by applying a porous insulation substrate.<br>The fly ash is a great insulation material with decent structural stability. |
| Zhang et al. [134] | Experimentally | Fly ash | – | Coal fly is an environment-friendly material and is proper for wall application for the purpose of thermal insulation of walls. |
| Buratti et al. [16] | Experimentally | Basalt fibre | – | The basalt fibre insulation layers can be used in buildings.<br>The thermal conductivity of this material and reported that in the range of 0.030–0.034 W $m^{-1}$ $K^{-1}$.<br>The heat transfer in walls decreases between 20% and 40% by using this material. |
| Alongi and Mazzarella [3] | Numerically | Rock wool | 2D | The contribution of thermal dispersion on the energy balance is negligible for the low values of Peclet number. |
| Hao et al. [41] | Numerically | Porous material with different thermal conductivity | 1D/2D | The variational technique can be used to determine the optimum distribution of porosity in porous media. |
| Hoseini et al. [44] | Analytically/ Experimentally | Aerogel blanket | 3D | Aerogel blankets retain the effective thermal insulation characteristics under compression.<br>Aerogel materials have a small density, large porosity (more than 90%), and small thermal conductivity (about 0.016–0.040 W $m^{-1}$ $K^{-1}$), which introduce them as a great thermal insulators. |
| Li et al. [70] | Experimentally | Fibre/powder hybrid core materials | – | The fibre/powder hybrid core materials can be used as vacuum insulation panels in building section. Note that the vacuum insulation panels have low thermal conductivity (less than 50% of still air) and also a very thin width, which is supernatural appropriate for space constrained demands. |
| Marangoni et al. [76] | Experimentally | $Si_3N_4$ and gypsum | – | They used a porous layer with low thermal conductivity on ceramic tiles to reduce penetration of heat into the building.<br>The porosity of the layer should be tailored in order to have both adequate mechanical strength and low value of thermal conductivity. |

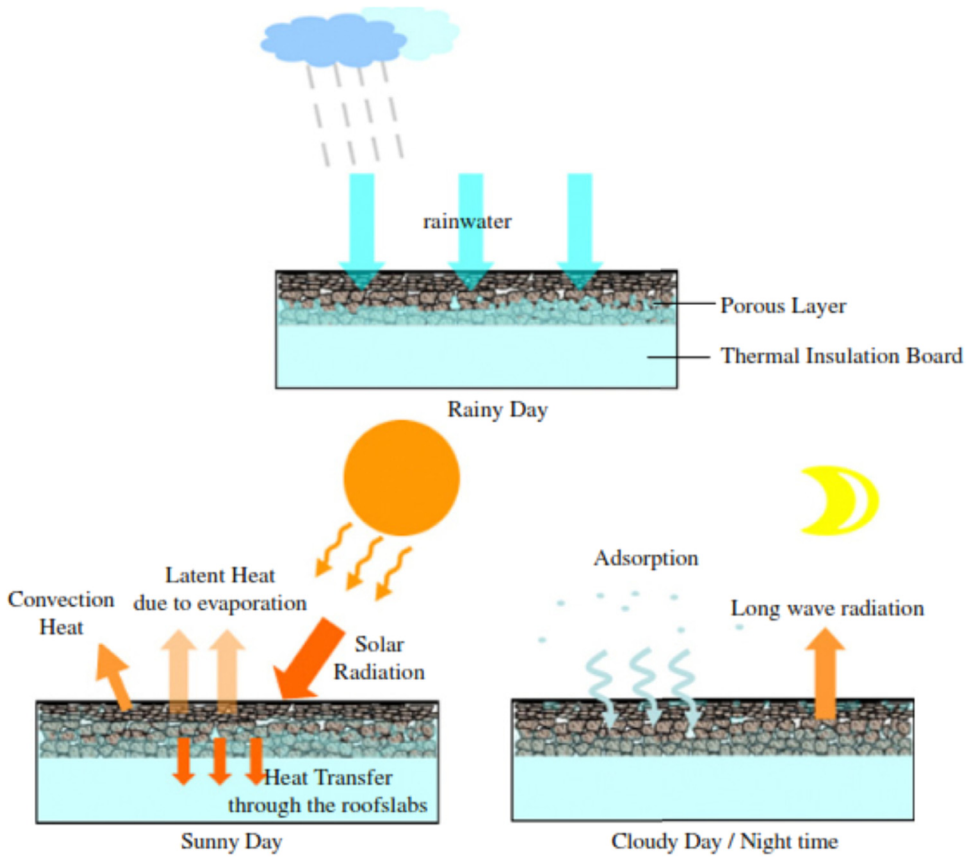


**Fig. 6.** Cooling mechanism of the porous roof (Reprinted from Wanphen and Nagano [127] with permission from the publisher).

humidity from the atmosphere and continues to reduce the temperature of the roof materials.

There exist some experimental and numerical investigations on this idea, which are reviewed in the following sections.

### 3.3.1. *Experimental studies*

Ibrahim et al. [46] investigated experimentally the efficiency of porous ceramic evaporators used as cooling systems in buildings. They observed a maximum cooling of about 224 $W\,m^{-2}$ by using porous ceramic evaporator with large porosity. These authors stated that the porous ceramic in direct evaporative cooling has considerable potentials for buildings' applications. Okada et al. [91] prepared porous ceramics by mixing the allophane and vermiculite for anti-heat island effect. They found this material useful as water-retaining materials to prevent "heat island" effects. Wanphen and Nagano [127] examined experimentally the evaporative cooling influences of several non-porous and porous materials in roofs. These materials were pebbles, silica sand, siliceous shale, and volcanic ash. They observed that siliceous shale has great potential for decreasing the daily mean surface temperature more than 8.63 °C. Vardoulakis et al. [123] investigated the potential application of Aluminium modified clays as solar coolers of roof surfaces. They concluded that during day and night times with relative humidity of 55%, the maximum temperature inside the pillared montmorillonite was 6.5 °C lower than that inside a typical soil sample. This was due to the evaporative cooling and desorption with minor effect of solar reflection. The findings of Vardoulakis et al. [123] showed the capability of aluminium pillared clays to decrease the roof surface temperatures. Gentle et al. [37] introduced polymeric mesh as a suitable material for cool roofs. Polyethylene mesh is a porous material and has an ability to forcefully reduce convective gain at night time and to have a great black body transfer that nominates it appropriate for applying in radiative cooling systems. Crawford and da Silva [27] investigated experimentally the potentials of a roof based evaporative system for decreasing the thermal loadings imposed on the internal space of a building. The vaporization system in this research was fabricated by a porous membrane joint to a water storage. Crawford and da Silva [27] showed that the salt was deposited as the water vaporized in the system. This blocks the pores, leads to decrease in vaporization rate from porous membrane and accordingly affects the cooling ability of the system. Shokri Kuehni et al. [114] studied experimentally the capability of an evaporative layer of porous material for decreasing the roof surface temperature. They used three types of sand with different particle size distributions. The results of their experiment for surface temperatures of sand with different sizes are depicted in Fig. 7. The colour map indicates the temperature. As shown in this figure, the surface temperature enhances by increasing the particle size. In interpreting this figure, it should be noted that the capillary length between the receding dehumidifying front and the evaporation surface decreases with an increase in the particle size. This causes an earlier cutting of the hydraulic pathways between the saturated region at the bottom and the surface. Accordingly, the evaporation surface dries out by disrupting the liquid connections and this leads to an increase in the surface temperature.

### 3.3.2. *Numerical/theoretical studies*

Liu et al. [72] studied analytically the moisture migration in unconsolidated sand, unsaturated with water. They evaluated the cooling influence induced by water evaporation when it was utilized as a cooling system for room air-conditioning. They found that evaporation on the free surface and also within the bed enhance as relative humidity decreases and ambient temperature increases. This has a main contribution in the variation of temperature gradient that affects the performance of the system. Chen and Liu [20] and Chen [19] conducted a thermal analysis for the cooling effects of a porous evaporative layer

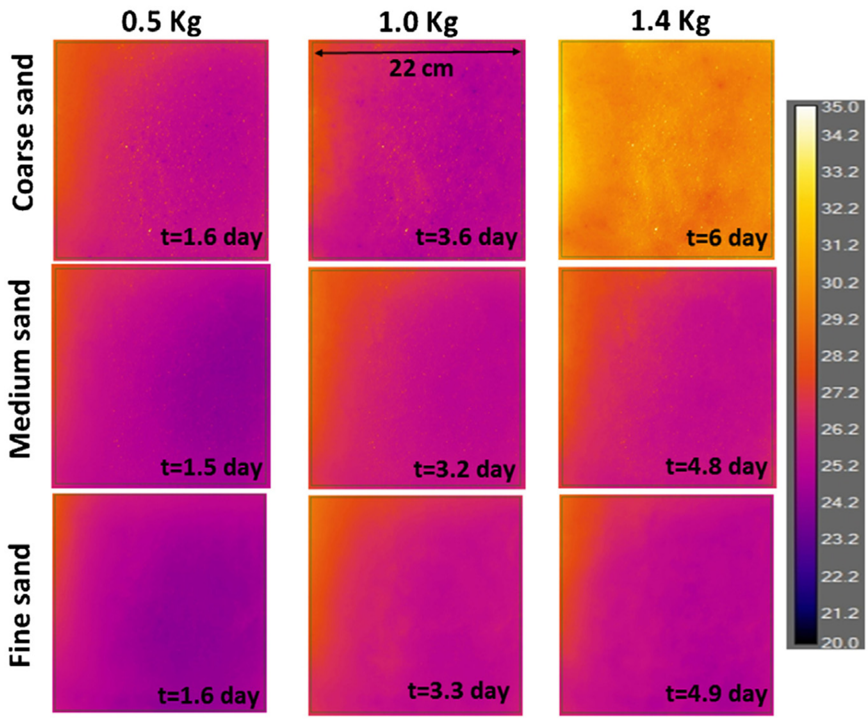


**Fig. 7.** Surface temperature of the coarse (upside row), medium (middle row), and fine sand (bottom row) during times from the beginning of the tests (Reprinted from Shokri Kuehni et al. [114] with permission from the publisher).

applicable to buildings. They showed that cooling of the porous evaporative layer increases as the ambient relative moisture reduces or the ambient temperature enhances. They further found that the ambient wind velocity has considerable effects on the temperature of the porous layer. Dos Santos and Mendes [31] proposed a mathematical model to simulate an unsaturated sandy roof used as passive cooling system in buildings. They considered the heat exchange due to short- and long-wave radiation, due to phase conversion and convection at the outer surfaces of their model. Further, convective heat and mass transfers and long wavelength radiation heat transfer in the inner surfaces were considered. They concluded that sand and moist sand substrates have a premier comfort index for the entire course of the day. Zhang et al. [137] investigated mathematically the effects of vaporization on a porous tile on roof thermal efficiency under Guangzhou's climatic conditions. They used multivariate nonlinear model to predict vaporization rate from the porous surface. These authors found that refilling the evaporative substrate by water mostly causes more decrement in the hourly peak heat flux.

### 3.3.3. Combined experimental and numerical studies

Meng and Hu [80] investigated numerically the effects of moist porous material on roof cooling. They used experimental data to obtain the physical properties for moist porous material. These authors used porous material on the roof. They decreased the temperatures of the external and internal surfaces of the roof with porous material by about 25°C and 5°C, respectively in comparison to an ordinary roof.

### 3.3.4. Summary

As a concluding remark to this section, it should be stated that about 50% of the heat load in the building is originated from the roof in arid and hot regions [84]. The impact of this heat load is not only limited to the top floor but it affects the entire building. Accordingly, the usage of novel techniques to decrease the temperature on the roof could further enhance the energy efficiency of buildings and decreases the cooling loads. Evaporative cooling through using porous materials is recognised as an efficient technique in this regards. This technique has many indirect advantages including water keeping during an intense rainfall, enhance of thermal insulation of the building, and absorption of many polluting elements [54]. This system has a great potential to be used as a green roof. Generally, a porous material with high porosity provides higher cooling than a material with moderate or low porosity. Table 4 summarizes research articles published on the applications of porous materials in roof cooling systems. The difference of the required depth of porous material substrate made by the weather difference should be investigated in future studies. Using water sprays in dry regions is suggested to improve the thermal performance of the system. The salt is deposited by evaporating water from the roof. This blocks the pores in the porous layer and leads to a decrease in the evaporation rate and, inversely affects the cooling capability of the system. Accordingly, the fouling effects should be considered in future investigations. Evaporative cooling should not be limited to roof and can be also used in sidewalls. Finally, evaluation of other aspects of this system such as cost, durability, and maintenance requires further research.

## 3.4. Thermal storage systems

Rapidly growing concerns on global warming and the use of fossil fuels has highlighted the significance of thermal energy storage systems for heating and cooling buildings and providing hot water. Thermal storage in buildings can be done at high and low temperatures corresponding to heating and cooling processes [118]. High temperature heat storage usually occurs in solar energy, waste heat utilisation or heat pump applications, while thermal storage in low temperature is common in air conditioning, refrigeration, or cryogenic-temperature processes (see Fig. 8).

Saving thermal energy by phase change material plays an important role in cooling and heating of buildings. Phase change materials (PCMs) have larger heat saving density with smaller temperature variation [53].

Some researchers reviewed the potentials of these materials in buildings. Soares et al. [116] reviewed the passive phase change materials used to store thermal energy in buildings. They concluded that

**Table 4**
The literature on the applications of porous materials in roof cooling systems.

| Authors | Type of research | Type of porous material | Spatial dimensions | Main results |
|---|---|---|---|---|
| Liu et al. [72] | Analytically | Unconsolidated sand | 1D | Evaporation on the free surface and also within the bed enhances as relative humidity decreases and ambient temperature increases. |
| Ibrahim et al. [46] | Experimentally | Porous ceramic | – | A maximum cooling of about 224 W $m^{-2}$ can be achieved by using porous ceramic evaporator with large porosity.<br>The porous ceramic in direct evaporative cooling has considerable potentials for buildings' applications. |
| Meng and Hu [80] | Experimentally/Numerically | Sand layer | 1D for numerical part | The temperatures of the external and internal surfaces of the roof can be decreased about 25 °C and 5 °C, respectively by using moist porous material on roof in comparison to an ordinary roof. |
| Okada et al. [91] | Experimentally | Porous ceramics | – | Porous ceramics prepared by mixing the allophane and vermiculite is useful as water-retaining materials to prevent "heat island" effects. |
| Wanphen and Nagano [127] | Experimentally | Pebbles, silica sand, volcanic ash, and siliceous shale | – | Among, pebbles, silica sand, siliceous shale, and volcanic ash, siliceous shale has great potential for decreasing the daily mean surface temperature more than 8.63 °C. |
| Chen and Liu [20]; Chen [19] | Mathematically | Ceramic material with porosity of 0.38 | 2D | Cooling of the porous evaporative layer increases as the ambient relative moisture reduces or the ambient temperature enhances.<br>The ambient wind velocity has considerable effects on the temperature of the porous layer. |
| Vardoulakis et al. [123] | Experimentally | Aluminium pillared clays | – | During day and night times with relative humidity of 55%, the maximum temperature inside the pillared montmorillonite was 6.5 °C lower than that inside a typical soil sample by using Aluminium modified clays.<br>Aluminium modified clays has great potential for decreasing the roof surface temperatures. |
| dos Santos and Mendes [31] | Mathematically | Sand | 1D | Sand and moist sand substrates have a premier comfort index for the entire course of the day. |
| Gentle et al. [37] | Experimentally | Polyethylene mesh | – | Polymeric mesh is a suitable material for cool roofs. Polyethylene mesh is a porous material and has an ability to forcefully reduce convective gain at night time and to have a great black body transfer that nominates it appropriate for applying in radiative cooling systems. |
| Crawford and da Silva [27] | Experimentally | Porous membrane | – | The salt deposited in vaporization system blocks the pores and leads to decrease in vaporization rate from porous membrane and accordingly affects the cooling ability of the system. |
| Shokri Kuehni et al. [114] | Experimentally | Sand with different particle size distributions | – | The capillary length between the receding dehumidifying front and the evaporation surface decreases with an increase in the particle size.<br>The surface temperature enhances by increasing the particle size. |
| Zhang et al. [137] | Mathematically | Porous tile layer | 1D | Refilling the evaporative substrate by water mostly causes more decrement in the hourly peak heat flux. |

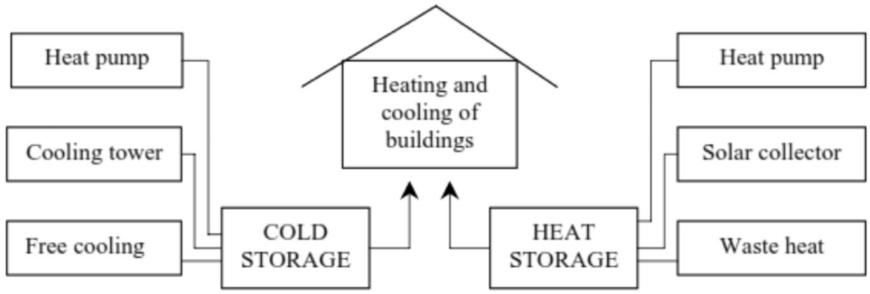


**Fig. 8.** Application of thermal storage for heating and cooling system in buildings (Reprinted from Stritih [118] with permission from the publisher).

implementation of these materials decreases the energy used in cooling and heating systems by decreasing or shifting the load. Moreover, these materials enhance indoor thermal comfort by decreasing indoor temperature fluctuations. Kenisarin and Mahkamov [58] reviewed the potentials of phase change materials to control the thermal energy in residential buildings. They reported that the costs of PCMs can be decreased by advancing and enhancing the generation technology. Pandey et al. [93] investigated the potential usage of phase change materials for solar energy systems. Note that some solar energy systems can be used in buildings. They reported that the properties of phase change materials can be obtained by employing more advanced compact equipment. Lizana et al. [73] evaluated the potentials of advanced low-carbon materials to store the thermal energy in buildings. They concluded that these materials should be combined with cooling and heating systems by demand-side management techniques. Rao et al. [99] reviewed ability of PCM-mortar for storing the thermal energy in buildings. Further, they reviewed the mechanical characteristics of these materials. They reported that the mechanical characteristics of PCM-mortar and ability of them for storing the thermal energy are depended on microstructure of these materials.

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 [105,106]. In this section, the studies about the impregnation of phase change materials into porous construction materials used in buildings (e.g. gypsum, concrete, plasterboard, etc.) are reviewed.

### 3.4.1. Experimental studies

Neeper [85] evaluated the benefits of passive thermal storage by using phase change material impregnated with porous wallboard. Results of this research showed that the use of PCM-impregnated wallboard with a 40-Btu/ft/sup2/ capacity provides sufficient storage for direct gain systems. Kedl and Stovall [57] filled porous wallboard with wax as a thermal energy storage material by an immersion process. They found that the immersion process achieves higher storage capacity than adding wax filled pellets to wallboard during its manufacture. Peippo et al. [96] used PCM- medicated plasterboard as a storage material in a weightless passive solar building. They observed about 5–20% direct savings in energy consumption by using this material. Later, Nomura et al. [89] added the phase change materials to the porous materials to recover the waste thermal energy in the form of latent heat. They used erythritol as phase change material and selected expanded perlite, gamma-alumina, and diatom earth as the porous structures. Nomura et al. concluded that the latent heat of the expanded perlite/erythritol is up to 83% higher in comparison with the conventional erythritol. Li et al. [67] prepared a thermal saving material for buildings by adding paraffin as PCM into porous structure of expanded perlite. Subsequently, they composed it by gypsum. Li et al. [67] reported that the adsorption of paraffin reduces the thermal conductivity of the expanded perlite/gypsum, which is useful for improving the heat preservation. Chen et al. [21] investigated production and thermal characteristics of n-octadecane/molecular sieve composites as form-stable thermal energy saving materials used in buildings. The molecular sieve 5A has a porous nature and is applied as the supporting material for improving the thermal stability of the composite PCMs. Some researchers introduced the composite PCMs made of fatty acids and porous building materials as a latent heat thermal energy saving used in buildings [10,42,53,66,79,107,133]. They found that this method is cost-efficient and easy to use. It is proven that fatty acids and their eutectics as organic materials have suitable chemical compatibility with inorganic porous building materials [108,109,64,65]. Further, fatty acids can be quickly stirred with inorganic porous materials and retained in the pores by surface tension and capillary forces. Sari [110] introduced composites of polyethylene glycol with gypsum and natural clay as novel types of building phase change materials for small values of temperature of thermal energy saving. This author selected gypsum and natural clay as porous building materials as they are porous, weightless, easy to incorporate with water, environmentally friendly, widely usable in building section due to simplicity and inconsiderable cost. He et al. [43] produced Capric–myristic acid/expanded perlite composite PCM as a new energy saving material used in buildings. The Capric–myristic acid eutectic mixture as PCM was inserted in the porous expanded perlite by mass fraction of about 200%. Chung et al. [25] investigated the thermal efficiency of organic composite phase change material for latent heat thermal energy saving used in buildings. The composite phase change material was made of octadecane and BioPCM as phase change materials and porous micronized silica. They observed that composite phase change material has good thermal durability, thermal energy saving characteristics, and thermal and chemical reliabilities. Evola and Marletta (2014) investigated the influence of PCM wallboards for improving summer thermal comfort in weightless buildings. They concluded that the location of the PCM wallboards inside the room, the rate of night time ventilation, and the value of the peak melting temperature for the particular PCM are some important factors that affect the efficiency of PCM in energy saving. Kim et al. [59] prepared shape-stabilized phase change material by adding hexadecane as a phase change material into xGnP as a supporting material. xGnP as a porous nano-sized carbon material is a fine container for the phase change material due to its well porous structure, great thermal conductivity, and great surface area. Zhang et al. [135] prepared gypsum based energy saving materials with capric acid–-palmitic acid /expanded perlite composite PCM. Capric acid–palmitic acid eutectic mixture can be efficiently distributed in the microporous structure of expanded perlite. They found that larger composite PCM volume content increases energy saving capability of the gypsum. Tang et al. [119] prepared fatty acid eutectics/expanded graphite composites as PCM to store the thermal energy in buildings. They found this material suitable for feasible radiant cooling system as it has excellent thermal properties containing great thermal conductivity, inflammable property, large latent heat, and great stability and thermal reliability. Pavlík et al. [94] improved lime-cement plasters by two kinds of phase change material to increase thermal and the ability of hygric for saving energy. They observed that the usage of small encapsulated PCM particles leads to about 10% enhancement in porosity in comparison with

**Table 5**
Research on the applications of porous materials for energy storage in buildings.

| Authors | Type of research | Type of porous material | Spatial dimensions | Main results |
|---|---|---|---|---|
| Neeper [85] | Experimentally | Wallboard impregnated with PCM | – | The use of PCM-impregnated wallboard with a 40-Btu/ft/sup$^2$/ capacity provides sufficient storage for direct gain systems. |
| Kedl and Stovall [57] | Experimentally | Wallboard impregnated with PCM | – | The porous wallboard was filled with wax as a thermal energy storage material by an immersion process. The immersion process achieves higher storage capacity than adding wax filled pellets to wallboard during its manufacture. |
| Peippo et al. [96] | Experimentally | PCM-impregnated plasterboard | – | 5–20% direct savings in energy consumption can be achieved by using PCM- medicated plasterboard as a storage material in a weightless passive solar building. |
| Nomura et al. [89] | Experimental | Expanded perlite, diatom earth, and gamma-alumina | – | The latent heat of the expanded perlite/erythritol is up to 83% higher in comparison with the conventional erythritol. |
| Li et al. [67] | Experimentally | Expanded perlite | – | The adsorption of paraffin reduces the thermal conductivity of the expanded perlite/gypsum, which is useful for improving the heat preservation. |
| Chen et al. [21] | Experimentally | *n*-octadecane/molecular sieve composites | – | Molecular sieve 5A with a porous nature can be applied as the supporting material for improving the thermal stability of the composite PCMs. |
| Yang et al. [130] | Experimentally/Numerically | Soil | 3D | As a novel type of soil cool saving system with seasonal natural cold source, the natural cool energy can be stored in soil during the winter and can be used for space cooling in the warm seasons. |
| Evola and Marletta (2014) | Experimentally | Wallboard impregnated with PCM | – | The location of the PCM wallboards inside the room, the rate of night time ventilation, and the value of the peak melting temperature for the particular PCM are some important factors that affect the efficiency of PCM in energy saving. |
| Sari [110] | Experimentally | Gypsum and natural clay | – | Composites of polyethylene glycol with gypsum and natural clay can be used as novel types of building phase change materials for small values of temperature of thermal energy saving. |
| Chung et al. [25] | Experimentally | Micronized silica | – | Composite phase change material including octadecane, BioPCM, and porous micronized silica has good thermal durability, thermal energy saving characteristics, and thermal and chemical reliabilities. |
| He et al. [43] | Experimentally | Expanded perlite | – | Capric–myristic acid/expanded perlite composite PCM can be used as a new energy saving material in buildings. |
| Kim et al. [59] | Experimentally | xGnP | – | xGnP as a porous nano-sized carbon material is a fine container for the phase change material due to its well porous structure, great thermal conductivity, and great surface area. |
| Novais et al. [90] | Experimentally | Weightless dense/porous PCM-ceramic tiles | – | Weightless dense/porous PCM-ceramic tiles decreases indoor space temperature variation by about 22%, which leads to improvements in the thermal comfort within buildings. |
| Tang et al. [119] | Experimentally | Expanded graphite | – | Acid eutectics/expanded graphite composites is suitable for feasible radiant cooling system as it has excellent thermal properties containing great thermal conductivity, inflammable property, large latent heat, and great stability and thermal reliability. |
| Zhang et al. [135] | Experimentally | Expanded perlite | – | Capric acid–palmitic acid eutectic mixture can be efficiently distributed in the microporous structure of expanded perlite.<br>The larger composite PCM volume content increases energy saving capability of the gypsum. |
| Cisek and Taler [26] | Experimentally/Numerically | Porous solid matrix composed of a ceramic bed and steel tubes | 1D | In an electric thermal saving unit, thermal energy can be stored in a porous medium during off-peak times and can be discharged during peak times. |
| Pavlík et al. [94] | Experimentally | Lime-cement plasters | – | The usage of small encapsulated PCM particles leads to about 10% enhancement in porosity in comparison with the conventional plaster. This causes a considerable enhancement in the heat saving capability of the lime-cement plasters. |
| Lv et al. [75] | Experimentally | Expanded graphite composite | – | The addition of expanded graphite causes an increase in the thermal conductivity of system considerably due to the benefits of porous nature of expanded graphite. |
| Xu et al. [129] | Numerically | Porous materials with different thermal conductivities | 2D | A porous material with large values of porosity and thermal conductivity and large pore size is suitable for increasing the melting efficiency of phase change materials. |

the conventional plaster. This causes a considerable enhancement in the heat saving capability of the lime-cement plasters. Lv et al. [75] investigated experimentally and numerically the thermal energy saving of polyethylene glycol/expanded graphite composite PCM. They reported that the addition of expanded graphite causes an increase in the thermal conductivity of system considerably due to the benefits of porous nature of expanded graphite.

#### 3.4.2. Numerical/theoretical studies

Xu et al. [129] numerically studied the melting efficiency of a latent heat thermal energy saving system partially filled with porous materials. They stated that a porous material with large values of porosity and thermal conductivity and large pore size is suitable for increasing the melting efficiency of phase change materials.

#### 3.4.3. Combined experimental and numerical studies

Yang et al. [130] presented a novel type of soil cool saving system with seasonal natural cold source. In this system, the natural cool energy was stored in soil during the winter and was used for space cooling in the warm seasons. It was demonstrated that this system has a great economic efficiency. Novais et al. [90] used weightless dense/porous PCM-ceramic tiles to control the indoor temperature of buildings. They found that this type of tile decreases indoor space temperature variation by about 22%, which leads to improvements in the thermal comfort within buildings. Cisek and Taler [26] performed numerical and experimental investigations on a solid matrix, electric thermal saving unit used in a residential heating system. An electric thermal saving unit is a compound of electric heating sections, which are placed inside a solid matrix with large density as a porous medium. Thermal energy is stored in porous medium during off-peak times and is discharged during peak times. Cisek and Taler [26] recommended this technology as a suitable and environment friendly heating system for residential buildings.

#### 3.4.4. Reviews of literature

There already exists reviews on the applications of PCM in buildings. Baetens et al. [6] reviewed the potentials of PCM to decrease the energy consumption of buildings. They concluded that a relatively high-energy savings are reported by using PCMs. Yet, the current properties of the available PCMs are not still optimal for widespread building applications. Stritih [118] reviewed heat saving technologies with phase change materials used in buildings. They stated that paraffin, fatty acids, and hydrate salts are promising PCM materials that can be used in buildings as latent thermal energy saving. Pomianowski et al. [97] reviewed PCMs used in buildings with focus on room application. They reported that data about PCM content and ratio of surface with PCM to total surface of the room should always be considered for the investigated case. Konuklu et al. [60] performed a review on microencapsulated phase change materials (MPCM) used in building applications. Microencapsulated phase change materials can be impregnated with many building construction materials. They concluded that MPCM enhances the thermal capacity of system considerably with a relative small reduction in mechanical properties. Recently, Souayfane et al. [117] reviewed PCMs used as cooling applications in buildings. They found that energy savings and subsequently effectiveness of PCM enhance as the thickness of PCM layer reduces to a certain optimum level.

#### 3.4.5. Summary

Table 5 presents a list of research articles published on the applications of porous materials as means of energy storage in buildings. The main findings of these can be summarized as follows:

- Most of PCMs have a solid–liquid phase change process when used in buildings to store the thermal energy. Accordingly, first they should be stabilised to prevent exudation in the process of phase change. There are some porous materials (e.g. expanded perlite) that can be used to adsorb the phase change materials by applying their own capillary actions even in the liquid condition. The porous natures of these materials prevent the exudation during phase change process due to the action of capillary and surface tension forces.
- Expanded graphite can be used to enhance the heat transfer in phase change materials, due to its favourable properties of excellent stability, great compatibility with organic phase change materials, high thermal conductivity, and weightless.
- Heat storage density of PCM increases by using a porous material with high porosity.
- Granular phase change composites are very appropriate, as they do not need to be encapsulated, have no corrosion, and exchange heat quickly.

In future, the effects of ambient conditions on the operation of these energy storage systems need to be investigated. In the field of solar energy storage, phase change materials do not operate economically at low temperatures as their costs are about the double of the cost of hot water systems [18]. An economic evaluation is essential along with each study in this field. Moreover, so far, research in this area has been mostly focused on the preparation of these materials. Thus, further research is needed to investigate the practical performance of these materials in the actual buildings. In the actual processes, parameters involved in heat storage materials during the melting and solidification are very changeable and this is the most significant difficulty before simulating this material.

### 3.5. Other systems

Miguel and Silva [81] used porous materials containing screens, shelters, and filters to control climate characteristic of enclosures used in screened greenhouses. They found that the permeability and porosity of the screen mainly affect the climate characteristic inside the greenhouse. Riffat and Zhu [102] modelled mathematically the indirect evaporative cooler containing heat pipe and porous ceramic. Porous ceramic was used as the cooling source to transfer the coolth to the indoor space of a building and a heat pipe was considered as the thermal system for evaporating in this research. They observed a good cooling capacity for this system subject to conditions of windy and dry climate. Bayrak et al. [9] performed experimentally the exergy and energy analyses for porous baffles incorporated inside solar air heaters used in building sectors. Closed-cell aluminium foams were selected as porous materials. They found that the efficiency of the solar air heater increases and the irreversibility of this device decreases by using porous baffles inside the system. Table 6 summarizes research on applications of porous materials in other building energy systems.

## 4. Conclusions and recommendations for future works

This review provided a comprehensive literature survey on the applications of porous materials in building energy technologies. These included roof cooling, ground-source heat pumps and heat exchangers, insulation, and heat storage systems. Different porous materials, used in these systems, to improve the energy efficiency in buildings, were introduced and the characteristics of them were closely discussed. The main findings of this review and some recommendations for future works are presented in the followings.

### 4.1. Conclusions

The performance of borehole heat exchangers is affected by several parameters. These parameters are the soil temperature distribution, humidity content, thermal properties, groundwater movement, and possible freezing and melting of water amount in the soil as a porous material. Moreover, in borehole heat exchangers, the thermal resistance between the borehole wall and the heat carrier fluid in soil as a porous

**Table 6**
Research on applications of porous materials in other building energy systems.

| Authors | Type of research | Type of system | Type of porous material | Main results |
|---|---|---|---|---|
| Miguel and Silva [81] | Theoretical/ Experimentally | Enclosures used screened greenhouses | Screens, shelters, and filters | The permeability and porosity of the screen mainly affect the climate characteristic inside the greenhouse. |
| Riffat and Zhu [102] | Mathematically | Indirect evaporative cooler system | Porous ceramic | Porous ceramic can be used as the cooling source to transfer the coolth to the indoor space of a building in the indirect evaporative cooler. This system has a good cooling capacity for conditions of windy and dry climate. |
| Bayrak et al. [9] | Experimentally | Solar air heaters | Closed-cell aluminium foams | The efficiency of the solar air heater increases and the irreversibility of this device decreases by using porous baffles inside the system. |

material directly affects the performance of these systems. Thermal resistance is related to the physical properties of porous soil including the effective thermal conductivity and volumetric heat capacity. Considering transport in porous media leads to more accurate prediction of thermal resistance of boreholes. For example, for a porous material with high permeability, heat transfer is due to coupled processes of heat conduction and heat convection. However, for a porous material with low permeability, heat transfer in this medium is more due to heat conduction and the contribution of heat convection is less significant. Soil porosity, thermal conductivity, and backfill materials are some factors that considerably affect the thermal recovery of soil in ground heat exchanger systems. It is concluded that the moisture amount in the soil increases the thermal conductivity of this material and improves the heat transfer and thermal efficiency of the ground heat exchangers.

In a typical building, most of thermal energy is lost through uninsulated components. Using porous material with lowest possible heat conductivity and stable structure is a good option for insulating components of a building. Aerogels as a porous material with a small density and large porosity (more than 90%) are excellent option for thermal insulating in buildings. As another option, nano-porous silica has a low thermal conductivity, at atmospheric pressure, and a very low conductivity under primary vacuum. Accordingly, it is strongly recommended for the use in building as vacuum insulation panels. Further, fibre/powder hybrid core materials with a great porous nature, large porosity (80–90%), and fine average pore size in the range of 19.0–181.1 nm, can be considered as vacuum insulation panels in building sections. The previous studies showed that the accumulated moisture in porous insulation material can lead to the deduction of insulation performance. As a result, it is important to record the humidity amount in porous insulation materials with high accuracy. A well-established technique to measure the moisture of an insulation material is the hot-wire test.

Using humid porous materials on the surface of the roof results in cooling influences caused by the passive water evaporation. When heat transfer occurs between the upper surface of the roof and atmosphere, humidity diffuses from the internal substrates to the surface and evaporates in there and therefore generates a cooling effect. Generally, particles with smaller sizes are more suitable for the use in roof cooling systems as they increase the rate of evaporation. Moreover, cooling of the porous evaporative layer in a roof cooling system intensifies as the ambient relative humidity decreases or ambient temperature increases. Finally, the deposited salt produced by evaporating the water blocks the pores in a roof cooling system and this causes a decrease in vaporization rate from roof that affects the cooling ability of the system.

Saving thermal energy by phase change material plays an important role in cooling and heating of buildings. 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. Most of PCMs have a solid–liquid phase change process when used in buildings to store the thermal energy. Thus, first they should be stabilised to prevent exudation in the process of phase change. There are some porous materials (e.g. expanded perlite) that can be used to adsorb the phase change materials by applying their own capillary actions even in the liquid condition. The porous nature of these materials prevent the exudation during phase change process due to the action of capillary and surface tension forces. Also, expanded graphite can be used to enhance the heat transfer in phase change materials, due to its favourable properties of excellent stability, great compatibility with organic phase change materials, high thermal conductivity and low weight. As a new option for saving thermal energy in buildings, granular phase change composites have good capability, as they do not need to be encapsulated, have no corrosion and exchange heat quickly. Finally, the results of previous studies indicated that heat storage density of PCM enhances by using a porous material with high porosity.

### 4.2. Recommendations for future works

Following suggestions are made as for future work:

- In mathematical modelling of ground heat pump systems, researchers have often used constant thermal properties for soil parameters, while the effects of variable soil thermal properties on the characteristics of this system is seldom evaluated. This leaves an important gap that needs to be filled in future.
- Soil pore humidity phase changes have a significant role on the efficiency of ground heat pumps and are significant for designing an adaptable system. It is suggested to consider this important point in future research in this field.
- The relationship between compression, deformation, thickness, and thermal performance of porous insulation materials should be specified because it has a direct influence on the energy efficiency of the building. The review showed that this significant point has been investigated rarely in the former studies.
- Application of porous materials in dynamic insulation system used in buildings has a significant potentials for future research.
- Study on inorganic porous insulation materials such as geo-polymer foam is strongly advised as they are environmentally friendly.
- More studies should be performed to determine the necessary width of porous material substrate used in roof cooling under different weather systems.
- Using water sprays in dry regions is suggested to improve the thermal performance of roof cooling systems.
- The salt is deposited by evaporating the water from roof. This blocks the pores in porous layer and leads to a decrease in the evaporation rate that affects the cooling capability of the system. Hence, the fouling effects should be considered in future research.
- Evaporative cooling as an efficient method, should not be limited to roof. This method can also be used in sidewalls. The required water may be supplied by the rainwater, moisture in air or by a spray.
- Some important factors of roof cooling systems such as cost, durability, and maintenance need more discussion.
- Most of previous studies have focused on the preparation of PCMs by impregnation of them with porous construction materials used in

buildings (e.g. gypsum, concrete, plasterboard, etc.). However, further investigations are needed to explore the practical performance of these materials in the actual buildings.

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