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Assessment of solar chimney combined with phase change materials

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ABSTRACT

Using solar energy as a renewable and clean source of energy is developing rapidly. Usage of heat storage facilities in different solar systems enables dispatchability in the production of electricity and building space heating demands. It can help to decrease the intermittence issue of solar energy. Heat storage facilities also help to smooth out fluctuations of energy demands during several time periods of a day. Phase change materials (PCMs) have vital roles in developing sustainable energy modules with their notable features. The thermal energy absorbed and released by these materials, over particular temperature ranges, has become an outstanding contender in solar energy systems. This paper assesses the progresses regarding the usage of these materials in solar chimney power plants. Some descriptions about the solar chimney power plants and their mechanisms and superiorities are provided. Different techniques used in thermal energy storage are discussed. Applications of phase change materials in solar chimney are also investigated. Finally, the main results of the review and some directions for future studies in this field are provided.

1. Introduction

The multiplication in different industries and also in human societies has increased the demand for thermal energy consumption in several fields [1,9,59]. On the other hand, the preparation of this energy is made usually employing fossil fuels that results in severe environmental problems, such as air pollution, in addition to being non-renewable and decreasing their resources. Using renewable sources of energy may be a suitable solution for this problem ([63,64]; 5) [3,18,30,32,41,47–49,54]). Besides, most renewable sources of energy, such as solar energy, cannot be used all the time; accordingly, it is necessary to provide the balancing between supply and demand by using energy storage. By saving the energy in the form of heat, it is possible to enhance the performance of heat transfer modules in addition to balancing the mentioned above.

Some researchers have focused on the usage of thermal energy storage in different thermal systems. Liu et al. [16,39,52] reviewed the potentials of high-temperature PCMs to store solar thermal energy. They concluded that because the amount of radiation energy is directly related to the fourth power of the absolute temperature, accordingly, the influences of radiation heat transfer on the characteristics of PCMs become important for larger values of temperature. Katekar and Deshmukh [27] studied the potentials of PCMs for the usage in the solar stills. They found that the paraffin wax enhances the energy and exergy efficiencies and productivity of the single slope passive solar still about 67.20%, 40%, and 180%, respectively. In addition, the productivity enhancement of active solar stills due to the usage of paraffin wax is about 307.54%. Rajendran et al. [53] focused on the applications of PCMs on the efficiency of concentrated solar power collectors. Their review showed that the thermal conductivities of PCMs could enhance about 12 times by employing the graphite-based nanocomposites with a volume fraction of 5%. Javadi et al. [22] investigated the efficiency enhancement of solar thermal systems incorporated with PCMs. They reported that the PCMs suffer from the small value of thermal conductivity that can create a small value of thermal diffusion rate and decreases the storage capabilities in the practical solar systems.

The literature review showed that there are some papers published about the potentials of PCMs in different solar systems. However, there is no paper to assess the progresses about the usage of these materials in solar chimney power plants. Due to the importance of this line of research, this paper focuses on this topic. This work is organized as follows:

In Section 2, some description about the solar chimney power plants and their mechanisms and superiorities are provided. Different techniques used in thermal energy storage are discussed in Section 3. Section 4 provides some information about thermal energy saving in solar energy systems. Using of PCMs in solar chimney power plants is investigated in Section 5. Finally, the main results of the evaluation and some directions for future studies in this field are provided in Section 6. Valipour et al. [55] performed a discussion on the influences of magnetic field on the heat transfer from a cylinder wrapped

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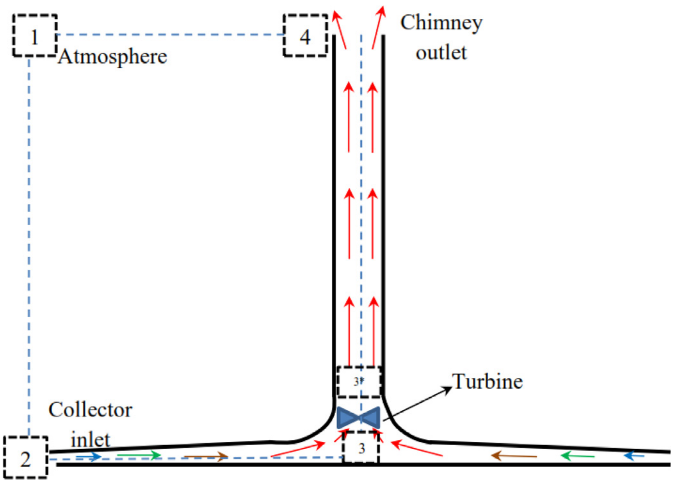

Fig. 1. A schematic view of a solar chimney power plant designed by Guo et al. [17].

with a porous substrate. They employed the least square technique to provide two equations for the mean Nusselt number [56,57,68].

2. Solar chimney power plant

2.1. What is a solar chimney power plant?

A solar chimney power plant, SCPP, or solar updraft tower power plant combined rather simple and reliable technologies, including a solar thermal receiver, chimney, and turbine, to offer promising options for the large-scale use of solar energy. A schematic view of a solar chimney power plant is displayed in Fig. 1. The solar radiation can pass through the transparent ceiling of the solar receiver, and this radiation is collected by the natural ground or a supplementary absorbing plate placed on the ground. The absorbing plate heats the cool ambient air, which flows through the system by the greenhouse influence. After that, the hot air enters the receiver output, also the input of the chimney. The density difference between the hot air within the chimney and the cool air of ambient produces buoyancy force, which can act as the driving force. The updraft airflow is afterward created in the chimney owing to buoyancy influence and is employed for driving the pressure-staged turbine inside the chimney bottom to produce electricity. Thermal energy can be saved inside the absorber when solar irradiance is intense during days on sunny times and can be released from the absorber when there is no solar irradiance during nights or cloudy times [26,71].

2.2. Superiorities of a solar chimney power plant

The solar chimney power plant, as an environmentally friendly energy system, has much superiority, which are listed as follows (Chikere et al., 2011) [8]:

- The beam and diffuse solar irradiance can be used that are critical for tropical countries, where the sky is mostly cloudy.
- The solar chimney power plants are independent of cooling water during their operation, and this makes their applications proper for the area, which suffer from water shortage.
- In a solar chimney power plant, the turbine and power generator are only moving parts. This results in low operating and maintaining costs and high permanence.
- The materials used to construct the solar chimneys, including concretes and glass, are cheap and readily available.
- It has a long lifecycle, about 80–100 years.
- It can be installed in any place in tropics, even in the desert area.

2.3. Governing equations for simulation of a solar chimney power plant

In this section, the governing equations, which can be used for the simulation of a solar chimney power plant, are presented. The continuity, momentum, and energy equations can be used for the simulation of the fluid flow and natural convection heat transfer in the solar chimney. The Reynolds Averaged Navire–Stokes (RANS) equations are [61]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = S_m \tag{1}$$

where t and $\vec{v}$ are the time and velocity component, respectively. S_m is the source term in the continuity equation. ρ is the density of fluid. $\overline{\overline{\tau}}$ is the shear stress.

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla.\mathrm{p} + \nabla.\left(\overline{\overline{\tau}}\right) + \rho \vec{g} + \vec{F} \tag{2}$$

where p and g are the pressure and the gravitational acceleration, respectively. F indicates the external body force.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\vec{v}(\rho H + p)) = \nabla.(k_{eff} \nabla \mathrm{T}) + S \tag{3}$$

where H indicates energy. S is the source term in the energy equation.

The shear stress, $\overline{\overline{\tau}}$, in Eq. (2) can be calculate by:

$$\overline{\overline{\tau}} = \mu\left[\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right) - \left(\frac{2\nabla}{3}.\vec{v}I\right)\right] \tag{4}$$

where μ is the dynamic viscosity of the fluid. In addition, I indicates the unit tensor.

3. Thermal energy saving materials

The materials employed to store the thermal energy are categorized into three classes according to their saving characteristics; chemical thermal energy saving, sensible heat, and latent heat [43,45]. The mechanism of chemical thermal energy saving is shown in Fig. 2. This method is based on the absorbing and releasing energy

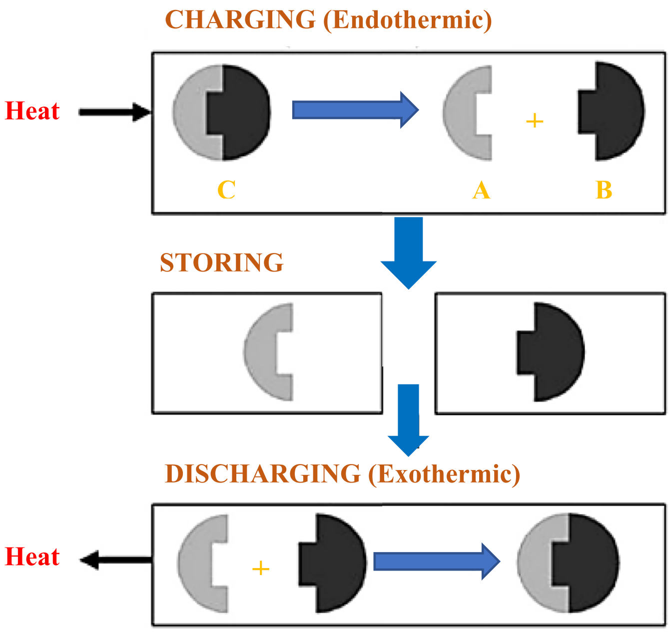

Fig. 2. The mechanism of chemical thermal energy saving offered by Abedin and Rosen (2007) [2].

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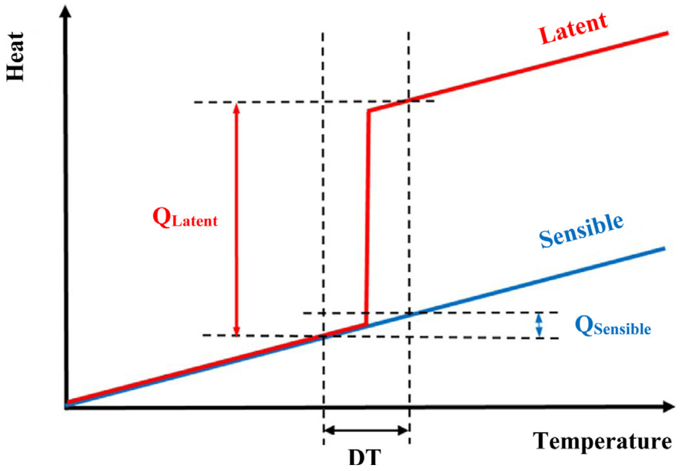

Fig. 3. Working principles in sensible and latent heat saving methods presented by Helm et al. [20] and Khan et al. [31].

when breaking and forming molecular chemical bonds in the fully reversible reactions. This method has the highest energy density as compared with other techniques [28]. This technique also has a great benefit of minimal losses as the thermal energy can be saved as reactants at environment temperature. Chemical thermal energy saving is the most complex class because it uses a chemical reaction. The irreversible processes and chemical instabilities are other drawbacks of this class.

Thermal energy can also be saved in the forms of sensible and latent. Working principles in sensible and latent heat saving methods are displayed in Fig. 3. Generally, in the sensible techniques, thermal energy is saved by the temperature increase, while in latent methods, the thermal energy is saved at a constant temperature. Indeed, in latent methods, the thermal energy is utilized to alter the solid or liquid phase of materials to liquid or gas phase at constant temperature and is saved as latent heat in the materials, respectively. It should be noted that during a phase transition processes, the temperature and sensible thermal energy are kept constant, but the internal energy is enhanced. Sensible thermal energy saving is the most popular technique of energy saving because of its simplicity and low costs. However, owing to the small saving capacity, more materials should be used. The best technique that has a higher thermal energy saving capacity without using any chemical reaction is latent heat saving. The major necessities for latent heat saving modules are high thermal energy saving densities and high-power capacities for charging and discharging the thermal energy. However, the defects of latent heat saving materials are the small values of thermal conductivities of these materials that lead to a smaller amount of power capacity.

The latent heat storage techniques are categorized into three kinds, including solid/liquid, liquid/gas, and solid/solid [19,58]. The solid/liquid is most common kind that provides a substantial value of energy saving density with slight changes in volume. The density of energy saving shows the amount of saved energy in a material and is directly related to the latent heat of fusion. The solid/liquid PCMs can save a specific amount of thermal energy in much lower volume and weight of materials, and this is the main superiority of these materials. Usually, solid/solid PCMs have low latent heat. The liquid/gas PCMs are not suitable for the closed modules owing to the high variation in their volume. At a constant temperature, latent thermal energy saving by solid/liquid phase change can provide a substantial value of thermal energy saving capacity. This considerable saving indicates that less material is required to save a specified value of energy.

3.1. Phase change materials

PCMs, as latent heat saving materials, are employed for saving thermal energy or controlling the temperature variation in a certain

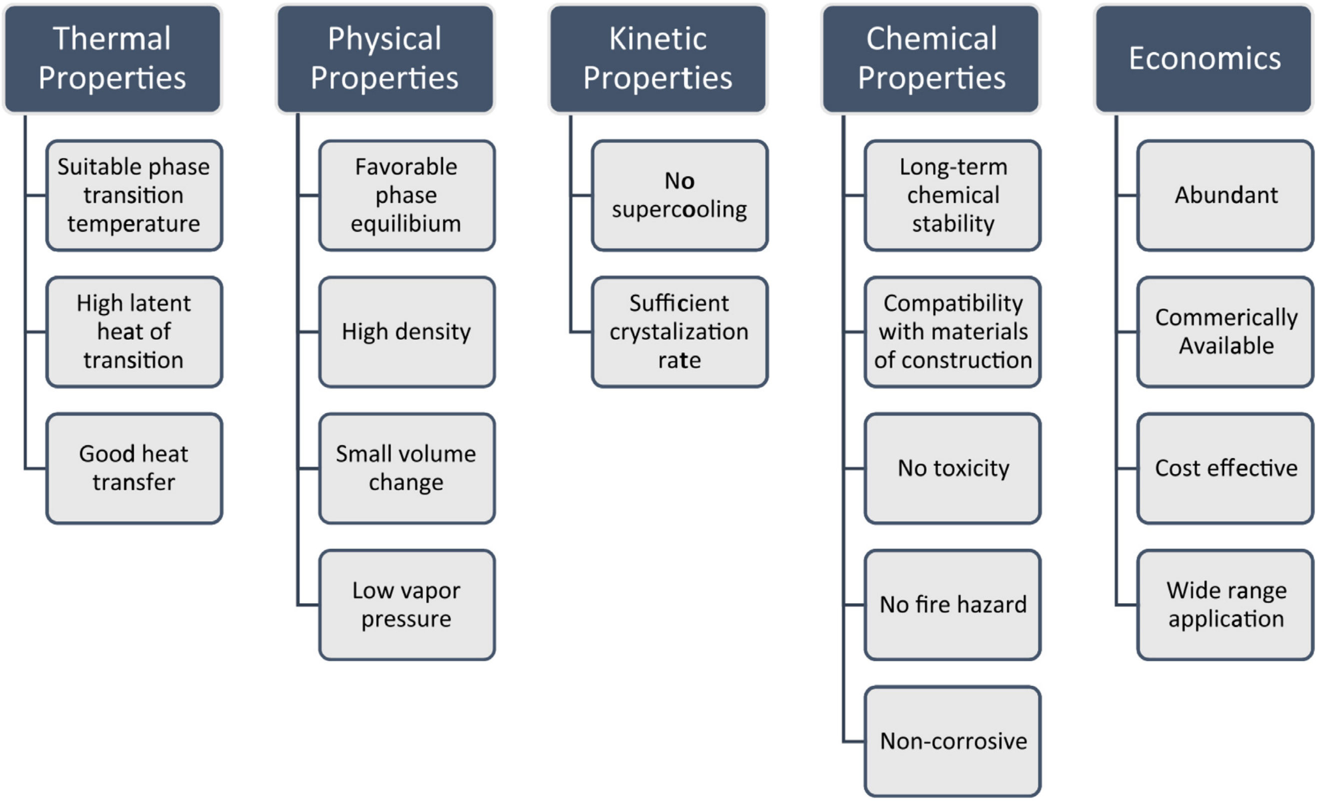

Fig. 4. Features of PCMs presented by Khan et al. [31] and Nazir et al. [45].

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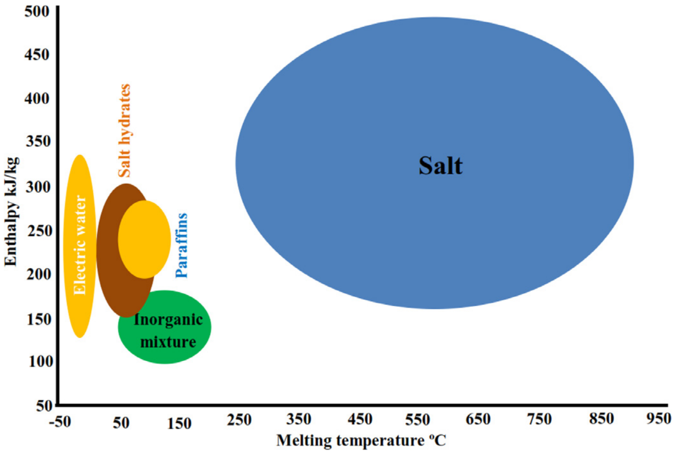

Fig. 5. Melting temperatures and enthalpies of several PCMs presented by Khan et al. [31].

range [23,65,67]. These materials receive thermal energy in the endothermic process during their melting. During the exothermic process, the thermal energy can be released again when they are solidified. Kinetic, chemical, and thermophysical characteristics, together with environmental and economic aspects, are the major parameters, which should be considered when selecting PCMs. PCMs are categorized into three groups including, eutectic, organic, and inorganic groups. The superiorities and defects of several kinds of PCMs are displayed in Fig. 4. The shortcomings from each type of PCMs must be considered to adjust the design of the application equipment. Fatty acids, salt hydrates, eutectic organic/non-organic compounds, and paraffin waxes are widely employed PCMs.

The major thermophysical characteristics of PCMs with a brief comment on their importance are listed as follows:

- **Melting point:** The melting point of PCM should be around the needed operating temperature range.

The melting temperatures and enthalpies of several PCMs are displayed in Fig. 5.

- **Density:** The larger value of density enhances energy saving density that reduces the system size.
- **Latent heat of fusion:** The larger value of the latent heat of fusion enhances energy saving density.
- **Specific heat:** The larger value of specific heat enhances density of energy saving of the system.

4. Thermal energy saving in solar energy systems

Solar energy is not accessible around some clocks that shows the major challenge to bridge the unconformity between times of energy supply and energy demand. Accordingly, as a smart solution, the thermal energy saving and particularly PCMs can be employed to increase the exploitation of solar energy as an excellent energy source [51]. Thermal energy saving equipment is very important for the continuous usage of solar energy. As already discussed, PCMs can provide better thermal energy saving capacity as compared with sensible heat saving materials owning to their high latent heat. Accordingly, employing PCMs are an essential part of solar heat release/storage systems. After loading the PCMs, the energy transferring mode is changed. Extra thermal energy from the sunlight can be saved during the daytime by PCMs. At night, thermal energy is transferred from the PCMs to the system to ensure more solar energy can be employed. Since several kinds of PCMs have various specifications and application ranges, it is critical to select the most proper type of PCMs for the special application. The potentials of PCMs on different solar thermal systems are investigated in the previous studies. The main results of these studies are presented as follows:

Solar water heaters

PCMs can be used in solar water heating modules. The studies in this field showed that the proper phase change temperature for these systems is varied from 40 °C to 70 °C. Among different designs, PCMs used in the water storage reservoir showed the best efficiency because it can keep the water temperature for long times. The extended time is owing to a larger amount of PCM that can be incorporated into the storage reservoir to supply more thermal energy during off-sunshine times (Yiing [29]). The previous studies showed that the PCMs used in the solar water heater should have the following conditions:

1. The PCMs should be enhanced by high thermal stability
2. The design of the system should be improved and the PCMs should be used to decrease the energy dissipation from water conveying pipelines
3. The equipment used in the thermal energy saving system should be standardized, and its economic value should be improved.

Solar stills

The results of previous studies showed that the usefulness of solar stills could be increased using PCMs. The productivity also increases as the phase change mass is increased. PCMs are also less effective at daytimes in comparison with night-times. The organic kind of PCMs, such as paraffins, are mostly employed in the solar stills owing to their practicable general and economic attributes, including medium storage, easy accessibility, safety, reliability, uniform melting, and moderate costs. However, other kinds of PCMs are rarely employed in solar stills owing to their instability, supercooling, and corrosiveness (Omara et al., 2020) [50].

Solar power industries

Thermal storages in the forms of sensible and latent heat or a combination of them are used in concentrated solar power industries. It was found that a considerable decrease in storage tank size can be obtained by employing PCMs. The previous studies in this field indicated that by adjusting the cutoff temperature near the melting temperature of a PCM, such a PCM could offer a smaller storage tank size that results in a considerable decrease in materials and construction costs [70].

Solar dryers

Solar dryer equipped with thermal energy storage materials is exactly efficient to have continuous drying agriculture and food productions at a steady state in the temperature range of 40–60 °C). For a better thermal efficiency of solar dryers, a PCM with a large value of latent heat of fusion and high surface area for heat exchange is essential [25].

Solar absorption refrigeration systems

Solar absorption refrigeration systems require an uninterrupted operation in different applications, including food storage, space cooling, etc. That, in turn, need effective thermal energy storage systems using materials with a large value of heat of fusion such PCMs. Using PCMs in solar refrigeration and air conditioning systems of residential and commercial buildings also have excellent potential to attain zero energy building concepts. Generally, in cold storage, PCMs with subzero temperatures are suitable. In addition, thermal reliability, subcooling, and phase-segregation issues should be considered [31].

5. Applications of phase change materials in solar chimney

In this section, the papers about the applications of PCMs in solar chimney are assessed. Li [33] focused on the solar chimney system

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Fig. 6. The design used by Kaneko et al. [24].

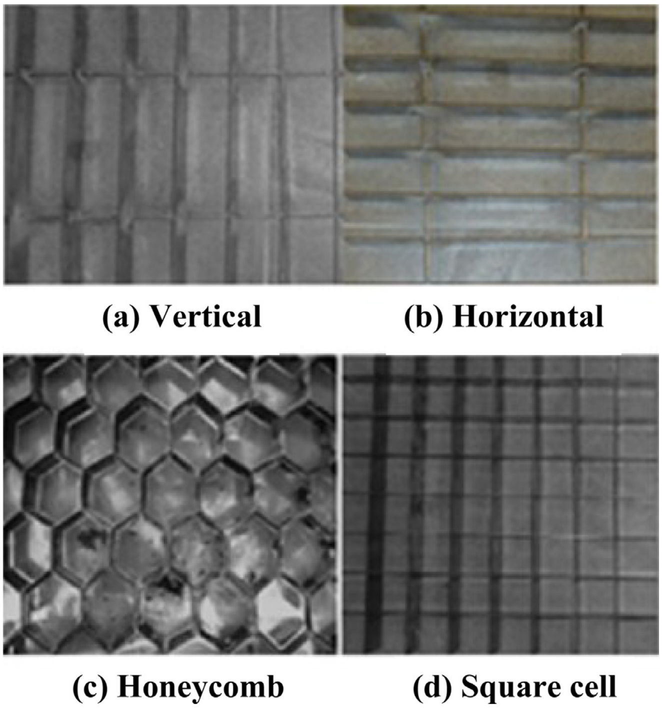

Fig. 7. Four finned structures used by Li et al. [36] to enhance the heat transfer rate.

combined with PCM, which can be used for natural ventilation and cooling/heating purposes. It was found that the outlet temperature and the flow rate of air are changed within a small range during phase change transition periods that are substantial for the solar air heating systems. Sharma et al. [62], Ochiai et al. (2008), and Kaneko et al. [24] designed a solar chimney along with PCM modules used for the natural ventilation. Their design is shown in Fig. 6. They used the Sodium Sulfate Decahydrate as the PCM. They concluded that the usage of PCM storage in the solar chimney can be effective for the free ventilation in the evening and night if the PCM is completely melted during the daytimes. In addition, the supercooling was observed in the freezing process of PCM. It should be noted that the supercooling is the process of cooling a PCM in the liquid phase below its freezing point without it becoming a solid. Indeed, the nucleation begins at a temperature below the real freezing point of the PCM. Accordingly, the PCM should be cooled significantly below its expected freezing point to initiate freezing. Once its nucleation is initiated, the temperature of PCM increases to its real freezing point. After that, the freezing is continued at that temperature. If supercooling to be considerable, it is a deficiency in a PCM because it negatively affects the operation of the thermal energy storage module. That is owing to the fact that the freezing does not begin at the expected freezing temperature, but only way below, with a practical demand of a large operating temperature range. Moreover, the higher degree of supercooling leads to the release of a smaller amount of energy because it can be released as sensible heat that is lesser as compared with the expected latent heat released.

Safari and Torabi [60] employed the PCMs to boost the thermal efficiency of a solar chimney and prepare constant temperatures and airflow rates for the guardroom. It was concluded that by employing PCM as the thermal energy storage module, the guardroom temperature could be kept uniformly for a whole day. In contrast, without using PCM, room temperature is changed during day and night. In addition, PCM makes the temperature of the solar panel more uniform and also decreases its peak temperature considerably. This service causes a more reliable system. Li and Liu [[34],b] investigated both experimentally and numerically the thermal efficiency of the solar chimney enhanced with the PCM. They extended the ventilation period for 13 h 50 min by using the PCM. In addition, the efficiency of the solar chimney enhanced with the PCM is much related to solar radiation. In a numerical investigation, Liu and Li [38] focused on the absorber properties and glass cover on the thermal efficiency of the solar chimney enhanced with PCM. It was concluded that the melting duration of PCM decreases about 26.3% by boosting the absorptivity of the absorber in the range of 0.8 to 1.0. In addition, by increasing the transmissivity of the glass cover up to 25%, the melting duration decreases about 26.7%. Li et al. [36] investigated the effects of thermal conductivity enhancers, TCEs experimentally, on the thermal efficiency in the PCM during the melting and freezing processes for the solar chimney applications. Four kinds of TCEs, including horizontal fin, HF, vertical fin, VF, square cell structure, SCS, and honeycomb structure, HS, were employed in this investigation. These TCEs are shown in Fig. 7. They found that the HF, VF, SCS, and HCS reduce the melting time by 12%, 8%, 16%, and 14.5%, respectively, in comparison with the pure PCM. In addition, the HF and VF with the identical volume fractions have various influences on the thermal performance in the PCM during the melting process, and this indicates that the distribution and geometry of fins have considerable effects on the heat transfer improvement. Recently, Nakhchi and Esfahani [44] proposed a stepwise fin for improvement of PCM performance in the specified cavity for energy storage.

Li et al. [37] focused on the influences of different parameters of a PCM on the thermal efficiency of solar chimney. It was concluded that the temperature of phase change of material has considerable influence on the thermal efficiency of the solar chimney. The PCM with a broader phase change temperature difference can be melted completely earlier as compared with a PCM with a narrower phase change temperature difference. Lu et al. [40] studied the influences of various PCMs on the night ventilation efficiency and thermal storage capacity of the solar chimney. The PCMs with temperatures of phase change of 38 °C, 44 °C, 50 °C, and 63 °C were considered. Their experimental setup is displayed in Fig. 8. They reported that the highest mean ventilation rate of 610 kg m^{-2} and the highest thermal storage of 4750 kJ m^{-1} could be achieved by using the PCMs with the temperature of phase change of 38 °C. However, for the temperature of 63 °C, the night ventilation cannot be observed in the same conditions. It was found that using PCM with a smaller value of temperature of phase change increases the chargeability and dischargeability of the

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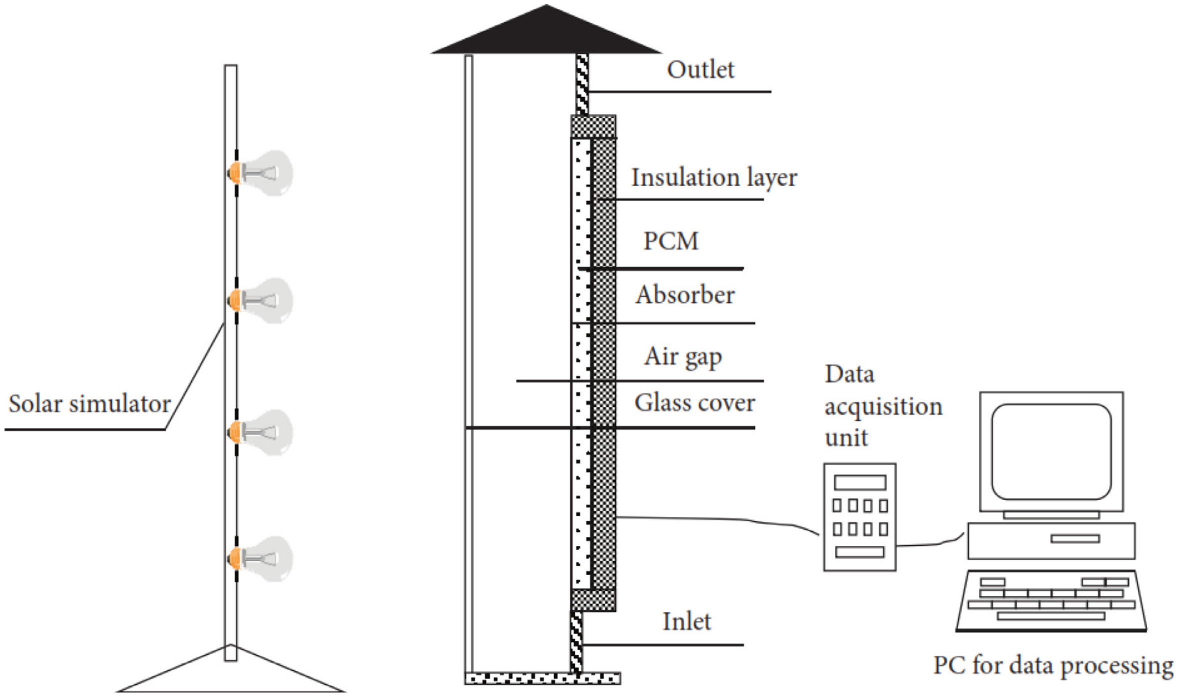

Fig. 8. The experimental setup used in the study of Lu et al. [40].

solar chimney. Because a PCM with a larger value of phase change temperature needs more solar radiation and longer charging times in the solar chimney. For PCM with a phase change temperature of 44 °C, most of the thermal energy saved in the PCM can be lost to environmental through glass cover by radiation, and just a small amount is employed to heat the air inside air duct.

Bin et al. [5] focused on the influences of the thickness of the PCM on the efficiency of a solar chimney. It was concluded that a larger value of peak temperature could be observed as the thickness of the PCM increases. In another study, Bin et al. [6] investigated the influences of the location of the PCM on the efficiency of a solar chimney. They found that when PCM is placed in front of the absorber, the air temperature is higher as compared when the PCM is placed behind the absorber.

Murtadha et al. [42] proposed a design for the closed loop solar chimney equipped with PCM and copper foam matrix. They found that employing the PCM and foam matrix as the heat saving material makes more successfully comfortable zone and can control the room temperature. Bashirnezhad et al. [4] accomplished an experimental investigation to investigate the influences of PCM as the energy storage on the efficiency of the solar chimney. They considered three cases. In the first case, the collector's ground was covered with natural soil without absorber. In the second case, the water-filled black pipes were used as the thermal absorber. In the third case, the paraffin-filled black tubes were used as the thermal absorber. Their results showed that the amount of produced electricity from the system using paraffin as a thermal absorber is more as compared with those of the other two cases, and this amount is 11.5 KWh/day. As a result, a smaller size turbine can be designed for this case, and this leads to a decrease in the costs of the system. The efficiency increases about 6.2% and 22% by employing the water and paraffin, respectively, as thermal storage materials in the solar chimney power plant as compared with the case of no absorber state. Carlos Frutos Dordelly et al. [[14],b,c,d] investigated the effects of integrating a PCM on the efficiency of laboratory solar chimneys. They used the paraffinic RT44 panels with a melting temperature of 44 °C as the PCM. It should be noted that the working temperature range of the PCM should maximize the time in which the chimney is operated at a high temperature to have stable ventilation. It was concluded that integrating the PCM can provide a larger value of ventilation rates. Generally, the using paraffinic PCMs in solar chimneys is an affordable choice for hybrid design solutions to provide a healthy indoor surrounding in residential buildings through clean solar energy.

In a numerical investigation, Xaman et al. [69] focused on the influences of three various kinds of absorbing materials, including the copper plate, PCMs, and concrete wall on the thermal performance of the solar chimney designed for the buildings. The physical model used in this study is illustrated in Fig. 9. The heat transfer mechanisms involved in this problem are also displayed in this figure. It was concluded that the mean thermal performances of the solar chimney with the copper plate are 27% for the orientation of west and 34% for the orientations of south and east. These values are 27%, 19.8%, and 28% for the solar chimney with the PCM. In addition, the solar chimney with the concrete wall can provide the least values of thermal performance.

Fadaei et al. [11] experimentally investigated the influences of PCM on the efficiency of the solar chimney pilot. They installed the container of PCM on the absorber of the solar chimney, as displayed in Fig. 10. They reported that the highest air velocities through the solar chimney are 2 ms^{-1} and 1.9 ms^{-1} for the solar chimney enhanced with PCM and the ordinary solar chimney without using PCM. This comparison indicates that by employing the PCM, the mean mass flow rate increases by 8.33%; consequently, the efficiency of solar chimney enhances.

Fadaei et al. [12] used the artificial neural network to predict the efficiency of solar chimney enhanced with PCMs. The comparison between the data predicted by the artificial neural network and obtained by the experiments showed the accuracy of the analysis. The mean relative error for all outputs was less than 3%. Thantong et al. [66] used the PCM inside the solar chimney to improve the natural ventilation and decrease the heat gain admission. Their solar chimney is displayed in Fig. 11. They used the PCM on the wall in the room. It was concluded that the indoor temperature of solar chimney equipped with PCM was smaller as compared with the single concrete wall room

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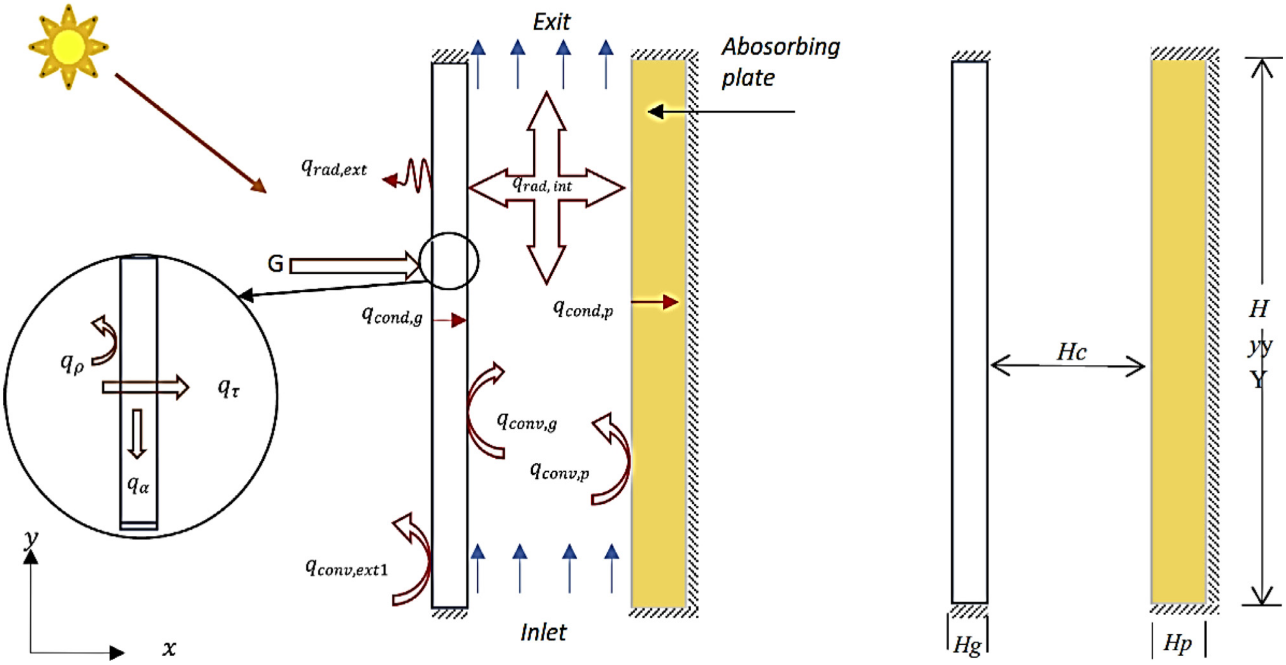

Fig. 9. The physical model used in the study of Xaman et al. [65].

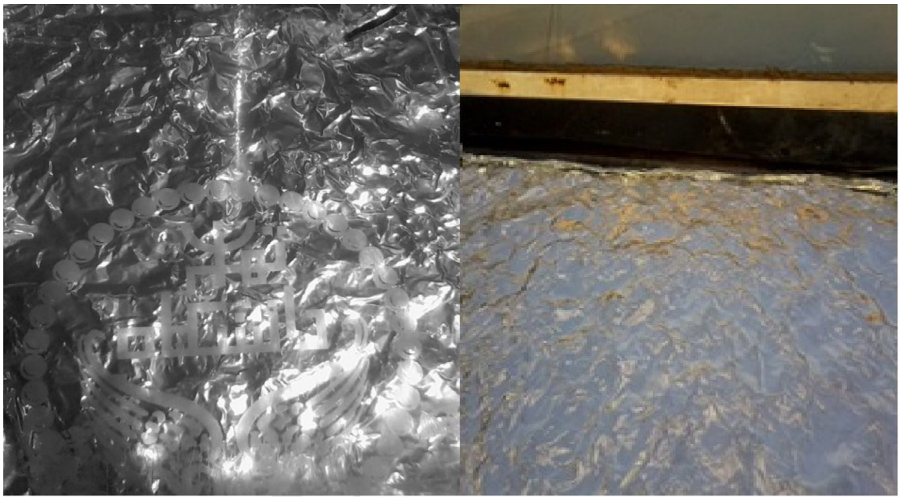

Fig. 10. The container of PCM placed on the absorber of the solar chimney considered by Fadaei et al. [11].

Ebrahimnataj Tiji et al. [10] simulated a solar chimney equipped with PCM and finned absorber. Their physical model is displayed in Fig. 12. It was concluded that using PCM as the storage medium results in achieve a uniform temperature in the room. The average room temperature of 14.68 °C is achieved that is quite less as compared with the thermal comfort conditions. In addition, the results indicated that the usage of fins is very effective to make up the saved heat in the PCM.

Chen and Chen [7] presented a new design of the solar chimney with the sieve-plate heat saving beds packed with phase change capsules. Their design is shown in Fig. 13. They found that the porosity and particle size in the porous substrate considerably affect the thermal efficiency of the system. As the porosity is increased from 0.4 to 0.6, hotter airflow across the beds causes the improvement of convective heat exchange in the substrate. Accordingly, the higher value of bed temperature can be achieved at the porosity of 0.6 as compared with the porosity of 0.4.

The benefits and drawbacks of various thermal energy storage methods used in solar chimney power plants are presented in Table 1. In addition, the studies conducted on the applications of phase change materials in solar chimneys are summarized in Table 2.

6. Conclusions and directions for future studies

In this paper, the progress about the usage of PCMs in solar chimney power plants was assessed. Some descriptions about the solar chimney power plants and their mechanisms and superiorities were provided. Different techniques used in thermal energy storage were also discussed. Applications of PCMs in solar chimney were also investigated. The main outcomes of this review are:

- The usage of PCM storage in the solar chimney can be effective for the free ventilation in the evening and night if the PCM is completely melted during the daytimes.
- The working temperature range of the PCM should maximize the time in which the chimney is operated at a high temperature to have stable ventilation. It was concluded that integrating the PCM can provide a larger value of ventilation rates.

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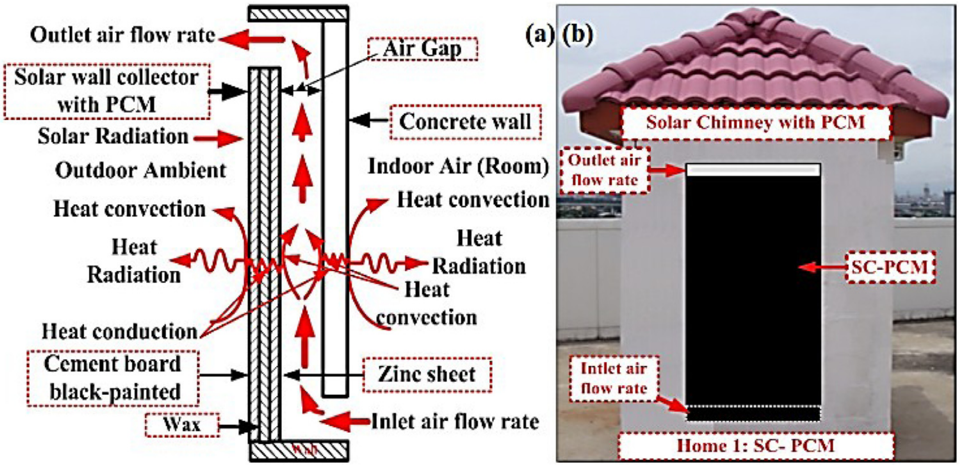

Fig. 11. The solar chimney system considered by Thantong et al. [63].

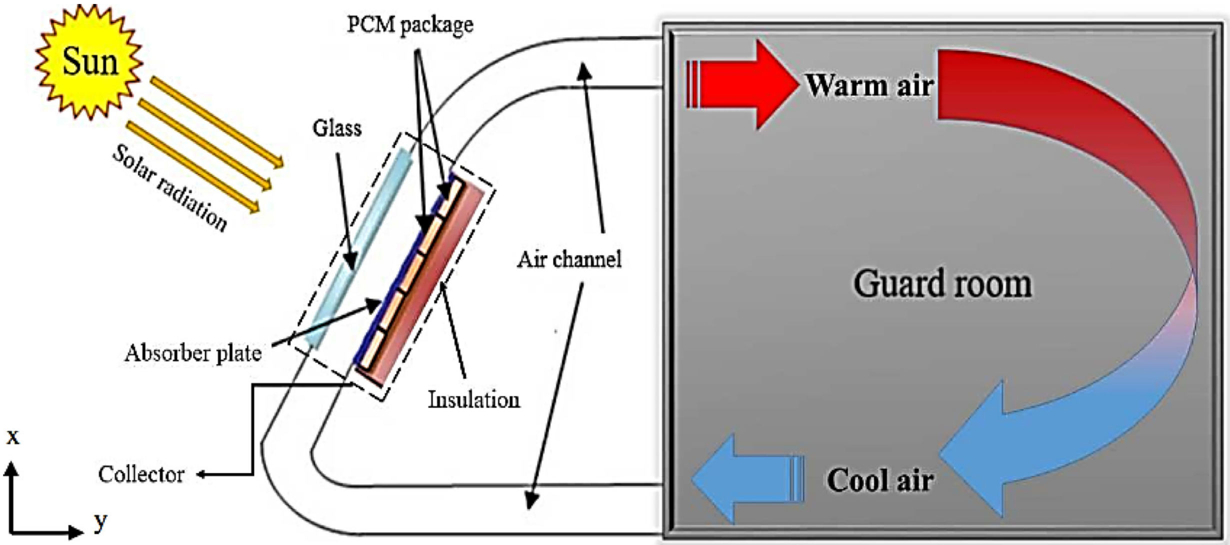

Fig. 12. The physical model considered by Ebrahimnataj Tiji et al. [10].

- Generally, the using paraffinic PCMs in solar chimneys is an affordable choice for hybrid design solutions to provide a healthy indoor surrounding in residential buildings through clean solar energy.

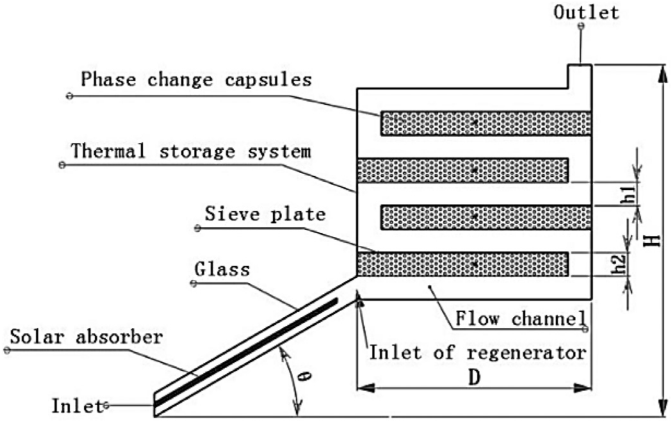

Fig. 13. The design considered by Chen and Chen [7].

- The phase change temperature of PCM has considerable influence on the thermal efficiency of the solar chimney. The PCM with a wider phase change temperature difference can be melted completely earlier as compared with a PCM narrower phase change temperature difference.
- Using PCM with a smaller value of temperature of phase change increases the chargeability and dischargeability of the solar chimney. Because the PCM with a larger value of phase change temperature needs more solar radiation and longer charging times in the solar chimney.
- Using fin, honeycomb structure, and square cell structure in PCMs can reduce the melting time.
- The melting time of PCM decreases by boosting the absorptivity of the absorber. In addition, by increasing the transmissivity of the glass cover, the melting time decreases.

The following directions are also made for future investigations in this field:

- Optimization of the thermophysical properties of PCMs such as melting point with some methods, including hydrocarbon chain length and eutectic mixtures, is important to improve the potentials of these materials for solar chimneys.

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Table 1
The advantages and disadvantages of various thermal energy storage methods used in solar chimney power plants [21].

Kind of thermal energy storage method	Classification of materials	Advantages	Disadvantages
Sensible	Natural materials	The installation costs of solar chimney can be decreased.	Thermal energy storage capacity is low.
Sensible	Industrial materials	Thermal energy storage capacity is high.	The installation costs of solar chimney can be increased.
Sensible	Hybrid solid-liquid materials	The performance of system can be improved. The system can generate the power at night.	The lack of water, especially at desert areas, will determine this method.
Latent	PCMs	The system can generate the power at night.	The materials used in this method has low thermal conductivity.

Table 2
The studies conducted on the applications of phase change materials in solar chimneys.

Sources	Method	PCM
Kaneko et al. [24]	Experimental	$Na_2SO_4\ 10H_2O$
Li [33]	Numerical and Experimental	Paraffin Wax
Safari and Torabi [4]	Numerical	Sodium sulphate decahydrate $Na_2SO_4 \bullet 10H_2O$
Li and Liu [34]	Experimental	Paraffin Wax RT42
Li and Liu [35]	Numerical	RT-42
Liu and Li [38]	Experimental and numerical	Paraffin RT42
Li et al. [36]	Experimental	Paraffin Wax RT 42
Ismaeel et al. [21]	Experimental	Paraffin Wax
Murtadha et al. [42]	Experimental and Numerical	Paraffin Wax
Lu et al. (2016)	Numerical	Myristoyl Dodecylic acid Myristelaidic acid Palmitic acid
Li et al. [37]	Numerical	RT42
Bin et al. [5,6]	Experimental	$Na_2CO_3 \bullet 10H_2O$
Frutos Dordelly et al. [13–15]	Numerical and experimental	Paraffinic RT44
Bashirnezhad et al. [4]	Experimental	Paraffin
Fadaei et al. [11,12]	Experimental	Paraffin wax
Thantong et al. [66]	Experimental	Paraffin wax
Xaman et al. [69]	Numerical	Paraffin wax 46–50
Ochiai et al. [46]	Numerical	Sodium sulfate decahydrate
Ebrahimnataj Tiji et al. [10]	Numerical	Sodium sulphate decahydrate ($Na_2SO_4 \bullet 10H_2O$)
Chen and Chen [7]	Numerical	Paraffin

- The exergoeconomic analysis of solar chimney in which several PCMs are used can recommend the cheapest and most efficient PCM for solar chimney in various climates.
- Composite PCMs can be the subject of future investigations for solar chimneys to recognize the influence of constituent elements on the efficiency of solar chimneys.
- The final concern about PCMs is their compatibility with the environment, which should be considered when selecting these materials for solar chimneys.
- The corrosion can decrease the lifetime of the PCMs, and accordingly, the efficiency enhancement will considerably reduce. This issue should be considered when using these materials in solar chimneys.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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