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Review article

Current developments, utilization, and effects of phase-change materials integrated with solar chimney: A comprehensive review

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ABSTRACT

This research addresses the growing need for sustainable energy solutions in building design by integrating phase change materials (PCMs) with solar chimney (SC) systems to enhance thermal performance and energy efficiency. Through a comprehensive review of existing studies, this paper evaluates the evolution, application, and benefits of PCM-integrated SC technologies across diverse architectural environments. The findings demonstrate that the integration of PCMs significantly enhances thermal performance by stabilizing indoor temperatures, improving ventilation rates, and reducing reliance on conventional heating systems, which leads to notable energy savings and promotes more sustainable building practices. Additionally, the operational efficiency of solar chimneys is extended, collectively improving indoor air quality. However, the study identifies several barriers to widespread adoption, including high initial costs, the limited thermal conductivity of certain PCM types, and a lack of awareness among stakeholders. To overcome these challenges, the study recommends further research into advanced PCM formulations with improved thermal properties, the development of intelligent control systems for optimized performance, and the promotion of regulatory frameworks that support PCM incorporation in building designs. The paper concludes that addressing these challenges is critical for unlocking the full potential of PCM-integrated solar chimneys in improving sustainability and energy efficiency within the built environment.

1. Introduction

One potential alternative energy source is solar energy, which is particularly appealing due to its renewable nature, non-polluting nature, and accessibility in the local area. Air conditioning, refrigeration, and electricity generation are among the numerous applications of solar

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energy. By harnessing solar energy, solar chimney (SC) is one kind of renewable energy technology that enhances a building's natural ventilation [1]. Passive solar design is the process of using solar radiation to heat and cool living rooms without the use of electricity or other mechanical devices. A thermal chimney, windows, and thermal mass are additional passive design components [2].

Passive solar energy alone cannot provide the needed load effect, particularly in big structures, throughout night and day. Because of this, the bulk of passive solar structures are really hybrids—that is, low-energy solutions are achieved by combining passive technology with mechanical equipment. As a result, the phrase "mixed-mode" was created to refer to this novel operating mode. Mixed-mode buildings are constructed using both passive and mechanical methods in order to attain the intended load impact [3]. The passive solar ventilation is unstable since the sun's light varies throughout the day. To provide a steady and dependable ventilation system, excess energy must be stored while the sun is present and released when absent. This is possible because to energy storage devices, which are actually a tactic for balancing the disparity between supply and demand for energy [4]. They enhance solar energy systems' dependability and efficiency. There are several energy storage techniques, including electrical, mechanical, thermal, and thermochemical. Thermal energy storage results from changes in internal energy of material, which can appear as latent or sensible heat or a combination. The late 1970s and early 1980s saw a significant increase in interest in latent heat due to its ability to retain heat indefinitely [5]. Latent heat storage is still being researched, and its potential uses include air conditioning, waste heat recovery, and building energy saving. PCMs are an example of a material with storage of latent heat. The storage of PCM involves the conversion of the substance from a liquid to a solid or from a solid to a liquid state [6,7]. They can retain 5–14 times the heat per volume as observable heat-absorbing materials, like rock or water. Thus, it is logical to utilize PCM in passive solar systems to store extra energy and utilize it during periods of limited thermal energy [8,9].

Several scholars have focused on utilizing storage of thermal energy in various thermal systems. Liu investigated the capacity of high-temperature PCMs to store energy of solar thermal [10]. He reveals that at higher temperatures, the impact of radiation heat transfer on the properties of PCMs becomes considerable since the quantity of radiation energy is proportional to the absolute temperature's fourth power. Rajendran et al.'s study focused on how the efficiency of concentrated solar power collectors is affected by using PCMs [11]. Their analysis revealed that incorporating graphite-based nanocomposites at a volume ratio of 5 % could potentially enhance the PCMs thermal conductivities by approximately 12 times. Javadi et al. [12] studied improving efficiency in systems of solar thermal by introducing PCM. According to their analysis, PCMs have low thermal conductivity, which can lead to low thermal diffusion rates and a reduction in storage capacity in real-world solar systems.

Omara et al. [13] presented a literature assessment on the utilization of PCMs to enhance the efficiency of (SCs) in power plants and building applications. From the results of earlier investigation, PCM has a noteworthy deal of assurance for enhancing thermal comfort within buildings, growing times of ventilation, increasing SC power plants' capacity to produce electricity, and expanding their generating times. By highlighting their ideal design, benefits, drawbacks, and economics, Sharon [14] thoroughly analyzed the potential of SC systems for structure ventilation, power production, and generation of potable water in solo, hybrid, and poly-generation modes. The SC ventilation system, when paired with an earth-air heat exchanger and evaporative cooler, can mitigate the energy consumption for space cooling by 20 % to 75 %.

Vargas-López et al. [15] highlighted the efficacy of different mathematical frameworks for solar chimneys and underscores the potential advantages of integrating PCMs into these models. The analysis of the associated five mathematical models discloses that each has an exclusive merits and demerits, signifying that the choice of model can meaningfully affect the performance predictions for SC systems. Additionally, determined that incorporating PCMs into a transient mathematical model for a double-channel superconductor can improve the thermal performance and competence of solar chimney systems. This integration not only recovers energy management but also corroborates to more sustainable building practices by optimising the utilization of renewable energy sources. Generally, the results of underline the significance of selecting suitable mathematical frameworks to precisely evaluate the performance of PCM-integrated solar chimney technologies.

Although the growing concentration in PCM-integrated solar chimney technologies, detailed investigations systematically appraising their performance across different architectural contexts are deficient. The interactions between different PCM materials and design strategies have not been fully discovered, limiting the understanding of their combined impacts on energy efficiency and thermal comfort. The current review discourses these gaps in the open literature by revising existed research and recognizing underrepresented areas, such as the long-term stability of PCM materials, economic feasibility, and stakeholder awareness. The significance of this review lies in its complete method to inspecting the intersection of PCMs and solar chimney technologies, underscoring their potential to transform building design and energy utilization strategies. The chief aim is to predict the performance of hybrid systems that integrate renewable energy systems with improved design principles to elevate sustainable practices. Also, this review reveals advancements in intelligent control systems and innovative PCM formulations to upgrade solar chimney performance. By providing such substantial visions into PCM-integrated solar chimney technologies, this review intends to guide future research directions and improve energy management and sustainability objectives within the built environment.

2. Solar chimney operation combined with PCMs

The drive of PCM in SCs is to optimise energy management and enhance natural ventilation. The SC, which contains of a vertical shaft designed to collect solar energy, which signify the first step of the mechanism. Normally, the upper of the chimney has an absorber plate that collects sunlight and transforms it into heat [16]. The chimney's interior air warms up alongside the absorber plate, turning into less dense and increasing because of buoyancy. Natural ventilation is made possible throughout the arrangement by the ascending trajectory of hot air generating a pressure difference that draws cooler air from the environment up the chimney (Fig. 1).

Incorporating PCM into the SC system is vital for controlling temperature changes. To optimise the absorption and retention of thermal energy, PCM is positioned either inside the chimney or close to the absorber plate. As the temperature enhances during the day, PCM absorbs heat and transitions from solid to liquid. PCM can store a significant quantity of thermal energy throughout this process, preventing a rapid increase in the chimney's air temperature [17].

The PCM begins to solidify as the sundown and outside temperatures decrease, redistributing the heat which has stored into approaching air through the chimney. Through the release of thermal energy, this decreases the request for mechanical heating systems throughout colder months and aids to keep up a more consistent indoor temperature. The ability of PCM to assist a continuous cycle of heating and cooling enhances the overall efficiency of solar chimney, ensuring a steady circulation and better interior quality of air [18].

3. Solar chimeny integrated with PCMs

The increasing requirement for more solutions of energy-efficient and better inside climate management has prompted imaginative thinking in technology of building and design. The implication of PCMs in SCs is one such breakthrough. Although PCMs afford a practice of thermal energy storage that allows the control of temperature

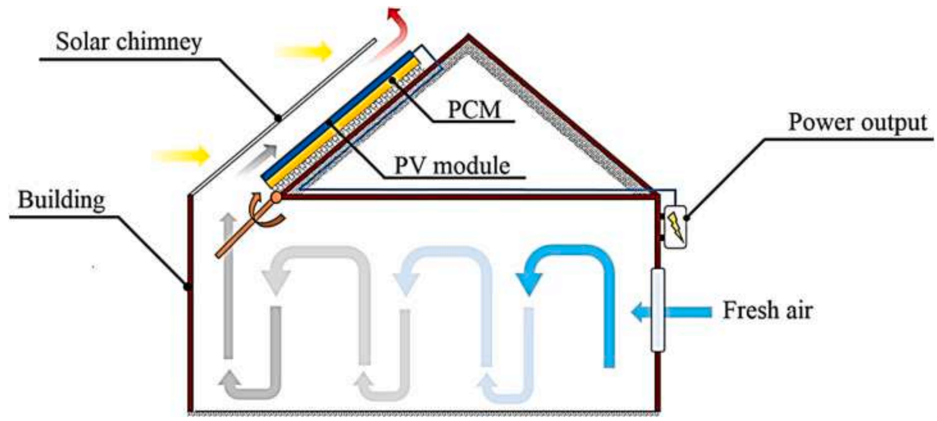

Fig. 1. The operating mechanism of the SC integrated with PCM [38].

alterations, SCs use solar energy to enhance interior air quality and upgrade natural ventilation [19]. This combination augments building comfort and sustainability while magnifying efficiency of energy. However, it might be appreciated to further emphasize how the combination of PCMs and SC systems discourses current challenges in energy efficiency, affording useful solutions for sustainable building design. Furthermore, underlining the potential for future progressions in PCM compositions and hybrid system applications could deliver a forward-looking perspective. The investigation of SC systems integrated with PCMs provides a feasible path toward energy-efficient construction and a reduction in the need for customary cooling and heating techniques as the world shifts to greener approaches. It is vital to understand the difficulties, tenets, and advantages of this combination as it has the capacity to fully change the way we approach design of building [20].

3.1. Enhancement the thermal performance

Integration with PCM with SC systems is a principal growth toward enhancing efficiency and thermal performance of building energy. These systems utilize the latent heat storage capability of PCMs to regulate the internal temperature. This imaginative approach method encourages sustainable building fundamentals in addition to maximizing the use of solar energy. For engineers and architects, it is becoming more and more significant to understand the thermal performance benefits given by PCM-integrated SCs as the need for energy-efficient solutions ascends [21].

For the purpose of ascertaining the influence of using PCM in the SC to keep up a steady temperature and rate of air flow for a guardroom, Safari and Torabi (2014) [22] ran a computational fluid dynamics simulation. The simulation was run in two situations over the course of a single day of winter: one without and one with the application of PCM. The stability of temperature of the guardroom is considerably enhanced by applying PCM as an energy storage media, based on the results. The panels matched with PCM never experience temperatures below ten degrees and rarely above seventy degrees (Fig. 2).

Albaldawi [23] utilized PCMs in SC power plant construction. The collector had a radius of 2 m, and the chimney had a height of 4 m. To assess the effects of incorporating PCM and examine the influence of inclination angles (16°, 8°), scientists designed and built a SC to calculate the resulting impact. The results indicate that the rate at which mass flows and the temperature difference (ΔT) have a substantial influence on the efficiency of the collector in the SC power plant. Furthermore, the point at which the temperature reaches the melting point varies in each case. The highest difference in temperature of 42.2 °C was recorded between the aluminum plate and the air nearby.

To examine the impacts of seven operational and design factors on the heating efficiency of an SC integrated with PCM, Li [24] constructed a numerically modeled study validated by experimentation. When increasing the latent heat from 70 to 170 kJ/kg, freezing and melting periods increase by 60 % and 103 %, respectively. Melting time reduces

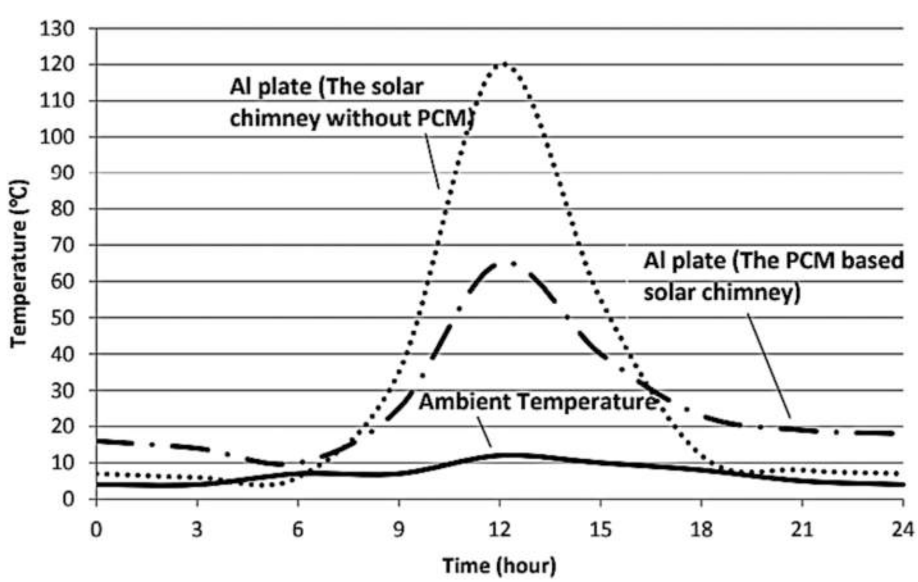

Fig. 2. Temperature comparison of Al plate in two situations: one with a SC based on PCM and the other without PCM [22] (published under open access).

by 36.4 % for every 33 % enhancement in flow of heat. By increasing the thermal conductivity of the insulating material from 0.02 to 0.06 W/m K, the melting time is extended by 47.2 %. The absorber absorptivity decreases by 26.3 % when its value is increased from 0.8 to 1.0. An enhancement of 25 % in the transmissivity of the glass cover leads to a corresponding decrease of 26.7 % in the melting time. The time of freezing decreases by 39 % when the inlet temperature of air decreases from 25 to 15 °C. Enhancing the absorber thermal conductivity by a factor of 25 merely leads to a modest 8 % decrease in the time it takes for melting to occur.

To check the effect of various parameters on the thermal efficiency of an SC paired with PCM, Li [25] introduced a verified computational model. The elements considered include the difference in temperature between the air input and outlet, the air flow rate, and the freezing or melting duration. The numerical findings indicate that the thermal performance of the SC is significantly impacted by the phase transition temperature of PCM. A PCM with a more significant disparity in phase transition temperatures will completely melt earlier than a PCM with a smaller disparity. However, it also alters the surrounding temperature, perhaps causing heat-related discomfort. The contribution of sensible heat to the freezing/melting process is determined by the heat capacity of the PCM. When the PCM thermal conductivity increases from 0.2 to 0.6 W/m °C, the average rate of mass flow and the difference in air temperature increase. The increase in mass flow rate from 0.033 to 0.038 kg/s, and the temperature difference increases from 1.5 to 2 °C. The early melting phase of the PCM is minimally affected by the starting temperature.

Fadaei [26] presented an experimental study that examined the impact of LHS on a SC pilot. In order to assess the SC efficiency, two types of examinations were conducted, one with the presence of PCM and one without. Velocity and temperature were estimated as well as other relevant data. On the Tehran campus University, a built SC measuring 3 m in height for the chimney and 3 m in diameter for the collector and integrated with paraffin wax as a PCM. The findings indicate that the conventional sun chimney (CSC) and the SC with PCM have maximum absorber temperatures of surface of 69 °C and 72 °C, respectively. Additionally, Fig. 3 illustrates that the highest velocity of air for the CSC is 1.9 m/s, whereas it reaches 2 m/s for the system merged with PCM. Therefore, the LHS system leads to an 8.33 % increase in the pilot's average mass flow rate. Implementing an LHS system in SC enhances its overall efficiency.

Fadaei [27] conducted a numerical and experimental studies to evaluate the impact of PCM on the performance of a SC. A SC, with a collector radius of 1.5 m, height of chimney of 3 m, and chimney diameter of 20 cm, was installed on the Tehran University of campus. The chimney was equipped with paraffin wax, which served as a phase transition medium (Fig. 4). Researchers demonstrated how to use an appropriately built Artificial Neural Network model to forecast the solar chimney's PCM performance. MATLAB software was utilized to create a multi-layer neural network and determine the correlation between the inlets and outlets. Eight inlets and four outputs made up the process, and it was evident that the trained network worked effectively for the issue modeling. The accuracy of the analysis was assessed by comparing the findings with the empirical data. The analysis resulted in a correlation of over 99 % for all outputs between the predicted values of the network and the experimental results.

Bashirnezhad [28] investigated the functioning of a laboratory solar chimney (Fig. 5) by employing thermal PCM. This prototype's geometric measurements are as follows: an air collector measuring 0.65 m in height and 11 m in circumference, and a chimney measuring 0.3 m in length and diameter. The airspeed meter, processor, and temperature sensors, were utilized as measuring devices to document temperature fluctuations of the ground, air confined in the collector, and intake air, as well as variations in intake air velocity, in three distinct modes involving the use of paraffin, water, and soil as thermal storage materials. Compared to the condition without an absorber, the findings indicate that using paraffin and water as thermal storage materials enhanced time productivity by 9 % and 20 %, and electric energy output by 6.2 % and 22 %, respectively. The thermal absorber concentrations for the two experiments 0.1, 0.103, and 0.11 kg/s for water and paraffin, respectively—are as follows. Fig. 6 depicts the highest mass flow rates, with values of 0.29, 0.28, and 0.27.

The influence of including a PCM on the performance of two various laboratory setups SC prototypes were investigated experimentally by Dordelly et al. [29]. It has been stated that SCs can enhance air quality of building and present continuous ventilation. The research provided an alternative strategy for improving the efficiency of SCs, which is now mostly attained by altering the size of the air gap, the tilt, or the diameters of the inlet and outlet. The prototype SC has dimensions of 3.50 × 1.00 × 0.30 m and is constructed with plywood plates that are 2 cm thick. The thermal conductivity of the plywood plates is 0.15 W/m K. An arrangement of seven halogen lamps directed toward a collector area of

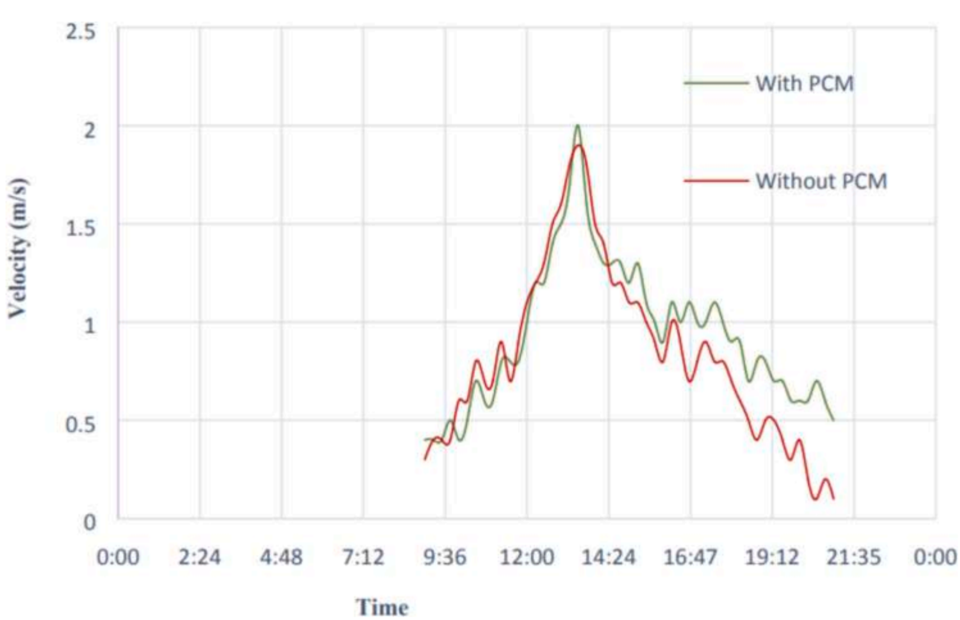

Fig. 3. The fluid's velocity both with and without PCM [26].

Fig. 4. Diagram showing how the SC was built [27].

$3m^2$ can provide an average airflow rate of 70 m^3/h and a relatively moderate increase of 550 W/m^2 after a charging period of 6 h. The findings demonstrate that when the halogen lights do not supply any energy to the SC, integrating PCM during a 6-h discharge period leads to increased ventilation and a delayed decrease.

Tiji [30] compared a PCM-enhanced SC with and without absorber plate fins against a non-PCM chimney based on room temperature, velocity, and airflow. CFD simulation simulates a winter day. Using PCM as a storage medium increases the room's temperature homogeneity, but the average temperature is 14.68 °C, considerably below the thermal comfort requirements. Moreover, the use of fins in the PCM-based SC system increases the average temperature of the room by 20 % compared to the non-finned version. Chen [31] introduced a new phase change heat storage technology for solar heating, enabling different porous layers of heat storage. The SC utilizes the buoyancy force to generate the heating airflow in the system, while several sieve beds are used to stack phase change capsules (PCC) (Fig. 7). Local thermal non-equilibrium (LTNE) is thought to develop in porous beds. Hence, the process of flow and heat transfer within the porous layer of thermal storage is examined by employing the double energy equations and the Brinkman-Forchheimer extended Darcy model. With the above formulae and the k-ε turbulent model, researchers can also look at how different materials, PCC porosity, particle size, and flow channel characteristics affect the effectiveness of thermal storage. Fig. 8 illustrates how thermal storage Q varies over time in the beds of various materials. Heat Q values above zero mean that the beds are charging with heat, while values below zero mean that the beds are losing heat.

An experimental investigation was presented by [32] to investigate the impact of heat flow and inclination angle on the thermal performance of a SC combined with a PCM. Three heat fluxes (400 W/m^2, 500 W/m^2, and 600 W/m^2) and three inclination angles (30°, 45°, and 60°) were employed. The obtained results showed that the PCM's natural convection intensity is influenced by the inclination angle in addition to the buoyancy impact. Compared to the PCM complete melting times at 60°, the times at 45° and 30° were 6.7 % and 8.6 % longer, respectively. The 400 and 500 W/m^2 heat fluxes lengthened melting time by 16.1 % and 8.0 %, respectively, compared to the 600 W/m^2. The angle of inclination affected PCM heat transfer more than heat flow.

The influence of integrating a vertical SC with a PCT storage system was examined by Fu [33]. Important factors influencing the multi-curved trough collector's capacity to collect heat for solar greenhouses are the velocity of air within the collector and the sun's radiation intensity. The heater has the best overall heat-collecting performance, and as solar radiation intensity rises, so does heat collection. The distance between vertical air channels, the direction of airflow, and the velocity of air, specifically the ability of the middle layer of block wall to store

Fig. 5. Solar power plant experiment [28].

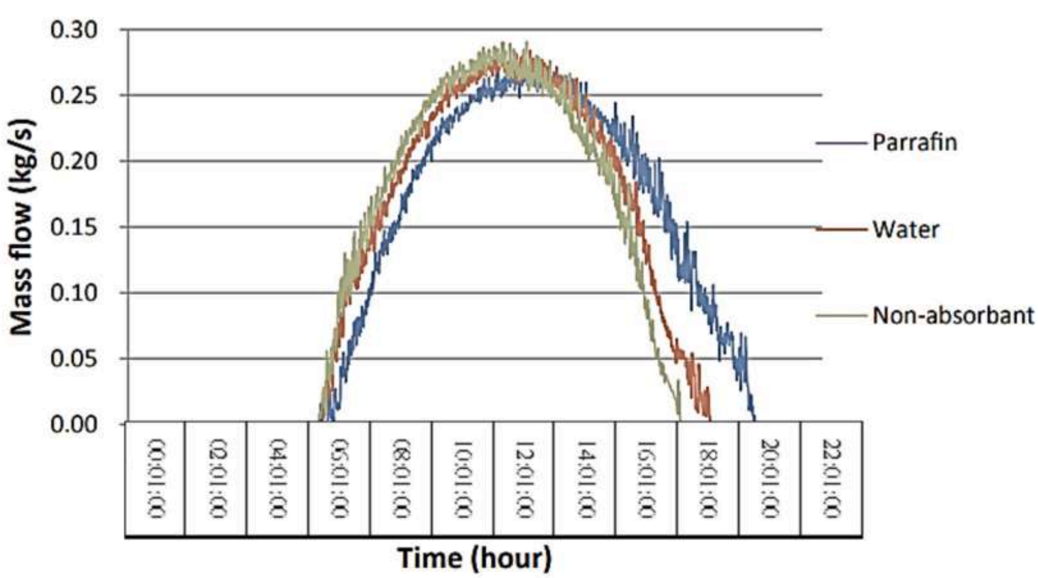

Fig. 6. Mass flow over a period of 24 h [28].

solar active heat and facilitate heat transfer, all impact the heat storage of phase change wall with vertical air channels. With a velocity differential of around 0.67 m/s between the entrance and output, the air traveling through the chimney flow channel reaches the top at its fastest speed. Table 1 introduces a summary of the thermal performance enhancement investigations published between 2014 to 2023.

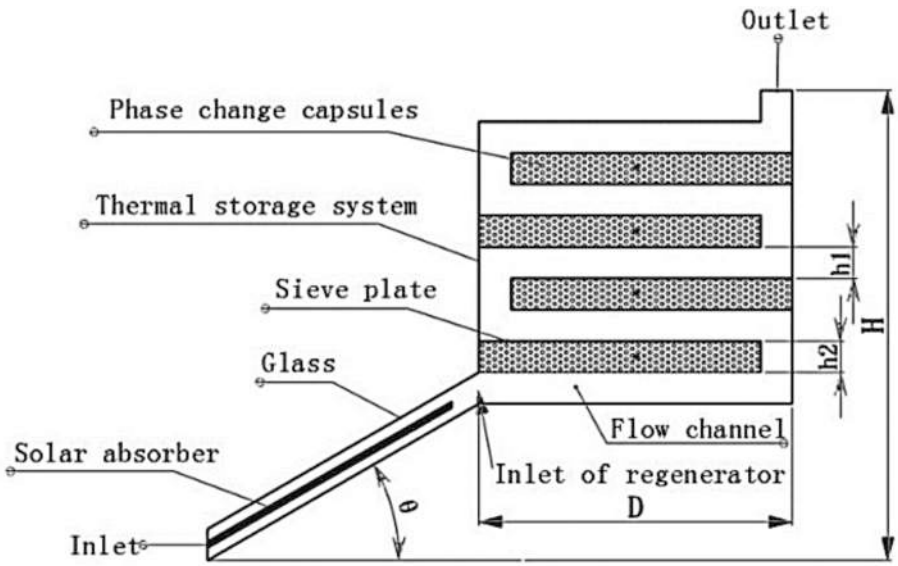

Fig. 7. Sketch of a SC thermal storage bed with capsules of phase-change on sieve plates [31].

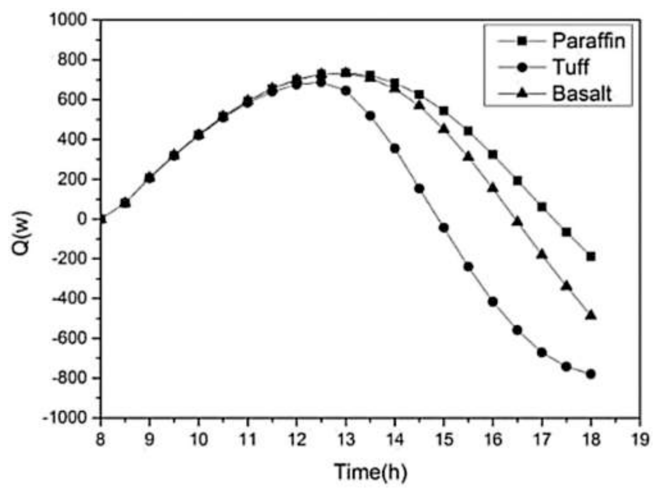

Fig. 8. Changes in the system's heat storage capacity over time while using various particle materials [31].

3.2. Indoor climate and ventilation control

An innovative method for enhancing the management of ventilation and interior climate is given by the integration of PCMs with SC systems. These systems enhance ventilation while maintaining delightful interior temperatures by utilizing thermal storage properties of PCMs. This creative combination stimulates better conditions of living in addition to enhancing energy efficiency. It is vital to understand the workings of PCM-integrated SCs in order to encourage environmentally friendly construction practices and improve inhabitant comfort.

A certain dimensions of test room was built in 2016 in Baghdad by Murtadha et al. [34], where SC was placed with the south-facing wall and designed with an AR greater than 12. The SC collector is built with paraffin wax, which serves as a PCM, and is supported by a copper foam matrix (CFM) in order to improve the overall performance of the thermal energy storage material box (TESMB). The experimental findings indicate that TESM is effective in closed loop SC throughout the day and that its consequences prolong into the evening. The heating system of test room attains its maximum temperature just after sundown, when the temperature difference between the outside and inside is about 15 °C. Five hours later, the difference in temperature is even larger, at about 8 °C. CFD is applied as a numerical solution, while the FVM is utilized to solve the PDEs. Long after the sun sets, there is still a heating impact because heat is retained as a latent heat of fusion with just a slight temperature difference. This implies that this solar chimney design is successful not just during the day but also at night.

Thantong and Chantawong [35] reported on the effectiveness of a solar wall collector with PCM (SC-PCM) concerning the natural ventilation of experimental dwellings. The system comprises of an inner wall built of concrete material, an air gap, and a solar wall collector with a PCM panel (Fig. 9). Height 1.40 m and width 0.80 m are the dimensions of the SC-PCM. Both the inside concrete wall and the exterior solar wall collector with PCM have a comparable thickness of around 15 cm. To improve ventilation, opening sections on the top (outdoor) and bottom (inside) discharge heated air into the atmosphere. Furthermore, an insect-repelling net covers the upper entrance region. This study focuses on a solar wall collector with a PCM system located in the south façade of a small home. The home's walls are made of concrete and are 10 cm thick. The SC-PCM house has reduced heat conduction compared to the SW house due to its single-wall design, which acts as a barrier preventing inside heat from escaping. Specifically, only 59.63 % of the heat transfer occurs during the day via the south wall of both houses (Fig. 10).

Lu [36] conducted a quantitative investigation on a SC's heat storage capacity and airflow rate linked with several PCMs during nighttime (Fig. 11). PCMs at the following temperatures were used in their numerical study: 38 °C, 44 °C, 50 °C, and 63 °C. The largest thermal storage capacity of 4750 kJ/m^2 and the maximum average ventilation rate of 610 kg/m^2 are seen at a phase transition temperature of 38 °C. Under the same circumstances, nocturnal ventilation does not happen at a phase transition temperature of 63 °C. A more significant temperature of phase change requires more solar radiation intensity and longer charging durations for solar chimneys, whereas a lower temperature improves changeability and discharge ability. The PCM loses most of its heat to the surrounding air through radiation-tight glass coverings, with just a small portion being used to heat the air inside air channels. The temperature of phase change of the PCM is 44 °C. The air temperature differential between the input and output exhibits a similar shifting tendency to that of the ventilation rate. A higher temperature of phase change shortens the ventilation duration and makes the chimney less chargeable (Fig. 12).

Thantong [37] presented an experimental study on the thermal performance of a novel type of SCs that includes a PCM. Researchers aimed to reduce heat gain and increase natural ventilation. The SC-PCM consists of two walls with a 0.05 m air gap between them. The sun-

Table 1
A summary of thermal performance enhancement investigations.

Author year [reference]	Geometry	Study type	Examined variables	Results and remarks
Safari and Torabi (2014) [22]	SC with PCM.	Numerical	Phase change materials.	The temperature stability of the guardroom improves significantly when PCM is used as an energy storage device.
Albaldawi et al. (2014) [23]	SC power plant with PCM.	Experimental	Phase change material.	In both situations, the melting point temperature occurs at a different time. The highest temperature differential of 42.2 °C was observed between the aluminum plate and the surrounding air.
Li (2015) [24]	SC combined with PCM.	Numerical	Design and operational parameters.	When the latent heat enhances from 70 to 170 kJ/kg, increases the melting time by 103 %, and freezing time enhances by 60 %.
Li et al. (2017) [25]	SC equiped with PCM.	Numerical	The air temperature differential between the input and output, air flow rate, and melting/freeezing time.	A PCM with a larger phase transition temperature differential melts completely sooner than one with a smaller one.
Fadaei et al. (2018) [26]	Solar chimney integrated with PCM.	Experimental	Latent heat storage.	The LHS system results in an 8.33 % increase in the pilot's average mass flow rate.
Fadaei et al. (2018) [27]	Solar chimney filled with PCM and equipped with artificial neural network.	Experimental	Model suitability.	The analysis verified a correlation exceeding 99 % for all outputs when contrasting the forecasted values from the network against the experimental results.
Bashirnezhad et al. (2018) [28]	SC's components include an air collector with an 11 m diameter and a 0.65 m height, as well as a chimney with a diameter of 0.3 m and a length of 12 m.	Experimental	PCM and water.	Electric energy generation has grown by 6.2 % and 22 %, and time productivity has increased by 9 % and 20 % when water and paraffin are used as thermal storage materials.
Dordelly et al. (2019) [29]	SC integrated with PCM under laboratory conditions.	Experimental	Phase change material.	When PCM integration is used, the ventilation rate increases and decreases more gradually during ventilation-only periods (6-h discharge), when the solar chimney receives no energy from the halogen lights.
Tiji et al. (2020) [30]	PCM-base passive SC with a finned absorber.	Numerical	Thermal energy storage and fins.	The average room temperature increased by 20 % when fins were incorporated into the PCM-based SC system as opposed to the non-finned model.
Chen and Chen (2020) [31]	SC with the sieve-plate thermal storage bed packed with PCM.	Numerical	Materials, porosity and particle size of PCC.	The thermal period of storage of the PCC layer is 7 % to 25 % larger than that of the basalt and tuff layers. The heat storage in the system is influenced by the particle size and porosity of the porous layer. Achieving optimal thermal storage performance may be possible by maintaining a specific ratio between the width of the flow channel and the thickness of the bed.

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Table 1 (*continued*)

Author year [reference]	Geometry	Study type	Examined variables	Results and remarks
Li et al. (2022) [32]	Inclined SC integrated with PCM.	Experimental	Angle of inclination and heat flux.	The buoyancy effect and the PCM's natural convection intensity are both influenced by the inclination angle. At 45° and 30°, the PCM complete melting durations were extended by 6.7 % and 8.6 %, respectively.
Fu et al. (2023) [33]	Vertical SC in greenhouse integrated with PCM.	Experimental	Phase change material.	Air moving through the chimney flow channel reaches the top at its fastest speed with a velocity differential of 0.67 m/s between the entry and exit.

exposed exterior wall is composed of three layers: a 0.01-meter-thick cement board panel painted black is the first layer. A paraffin-filled tank measuring 0.015 m × 0.8 m × 1.28 m makes up the second stratum. Based on the test results, the interior temperature of the room with a single concrete wall was higher than that of a single concrete wall containing PCM. In addition, the ventilation rate induced by SC-PCM varied in response to the solar radiation intensity. According to Fig. 13, the SW (TC) temperature is 2 to 18 °C lower than the temperature of the S-PCM walls (TG).

Salari [38] made a finite-dimensional computer model of the new compound SC, including a PCM and a photovoltaic (PV) module. The model is almost steady. This combination is called as the SC-PV-PCM system. It is demonstrated that, out of all the PCMs investigated, the RT-50 executes better. An SC-PV-PCM system in a Shanghai office and residential building was compared to standard SC, standalone PV modules, combined SC-PV systems, and combined SC-PCM systems in terms of performance. Power generation performance was superior for the SC-PV-PCM system compared to other systems. The SC-PV-PCM system has been proven to be the most suitable option for residential structures. In contrast, the SC-PV system is optimal for office buildings situated in subtropical regions. Additionally, using PCM in the system improves its ability to ventilate (Fig. 14).

A 2-D numerical study of a prototype SC system incorporated with an absorbent capacity wall of a structure's south face was presented by [39]. The capacity wall is composed of a metal foam embedded with a specific thickness of PCM and a high-absorbing plate. The chimney is made out of a glass plate that is inclined by two degrees and a converging duct with a single vertical absorbing wall. The channel gap is 0.20 m at the exit and 0.34 m at the inlet, while the channel height within the chimney is 4.0 m. The device for storing thermal energy is 4.0 m high. The goal of the numerical research was to assess the SC's incorporated latent thermal energy storage system's fluid dynamics and thermal behaviors. According to the study, the PCM has not melted completely in any of the examples throughout the day, and the aluminum foam within the box reduces the daytime temperature variance.

Nateghi and Jahangir [40] developed a computer model of a home using three different EnergyPlus modes: one without SC, one with SC, and one with SC combined with a layer of PCM. The standard SC with PCM diagram is shown in Fig. 15. Three distinct climates have been used to develop terms of thermal comfort for these cases: Yazd, hot-arid; Bandar Abbas, hot-humid; Tehran, cold semi-arid. The findings demonstrated that employing PCM in SCs produced unhappiness in hot, dry regions for both heating and ventilation modes of SC operation. PCM aids SC in achieving optimal interior thermal comfort in Hot-Humid and Cold Semi-Arid climates (Fig. 16). In the hot and humid city, the average thermal comfort indices PMV rise from "0.75" to "0.67" during the summer and from "-0.07" to "0.04" during the winter. After implementing PCM, the PMV index of the Semi-Arid city also changed. In the summer, it decreased from 1.24 to 1.16; in the winter, it decreased from −1.1 to −0.85.

Buonomo et al. [41] conducted a two-dimensional numerical analysis of an SC combined with an absorbent capacity wall located on the southern side of a building. In July and December, the analysis was carried out in Aversa, Italy, from dawn until dusk. The chimney consists of a glass plate with an angle of two degrees, a vertical absorbing wall, and a converging channel. Its height is 5.0 m, and the channel's height is 4.0 m, with an inlet of 0.34 m and an outflow part of 0.20 m. A PCM and metal foam were combined in the thermal energy storage system. Four alternative configurations are analyzed to determine the optimal hybrid

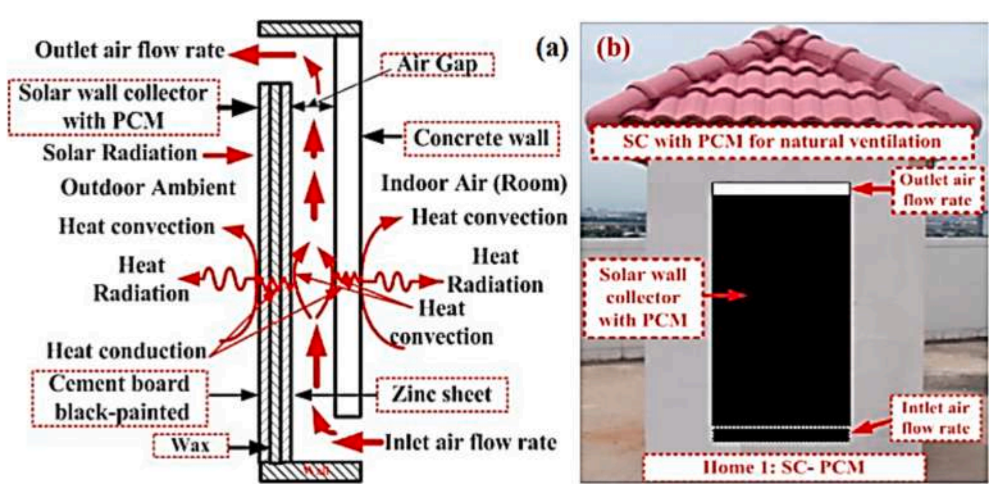

Fig. 9. Heat transfer via the experimental home equipped with SC-PCM (b) and the Solar Wall Collector with PCM (a) [35].

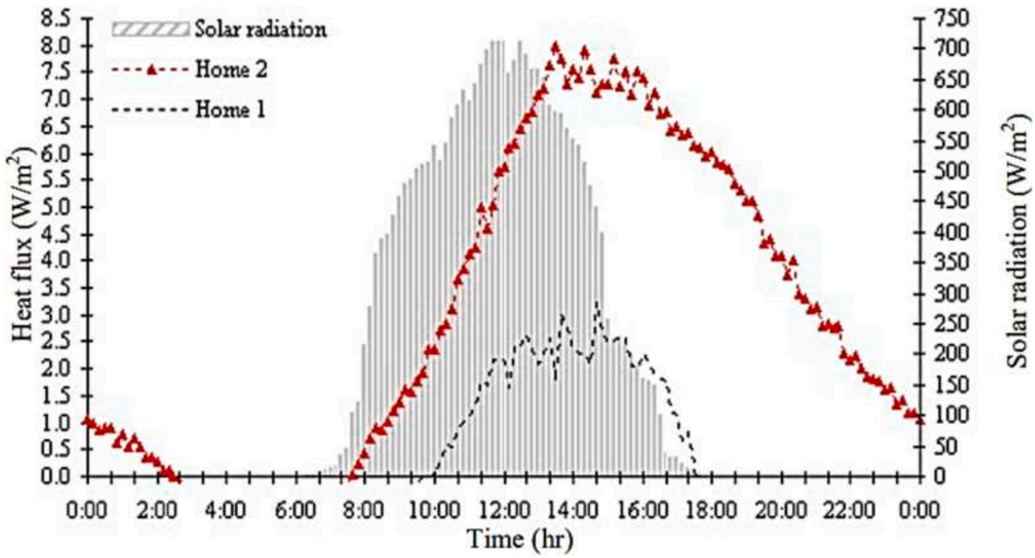

Fig. 10. Changes in the sun's rays on a vertical plane every hour and the flow of heat between the two homes [35].

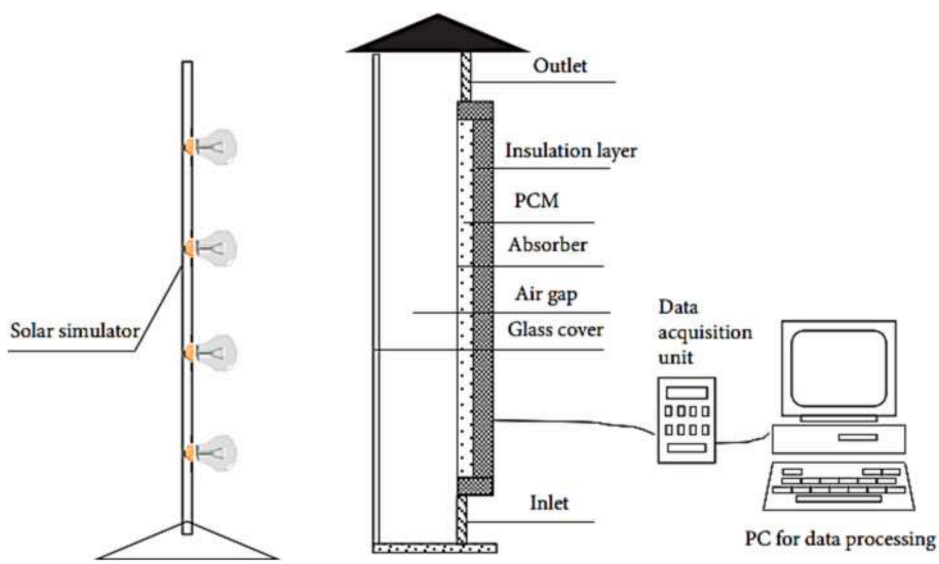

Fig. 11. The experimental solar chimney's schematic design [36] (published under open access).

system layout in terms of thermal performance. This analysis is conducted using the commercial software ANSYS-Fluent. The results show that the energy gathered will increase as the storage plate gets thicker (Fig. 17).

Using ANSYS 2022/R1, Abduljabbar et al. (2022) [42] created out a simulation for a two-story structure connected to a vertical solar chimney. The study was carried out on May 8, 2016, in the climate of Al-Kut City, Iraq. The purpose of the study was to compare the ventilation performance of SC with and without the addition of energy storage. To determine the ideal ES, three different types of PCM were examined: block-shaped paraffin wax, RT-42, and Al-dura. Based on Average Air Change per Hour (ACH), average temperature of interior, and time of ventilation after sunset, the numerical findings indicated that Al-dura was the best paraffin wax. After using Al-dura wax, the ACH rose by 18.3 % and 9.95 % for the first floor and the second floor, respectively, as compared to the first model (without ES). Conversely, on the first and second floors, the inside temperature dropped by 1.17 K and 0.68 K, respectively. As seen in Fig. 18, the maximum and lowest amounts of (ACH) for the first and second floors were, respectively, 9.5 and 3.

Through experimental investigation, Huang et al. (2024) [43] explored the efficacy of solar chimneys at several inclination angles (30°, 45°, and 60°) without and with PCM. The experimental findings showed that it is unable to overlook how the inclination angle affects convective heat transport inside the PCM. The 45° instance had the lowest time of solidification, but the 30° and 45° cases had PCM melting periods that were 3.3 % and 13.3 % longer, respectively, then in the 60° example. The best inclination angle was discovered to be 45°, at which point the SC, both without and with the PCM, achieved maximum velocity of air values of 0.37 and 0.4 m/s. After the source of heat was switched off, the SC with PCM integration allowed for a prolonged ventilation period of more than 10 h.

The effect of PCM on the exergy efficiency and performance of a SC was investigated by Nia and Ghazikhani [44]. Two identical-sized pilot solar chimneys were built by researchers; each had a 5 m diameter of collector and a height of chimney of 4 m. As an energy storage layer, one solar chimney had hydrated salt PCM installed, whereas the other didn't. Theoretical turbines were used to assess the power generation and ventilation capabilities of both systems. An exergy study that

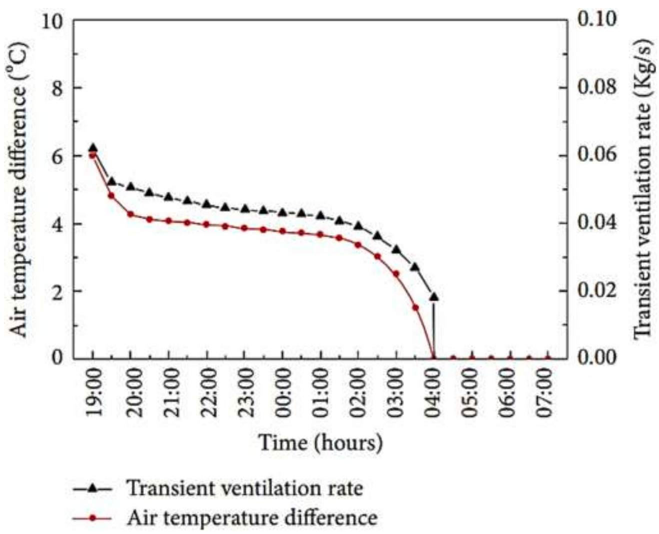

Fig. 12. Variation in ventilation rate and air temperature during 44 °C phase transition [36] (published under open access).

followed allowed for the determination of the systems' operating behavior and efficiency. According to the study, PCM dramatically raised the solar system's average air mass flow rate, which was found to be 0.045 kg/s on a daily basis. Over the course of a full day, the airflow through the turbine resulted in mean pressure decreases of 1.83 and 2.44 Pa, respectively. The enhanced thermal energy storage of PCM also contributed to a nearly 19 % increase in energy efficiency. A summary of the relative studies published between 2016 to 2024 of indoor climate and ventilation control is depicted in Table 2.

3.3. Hybrid systems integration

A multidimensional approach to energy efficiency and climate management is provided by the hybrid integration of several solar technologies, such as photovoltaic panels and solar thermal systems, with solar chimneys and phase change materials (PCMs). This integration would enhance the implication of renewable energy sources while also improving the performance of each individual element. Jointly, these solutions of cutting-edge can source improved interior comfort and lower energy usage. It is important to perceive the dynamics of these hybrid systems to ascertain green building activities and sustainable construction processes.

An examination room of $(2 \times 1.5 \times 1.5)$ m^3 was created by Murtadha et al. (2016) [45] and combined to SCs that had an AR greater than 12. Several SCs were constructed in the examination room, including a vertical single side air pass with AR equal to 25 and a 45-degree slanted double side air pass with AR equal to 50 for each pass. The parts of both collector types are flat box of thermal energy storage collectors (TESB). The third category of collector is a series of evacuated tubular collectors with a 45^o thermosyphon placed at the bottom of the TESB. The approved system can lessen the temperature of the examination room by up to 8.5–9.2 °C between 11:00 am and 3:00 pm when the EC is operating at an extreme efficiency. Moreover, the findings showed that the TESB was less fruitful for ventilation and EC at night than it was throughout the day.

Bin et al. [46] looked at how the placement of PCM in a hybrid wall affected the SC effect. The PCM thickness was 1 cm, the gap of air was 30 cm, and the output of simulated solar light was 780 W. The findings exhibit that the air in the gap had a greater temperature when PCM was ahead of the absorber than when it was in rear the absorber (Fig. 19). The study discovered that when simulated solar light was turned on, the air velocity with PCM ahead of the absorber was higher than that with PCM in the rear absorber, and when solar light was turned off, the air velocity with PCM in the rear absorber was lower.

Unsteady state numerical simulation of a SC syatem was given by Xamán et al. (2019) [47] on the hottest day in Madrid, Spain, considering radiative and convective gains/losses to the outside surrounding. A conjugate heat transfer study was carried out for SC using three different kinds of absorbing materials: (1) SC with a reference case of a lightweight plate made of copper, (2) SC with a PCM 46–50, and (3) SC with a heavyweight wall made of concrete. As per the findings, the SC featuring a copper plate demonstrates higher mass flow rates of 0.016, 0.019, and 0.016 kg/s for east, west, and south orientations, respectively. Although the PCM arrangement removes mass at a faster rate than the concrete wall configuration, it does so at a slower rate than the copper plate. The average heat efficiencies of the SC for east, west, and south directions are 34, 27, and 34 % for copper plates and 28, 19.8, and 27 % for PCMs (Fig. 20).

A 2-dimensional numerical analysis of a prototype SC system integrated with an absorbent capacity wall of a structure's south face was reported by Buonomo et al. (2019) [48]. A higher-absorbing plate and a certain thickness of PCM make up the capacity wall. The chimney is made up of a glass plate that is 2° inclined toward the vertical and a converging duct with a single vertical absorbing wall. The height of channel is 4.0 m, and the chimney is 5.0 m high. The gap of channel is

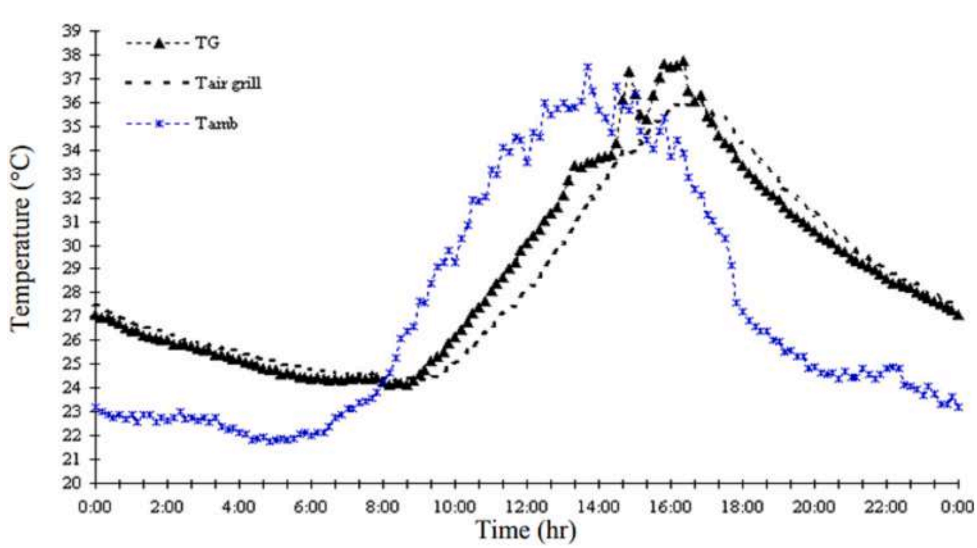

Fig. 13. Temperature fluctuation over an hour at several locations within the SW home [37].

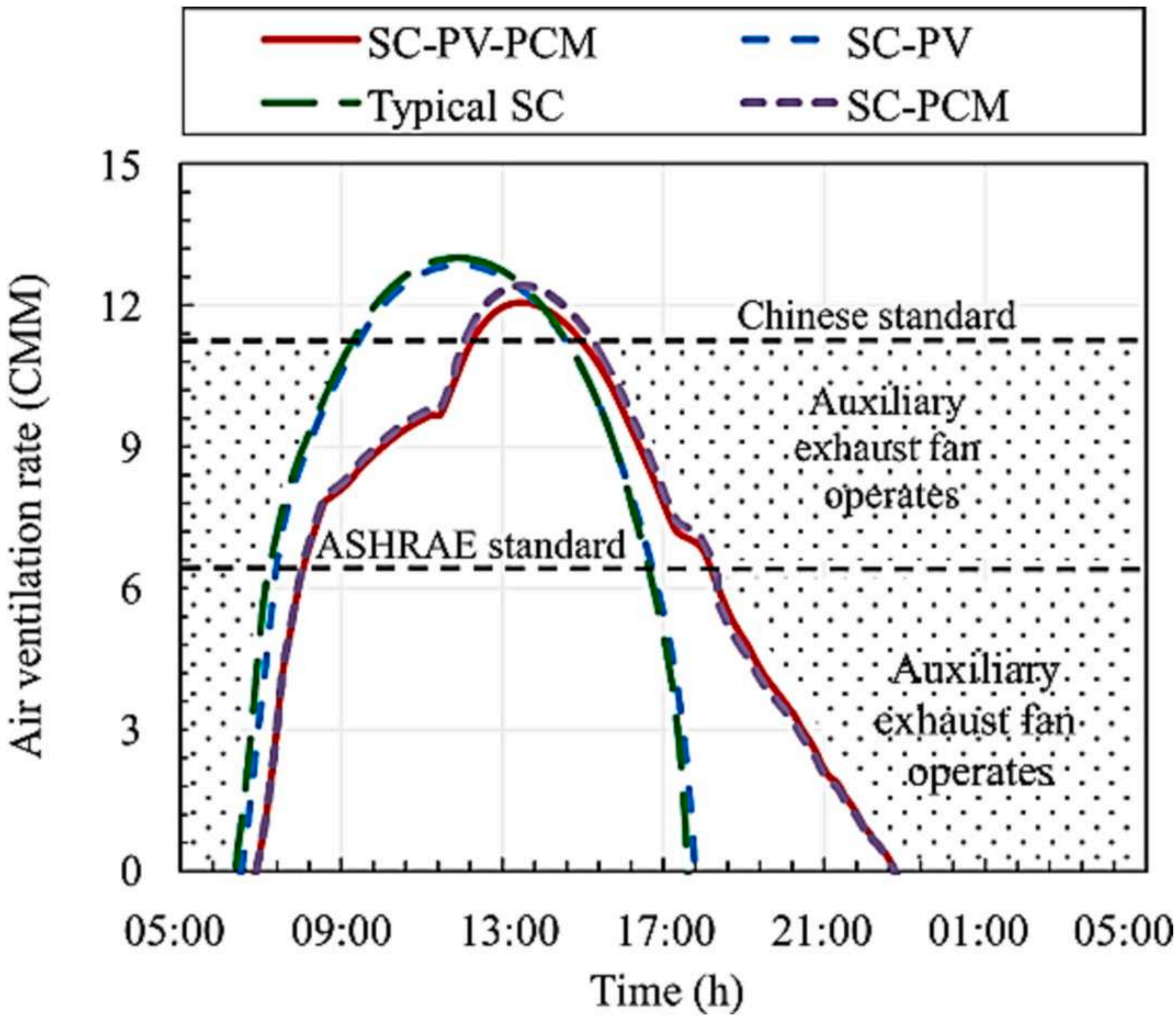

Fig. 14. The ventilation capability of investigated SCs for a residential building [38].

0.20 m at the exit and 0.34 m at the intake. The mechanism for storing thermal energy is 4.0 high. The governing equations are provided in terms of the k-ε turbulence model, and the transient analysis is performed on a 2-dimensional model in airflow. The PCM is not entirely liquid, according to the results; instead, it is changing phases and increasing in temperature regardless of radiant energy. Additionally, the wall temperature is lower with PCM than it would be without it; hence, PCM's ability to absorb energy during the hotter hours and return it during the colder ones is sufficient.

The inclined rooftop SC performance combined with a PCM and photovoltaic (PV) module referred to as the SC-PCM-PV system is improved by Ashouri and Hakkaki-Fard (2021) [49]. Using the finite volume approach, a 3D-CFD model is created to investigate how different design parameters such as fin number, thickness of fin, type of PCM, and mass of PCM affect the duration, capacity of ventilation, and power output of natural ventilation. The findings show that while increasing PCM mass does not considerably lengthen ventilation, it does reduce finless case ventilation capacity. On the other hand, for the finned cases, enhancing the mass of PCM improves power generation, duration of ventilation, and capacity. Using a finned absorber enhances capacity of duration and ventilation by 17.6 % and 7.7 %, respectively. It is discovered that the SC-PCM-PV system's ventilation duration is increased by composite PCMs based on copper foam. Moreover, using SAT/CF (Sodium Acetate Trihydrate/Copper Foam) as the PCM improves capacity of ventilation by 19.8 % when compared to a SC plus a PV module, also known as the SC-PV system.

Through the use of a validated 3-dimensional numerical investigation, Cao et al. (2021) [50] proposed an inventive tilted SC Ventilator with PCM incorporated with Photovoltaic technology (SCV-PV-PCM) and studied under real transient weather conditions (based on Hong Kong climate) (Fig. 21). The features of SCV-PV-PCM are investigated throughout the day (across many months, including March, June, September, and December) and contrasted with those of the traditional SCV-PV system. The findings show that the SCV-PV-PCM has a greater generated power and capacity of ventilation than the standard SCV-PV system. Nevertheless, because of the low outside temperature and intense solar radiation, the system is unable to supply the building with the necessary ventilation power throughout the winter. In addition to providing the building with enough daytime ventilation in June, the SCV-PVPCM also increased the building's electrical power consumption

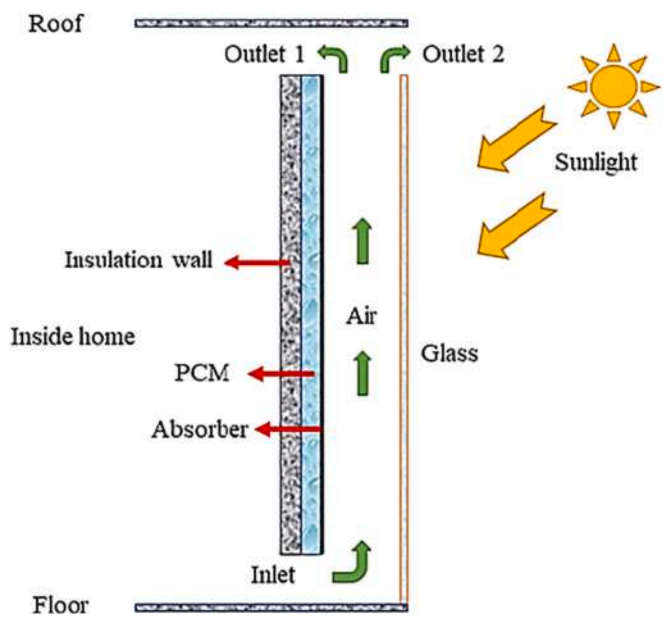

Fig. 15. PCM is designed on the south side of the home in the general scheme of the SC [40].

(Fig. 22).

An efficient hybrid SC, photovoltaic panel, and PCM (SC-PV-PCM) were studied by Cao et al. [51]. Researchers used a thorough 3D verified numerical simulation to determine the most effective properties of PCM for this particular application. It should be noted that the ideal PCM should have the capacity to increase power generation and ventilation efficiency at the same time. The aforementioned system's economic features are also assessed. The simulation runs from sunrise to sunset in June under the transitory actual meteorological conditions of Hong Kong, including intensity of solar radiation, temperature of ambient, temperature of sky, and speed of wind. The findings indicate that thermal conductivity somewhat impacts the SC-PV-PCM system's

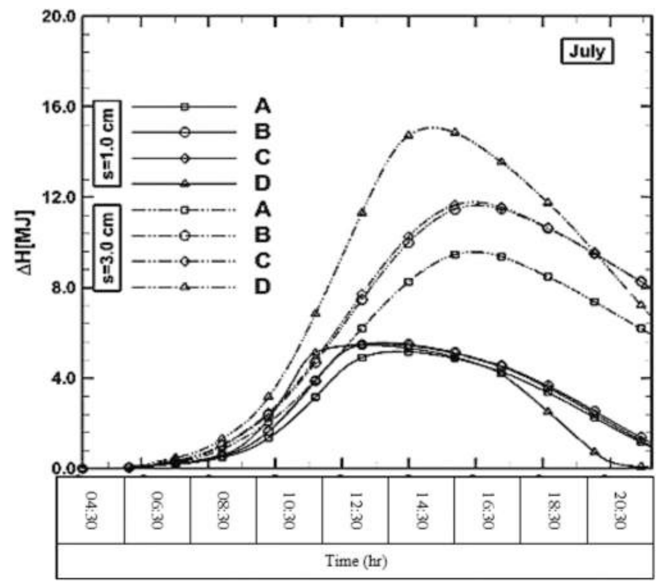

Fig. 17. Energy held for s = 1.0 cm and 3.0 cm as a function of time [41] (published under open access).

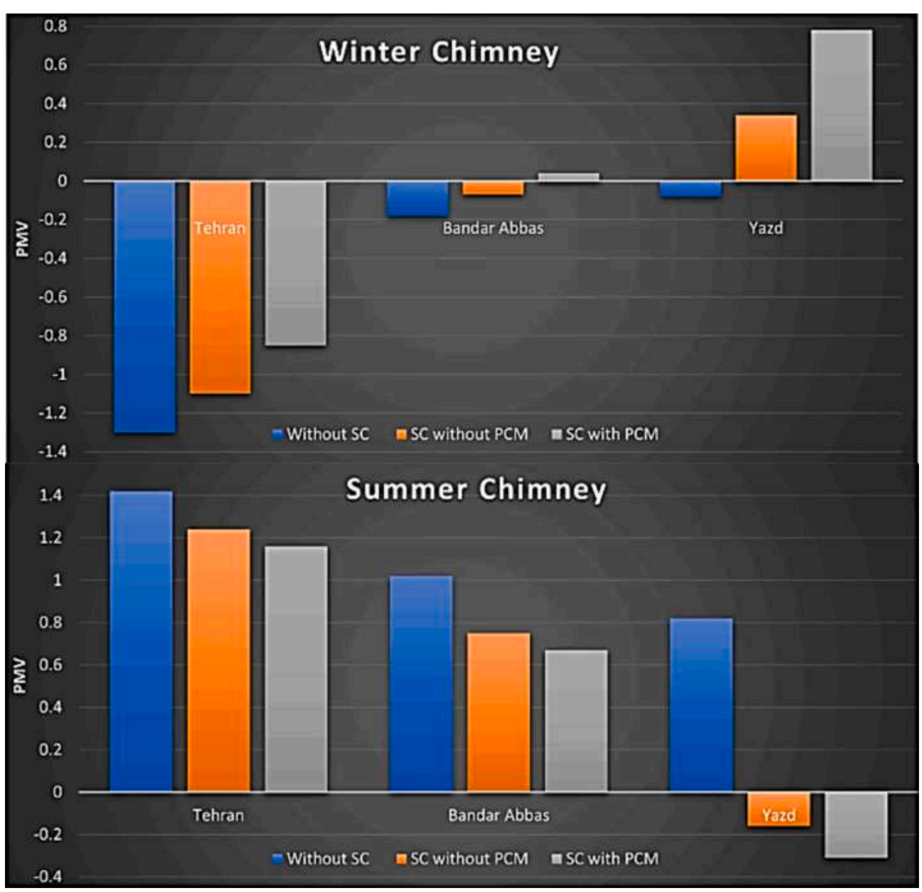

Fig. 16. Results summary [40].

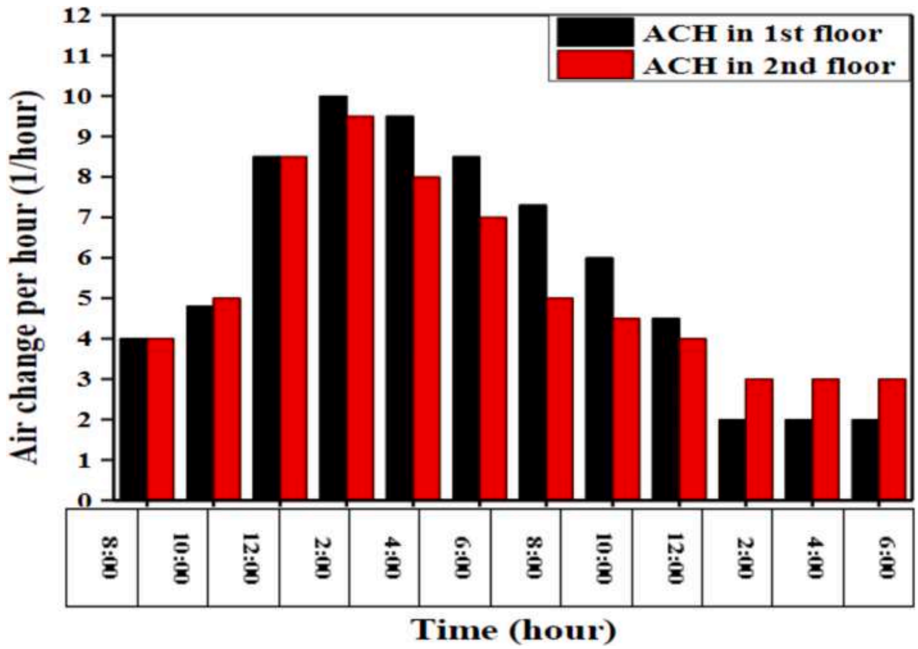

Fig. 18. Air changes per hour using RT-42 wax [42] (published under open access).

Table 2
A summary of studies related to ventilation and indoor climate control.

Author year [reference]	Geometry	Study type	Examined variables	Results and remarks
Murtadha et al. (2016) [34]	Closed loop SC integrated with PCM and CFM.	Experimental and Numerical	PCM and CFM.	Long after the sun sets, there is still a heating effect due to retaining of heat as the latent heat of fusion with just insignificant temperature difference.
Thantong and Chantawong (2017) [35]	The solar wall collection has an air gap, a PCM panel, and a concrete wall on the inside.	Experimental	PCM panel, an air gap, and a solid wall on the inside.	The inside of the solar wall collector with PCM chamber was much cooler than the inside of the single concrete. A solar wall collector with PCM can change the rate of ventilation based on how much sunlight is hitting it.
Lu et al. (2017) [36]	SC coupled with various PCMs at night.	Numerical	PCM	The greatest average rate of ventilation of 610 kg/m^2 and the highest thermal storage of 4750 kJ/m^2 are attained at the temperature of phase transition of 38 °C. Nocturnal ventilation does not occur at a phase transition temperature of 63 °C, even under identical conditions.
Thantong et al. (2018) [37]	The SC-PCM consists of two walls with a 0.05 m air gap between them.	Experimental	PCMs, double walls, and air gap.	The solar chimney with PCM chamber had a colder interior than the room with a single concrete wall. Additionally, the ventilation rate that SC-PCM caused changed in response to the solar radiation intensity.
Salari et al. (2020) [38]	A sloped roof SC incorporated with PCM and a PV module.	Numerical	PCMs with various melting points.	The SC-PV-PCM system surpasses other systems in power generation terms.
Buonomo et al. (2020) [39]	SC integrate with PCM and metal foam.	Numerical	PCM and metal foam.	The aluminum foam within the box reduces the change in temperature during the day, and the PCM has not melted completely.
Nateghi and Jahangir (2022) [40]	SC combined with a layer of PCM.	Numerical	Layer of PCM.	Combining PCM in SCs leads to dissatisfaction with the ventilation and heating modes in hot and dry areas. PCM, however, helps SC offer suitable interior temperatures in cold, semi-arid, and hot, humid conditions.
Buonomo et al. (2022) [41]	SC integrate with PCM and metal foam.	Numerical	PCM and metal foam.	The collected energy will increase with the thickness of the storage plate.
Abduljabbar et al. (2022) [42]	SC with energy storage material (Al-dura wax).	Numerical	Al-dura wax.	After applying Al-dura wax, the Air Change Rate (ACH) increased by 18.3 % and 9.95 % for the first and second floors, respectively. In contrast, the temperature indoors decreased by 1.17 K on the first floor and by 0.68 K on the second floor.
Huang et al. (2024) [43]	SC with PCM at various angles of inclination.	Experimental	PCM and inclination angle.	The optimal inclination angle was determined to be 45°, at which the SC, both without and with the PCM, attained peak air velocity values of 0.37 and 0.4 m/s, respectively.
Nia and Ghazikhani (2024) [44]	SC with hydrated salt PCM.	Experimental	PCM	The average daily air mass flow rate with PCM was 0.045 kg/s, but without PCM, it was 0.033 kg/s.

performance in terms of both ventilation and electrical output. The air temperature drops prior to the PCM melting process beginning when the thermal conductivity is enhanced (Fig. 23).

A PCM-based SC incorporated with earth-air heat exchanger (SCEAHE) system was suggested by Long et al. [52]. By including PCM, the SCEAHE system's thermal inertia was enhanced. Simulated data

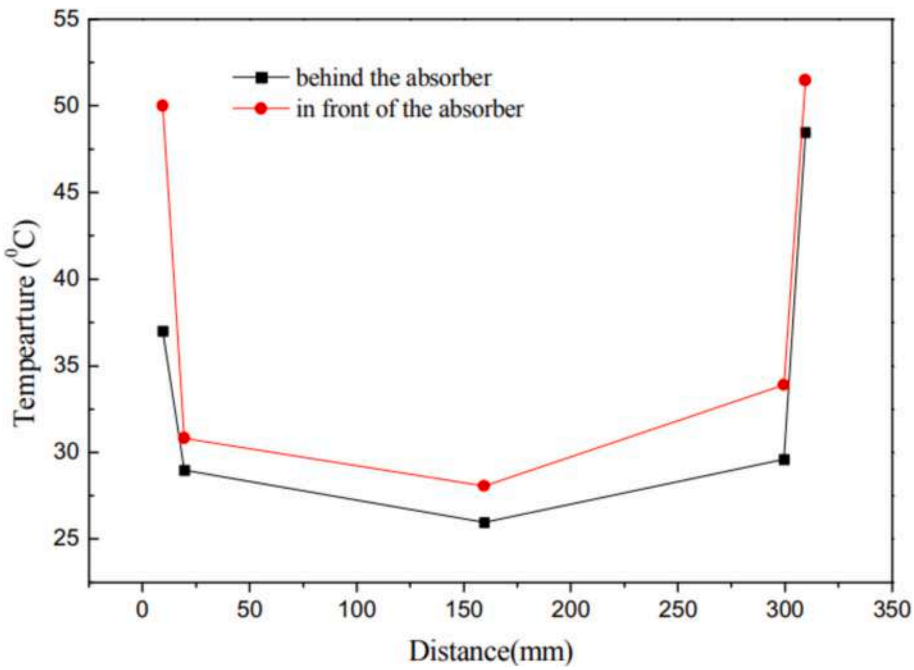

Fig. 19. The air temperature distribution inside the gap [46].

showed that the absorber of the SCEAHE system with PCM had a maximum surface temperature of 78.8 °C, 16.2 % lower than without PCM. The charging of PCM and draining times were around 14.5 h and 9.5 h (05:30–15:00), respectively. About 5 h passed between 15:30 and 20:30 during which the PCM fully melted; hardened PCM first emerged between 02:00 and 7:15, peaking at 24 % at 05:30. The maximum flow rate of air was lowered by 17.8 % to 209.5 m^3/h during the day and the airflow rate of SCEAHE was boosted by 50 % at night by incorporating PCM.

An experimental model of a hybrid PV SC that was erected and integrated with various materials was given by Saleh et al. [53]. It was investigated how different materials affected the PV/solar chimney's performance. The phase-change material (PCM) in this case was asphalt, and the porous medium was the gravel bed. The following experimental findings demonstrate that, at 8:00 a.m., the chimneys paired with porous medium and PCM had the greatest electrical efficiency values, reaching 13.16 % and 13.12 %, respectively. When these materials were mixed with the chimney, the PV panel temperature dropped compared to other chimneys. From the start of the test until the afternoon, the velocity of air leaving the collector for systems without these materials merged was higher than for systems with porous media and PCM, reaching 1.60 m/s and 1.45 m/s, respectively, around midday. Table 3 elaborates a summary of the published studies between 2016 to 2024 regarding the hybrid systems integration.

4. Critical analysis and associated challenges of integrated phase change materials and solar chimneys

The current section presents a critical analysis of the revised studies to better perceive the advantages and limitations of the integration of PCMs with SC systems. The existed literature presents different methodologies and outcomes, underlining improvements in energy efficiency and thermal performance. However, it is vital to discourse the limitations present in these investigations. For example, while several studies establish the potential of PCMs to enhance thermal regulation and lessen energy consumption [54,55], the variability in PCM materials and their thermal properties can lead to unreliable results. Also, specific studies lack inclusive long-term evaluations, which could deliver visions into the strength and performance of PCM-integrated SC systems under various environmental conditions. Furthermore, the procedures engaged in these studies vary meaningfully, leading to challenges in comparing results across different research. Some other investigatons were deeply dependent on numerical simulations, and others concentrated on experimental setups, which might familiarize biases in the results. The effect of design parameters and local climatic conditions on the performance of PCM systems is also frequently underexplored. Future research directions can therefore be knowledgeable by recognizing gaps in knowledge and underlining the need for standardized testing protocols and long-term performance evaluations.

Although the plentiful advantages of integrating PCMs with SC systems were identified, several challenges should be announced. A detailed understanding of these challenges is vital for engineers, researchers, and policymakers directing to maximizing the implication of these technologies in real-world scenarios. First of all, one of the principal concerns is long-term stability. Undoubtedly, the PCMs might experience performance degradation as a result to repeated phase change cycles under variable temperature conditions. Second, the is still a necessity to assure optimal design of PCM-integrated SC systems, which guarantees optimum airflow, thermal dynamics, and material characteristics. Third, the current regulations also represent another challenge especially when existed building codes do not sufficiently accommodate PCM technologies, which can ultimately deter its incorporation into new projects. In this regard, the building design, orientation, and environmental conditions can make a challenge to forecast the efficiency of integrated PCMs successfully. Eventually, seasonal performance fluctuations can cause contradictions in system efficacy, mainly in regions experiencing important temperature variations. Indeed, resolving the aforementioned challenges and the complexities linked to the practical implication of PCM-integrated solar chimneys is vital for the effective integration of PCMs into solar chimney systems. This in turn would improve the competence and sustainability of building practices.

5. Conclusions

The incorporation of PCMs with SC systems has been investigated in this study, with a focus on how PCMs may enhance the energy efficiency and thermal performance. Several results of research show that

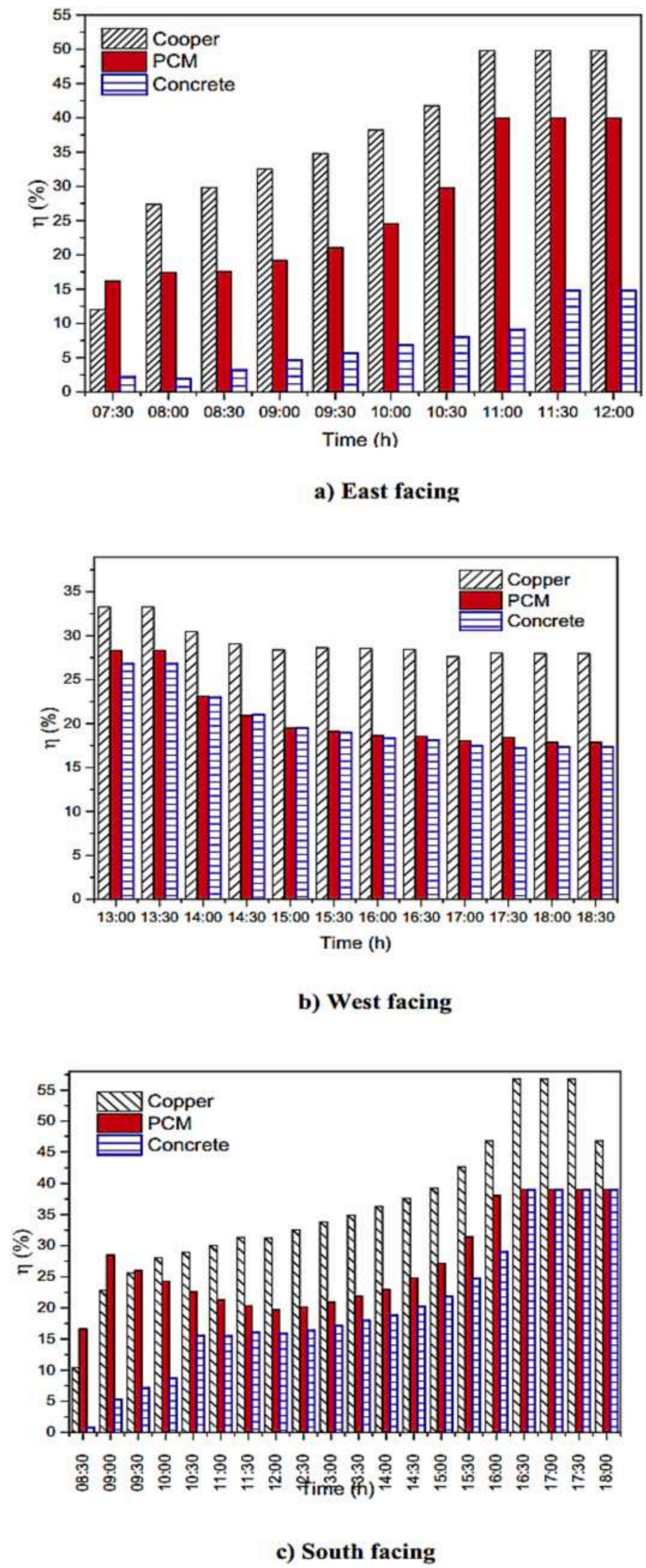

Fig. 20. The solar chimney's instantaneous thermal efficiency for every direction [47].

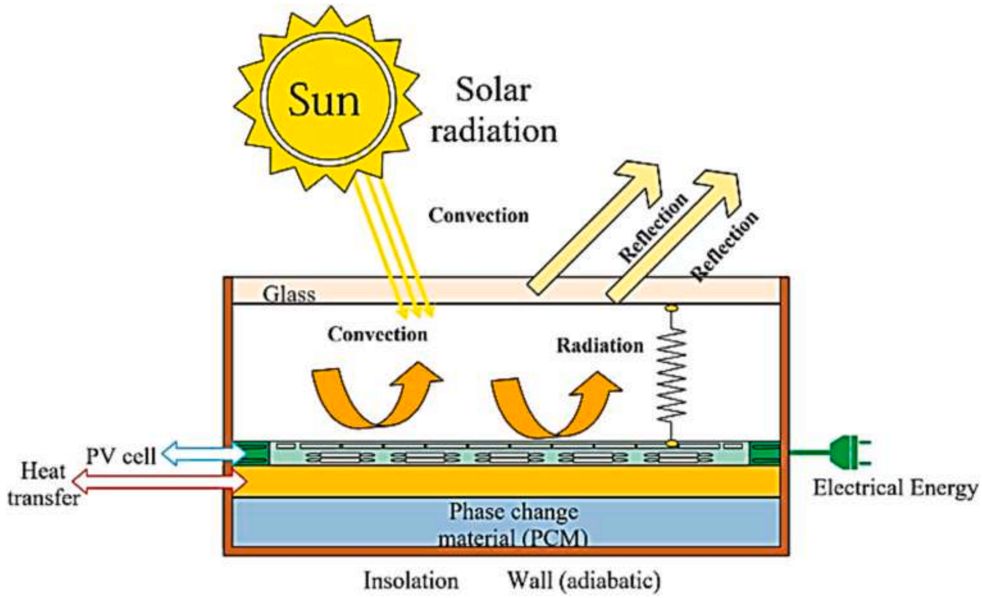

Fig. 21. An overview of the integrated system [50].

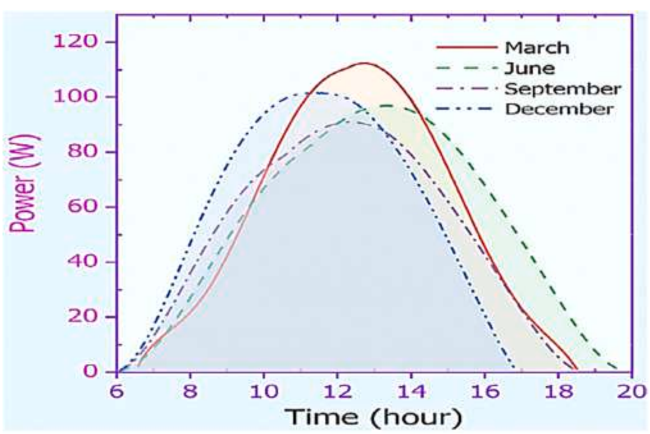

Fig. 22. The SCV-PV-PCM system's electrical power in various months [50].

incorporating PCMs enhances management of interior climate and enhances solar chimneys' ability to work effectively after daylight. The main comprehensions acquired from the study are summarized in the following conclusions:

1) Through heat storage and release, PCM incorporation greatly improves thermal performance in SC systems, resulting in more consistent interior temperatures night and day.
2) By effectively using latent heat that has been stored, SCs incorporating with PCMs may offer ventilation and heating after the sun sets, ensuring delightful within temperatures.
3) Based on researches, using PCMs can enhance the ventilation rates of building and accentuate interior air quality by causing airflow that is appropriate to the quantity of solar radiation.
4) Inspections of several PCM types, like paraffin wax and other materials with changing melting points, display that the selection of PCM can have a foremost influence on the competence and efficacy of the system.
5) The results of numerical simulations and experimental setups have supported one another, affording a solid base for perceiving the thermal dynamics of SC systems with PCMs.
6) Depending on what a given structure necessitates, SCs can be designed to integrate PCMs in variable combinations, such as integrating them with heavy weight or lightweight materials. This flexibility would enable modified solutions.
7) Reducing reliance on conventional heating systems, the application of PCMs in SC systems can result in noteworthy energy savings and support more ecologically friendly buildings practices.
8) Politicians should think about backing PCM-incorporated SCs as part of energy efficiency and renewable energy programs to lower carbon footprints and enhance building performance.

6. Upcoming upgrades and related difficulties

Numerous opportunities exist to enhance PCMs performance and applicability as SC systems' incorporation with PCMs develops. Upcoming changes in this area may result in more effective, sustainable, and economical methods to manage building energy. Possible areas of advancement are described below:

1) To boost the efficiency of the amount of energy stored and heat transfer, research should focus on creating novel PCM compositions with optimal melting points and heightened thermal conductivity.
2) PCM-incorporated SCs can work more effectively and responsively if smart control systems that make use of real-time climate and building occupation data are established.
3) Increasing the level of acceptance and use of PCM systems in a range of architectural settings will be made simpler by generating modular systems that are with use adaptable and scaled for various building sizes and kinds.
4) Extended field investigation to predict PCM-incorporated SC performance and durability in various weathers will yield significant information for future uses and designs.
5) Looking into inexpensive PCM production methods and using them into SC systems will help make these technologies more broadly accessible and financially attainable.
6) Investigating the direct integration of PCMs into wall materials and roofing might enhance thermal performance and decrease the requirement for additional systems.
7) To explore the environmental effect and sustainability of PCM-incorporated SC systems and influence upcoming design selections, thorough life cycle calculations should be performed.

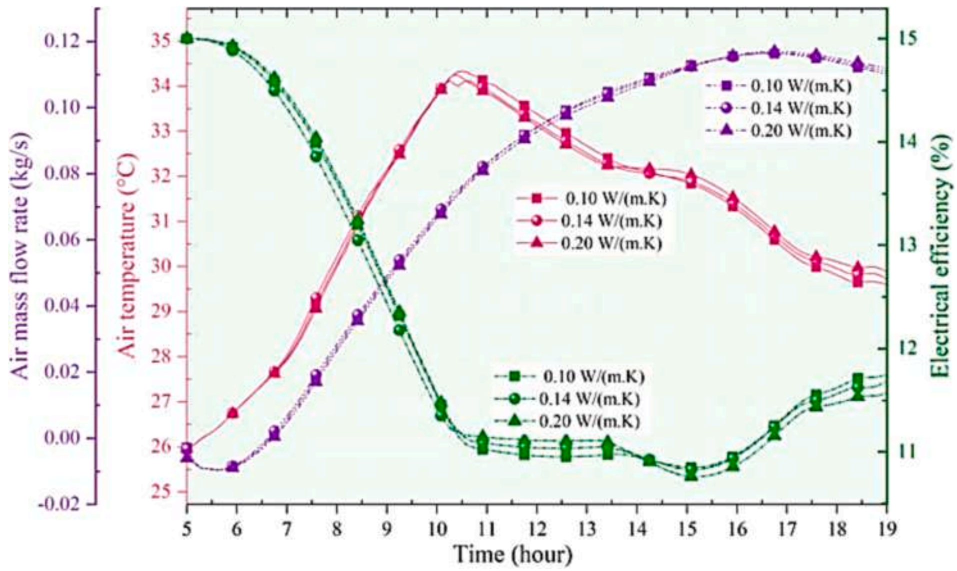

Fig. 23. The mass flow rate of air, temperature of outlet, and the PV module's electrical efficiency throughout the day at different thermal conductivity levels of PCM [51].

Table 3
A summary of studies related to hybrid systems integration.

Author year [reference]	Geometry	Study type	Examined variables	Results and remarks
Talib et al. (2016) [45]	SC integrated with solar chimneys made of an AR greater than 12.	Experimental	PCM	When the EC is functioning at its highest effectiveness, from 11:00 a.m. to 3:00 p.m., the system may lower the temperature of the test room by 8.5 to 9.2. During its lowest effectiveness, between 8:00 p.m. and 3:00 a.m., the system can lower the temperature by up to 3.5.
Bin et al. (2017) [46]	Solar chimney with PCM ($Na_2Co_3.10H_2O$)	Experimental	Position of PCM.	The temperature of the air in the gap was higher when the PCM was positioned in front of the absorber compared to when it was positioned behind the absorber.
Xamán et al. (2019) [47]	SC with three various kindes of absorbents: copper plate, PCM, and concrete wall.	Numerical	Copper plate, PCM, and concrete wall.	The average thermal efficiencies of the SC with a copper plate are 34 %, 27 %, and 34 % for the east, west, and south directions, respectively. When a PCM is used, the thermal efficiencies are 28 %, 19.8 %, and 27 % for the same orientations.
Buonomo et al. (2019) [48]	SC built in storage for latent heat energy.	Numerical	PCM	Although the PCM is not entirely liquid, it undergoes phase changes and increases in temperature regardless of light energy.
Ashouri and Hakkaki-Fard (2021) [49]	Rooftop SC that is inclined and integrated with the PV module and PCM.	Numerical	Finned absorbers and composite PCMs.	Utilizing a finned absorber enhances the ability to ventilate by 7.7 % and prolongs the duration by 17.6 %. Composite PCMs based on copper foam prolong the SC-PCM-PV system's ventilation period.
Cao et al. (2021) [50]	SC ventilator with solar panel and PCM.	Numerical	Solar panel and PCM.	The SCV-PV-PCM system outperforms the typical SCV-PV system regarding power generation and ventilation capacity.
Cao et al. (2021) [51]	SC with PV and PCM.	Numerical	Conductivity, melting point, heat capacity, and enthalpy.	Increasing the thermal conductivity of the PCM enhances power generation while having no noticeable effect on the capacity of ventilation of the system.
Long et al. (2022) [52]	SC integrated with EAHE and PCM.	Numerical	EAHE and PCM.	The maximum airflow rate experienced a decrease of 17.8 % to 209.5 m^3/h during the day, but the SCEAHE airflow rate was increased by 50 % at night by the integration of PCM.
Saleh et al. (2024) [53]	SC with asphalt PCM and gravel bed porous media.	Experimental	Asphalt and the gravel bed.	At 8 am, SCs with PCM and porous medium had the highest electrical efficiency ratings, 13.16 % and 13.12 %, respectively.

8) Inspiring legislation and additional incentives can support the development of integrated PCM-incorporated SC technology while achieving energy-saving objectives.

7. Recommendations for future studies

To improve the integration of phase change materials in solar chimneys, a number of important recommendations for future studies are proposed in this section. First of all, attaining a long-term durability testing is crucial. This specifically requires an extended experimental appraisal to gauge how repeated phase transitions can influence the longevity and performance of PCMs in real-world implications. Also, upgrading thermal conductivity is another vital area of research. Research into composite PCMs that integrate additives such as graphite, metal foams, or nanoparticles can expressively enhance thermal conductivity and associated heat transfer rate, which therefore sorting out the limitations of current materials. Second, the investigation of hybrid PCM systems is endorsed, concentrating on the potential advantages of integrating PCMs with other thermal storage solutions to optimise energy efficacy without noticeably rising the material volumes. The enhancement of bio-based and sustainable PCMs is another essential topic for research. Additional examination in this area can provide visions into the environmental impact, lifecycle sustainability, and integration viability of eco-friendly materials within construction practices.

The influences of regional climate variations and building orientations on the overall performance of integrated PCMs and SC systems should be addressed in the future. In turn, this would aid in the formation of variable solutions tailored to specific geographic conditions. Lastly, simulation, modeling and optimisation techniques is vital [56]. Future studies should emphasis on improving more truthful simulation models that can forecast the performance of PCM systems across a wide range of environmental conditions and optimise the overall performance, thus enabling better design and testing methodologies.

CRediT authorship contribution statement

Farhan Lafta Rashid: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Haider I. Alyasari:** Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Mohammed Ghanim Lafta:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis. **Ali Jafer Mahdi:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Mudhar A. Al-Obaidi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis. **Hussein Togun:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Investigation, Formal analysis. **Karrar A. Hammoodi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Ephraim Bonah Agyekum:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources.

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.

Data availability

Data will be made available on request.

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Nomenclature

PCM: phase change material
SC: solar chimney
CFD: computational fluid dynamics
LHS: latent heat storage
CSC: conventional solar chimney
PCC: phase change capsules
LTNE: local thermal non-equilibrium
Q: thermal storage
AR: aspect ratio
CFM: copper foam matrix
TESMB: thermal energy storage material box
SC-PCM: solar collector-PCM
SC-PV-PCM: solar chimney-photovoltaic module and phase change material
ACH: air change per hour
TESB: thermal energy storage box collectors
SCV-PV-PCM: solar chimney ventilator with phase change material integrated with photovoltaic technology
SCEAHE: solar chimney integrated with earth-air heat exchanger
ROI: the return on investment