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Passive cooling techniques for ventilation: an updated review

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Abstract. The consumption of energy for cooling is an important issue, especially in subtropical climates where there are high temperatures and dry weather in the summer; this climate forces homeowners to use mechanical-electric cooling and ventilation. The main advantage of passive cooling is to minimize energy demands which are required to achieve thermal comfort in buildings, especially with climates exhibiting high ambient temperatures. This paper presents a detailed literature review and concept breakdown for passive cooling and ventilation in building by offering the fundamental principles of the techniques of passive cooling and ventilation. Moreover, the status of passive cooling developments along with state-of-the-art research is critically reviewed in this paper. Furthermore, the article focuses on Buoyancy air-driven ventilation. Solar control techniques are explained and classified along with techniques for heat modification and dissipation. This paper offers insight into the design considerations of different passive ventilation systems and presents recommendations for future work to achieve cost-efficient, comfortable living. Moreover, novel systems are reviewed and discussed to better understand the role of Phase Change Material (PCM) in passive cooling systems.

Keywords: Passive cooling and ventilation / prevention of heat gains / modulation of heat gains / rejection of internal heat / buoyancy driven ventilation

1 Introduction

In the arid and hot climate, traditional architecture has a variety of passive cooling and ventilation techniques that support thermal comfort in buildings. A hot micro-climate depends on planting trees, vegetation, open courtyards, and white-painted exteriors. The passive design allows buildings to be more adaptable to local climates and to benefit better from natural energies such as wind and thermal boosters to help the condition in the interior environments. Besides, passively ventilated buildings offer the occupants a better and healthier environment than their mechanically ventilated counterparts. Around 40% of the world's energy is used in buildings during the year. The most important part of this energy is used in providing illumination, heat, cooling, and ventilation. The degree of damage to the earth has increased as a result of the increased demand for energy, resulting in the idea of building passive renewable energy systems in the infrastructure. Increasing concerns about worldwide temperature present the building engineers with the challenge of reducing our energy utilization. The climate control systems, specifically ventilation, cooling, and heating, can account for as much as 70% of the total energy use [1]. Otherwise, this component of energy consumption can be reduced greatly by using passive techniques as an alternative to mechanical ones. Passive cooling is needed in many third world countries which exhibit high ambient temperatures and may not afford the energy consumption associated with active cooling techniques. For instance, the country of Iraq is in the Subtropics region, where the climate of this region is characterized as hot and dry in summer; most of the areas have a desert climate [2]. The mean temperature in Iraq for summer (April to September) ranges from 40 °C to more than 50 °C. The high-temperature range during summertime requires more energy consumption [3]. Given that cooling is the basic requirement of building occupants, there is a deep need for further development in passive cooling techniques and strategies. This paper presents a simplistic summary of passive cooling and ventilation fundamentals coupled with a critical review of recent state-of-the-art research. The objectives of this review are to (i) introduce passive cooling

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techniques, (ii) review innovative studies on Trombe wall technology, and (iii) provide a critical review on the topic of passive cooling techniques for ventilation.

2 Passive cooling and ventilation fundamentals

At the beginning of the 1970 s, US researchers used the phrase "passive". This phrase characterizes systems that operate naturally without the use of mechanical devices driven by electricity. Cooling is the transfer of heat energy from indoor space into outdoors to obtain a temperature and a level of moisture that are lower than those in the natural environment [4]. Passive cooling is an expression used to involve a variety of design techniques that can be used in a building in order to cool it without the use of mechanical systems. Some of these systems' functions include the use of a fan or a pump with low energy consumption when its application might increase the system's effectiveness. Other passive systems need occupant interaction, like opening and closing windows [5]. The upper atmosphere is a natural heat sink (sky). To achieve proper construction and layout for the building, it is crucial to consider the effects of microclimate. Hence, practices such as shading and using reflecting surfaces or light colours for the building's exterior are all considered strategies of heat prevention. In addition to the use of insulated wrappers and management of internal thermal gains [4–6]. Heat modification is connected to the material that has the capacity for heat absorption and storage, thermal mass materials such as concrete and brick, in the structures of a building that serves as heat storage in the morning and cold storage at night. The use of these materials is very useful, especially for the buildings in a constant occupation like houses [6]. The functions of heat rejection are also to squander the indoor heat to the outdoors heat sinks; thus, the temperature indoors may be smaller than outdoor temperatures.

The heat transfer mechanisms and heat sinks play a significant part as sources of cooling. The distinction, conceptually, between passive cooling and ventilation, and bioclimatic design, is the emphasis on the first level, but both are interconnected [7]. The plan for cooling a building should be conceived on three levels [6]:

– Protection from solar and heat.
– Modification of heat gains.
– Rejection of internal heat from the building by ventilation to outdoors heat sinks, evaporative cooling, radiative cooling or earth cooling, as shown in Figure 1.

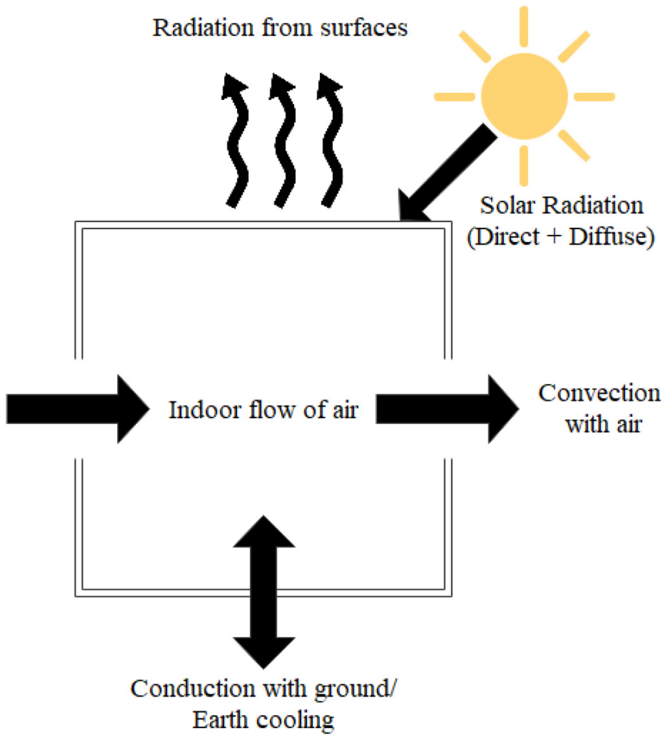

Fig. 1. Heat transfer modes in buildings to heat sinks [6].

3 Techniques of prevention of heat gains (protection from solar and heat)

The region's climate and its microclimate must adapt a building. Hence, it is crucial to minimize the building's internal gains to improve the passive cooling methods' efficiency. In relation to the incident sunlight and the wind, site design is affected by economic constraints such as zoning ordinances and the ongoing connected developments, which can all overlap with the building's design. Vegetation provides a pleasant appearance outside the building, and it improves the microclimate of the building and improves the building's overall energy efficiency. For instance, trees planted outside the building offer shading, evapotranspiration and wind channelling. Finally, the primary measure of design for heat gain protection is solar control.

3.1 Microclimate

The topography, ground, soil structure, and urban shapes influence small patterns of the climate, known as microclimates. Temperature, atmosphere, humidity, precipitation, and wind are the major characteristics of the climate. The city climate varies from the climate in the countryside environment, mainly because of the structure of the city and heat produced by vehicles, mechanical cooling devices, etc. The city climate is usually characterized by high ambient temperatures, as well as a decrease in humidity and wind speed and direction. Microclimates can be found in most places, for example, near bodies of water which may cool the local atmosphere, where these bodies of water change the surrounding area's microclimate to reduce ambient air temperature, whether through evaporation or the contact of the hot air with the cooler water surface. The sources of cooling that lower the temperature of outside air and air in the building include fountains, ponds, rivers, cascades or mist sprays.

In heavy urban areas where asphalt and concrete absorb the energy of the sun, this absorbed energy will increase the heat of asphalt and concrete; then, it will transmit it back into the environment air. As a result, urban heat areas are a kind of microclimate. Moreover, asphalt and concrete are typically too dense for water to permeate, thereby drastically reducing latent heat interchange. The passage of water and air permits latent heat exchange, thus reducing the pavement's temperature. In turn, this helps to better access air and nutrient to trees and other landscape root systems and provides cooler areas which result in greater and denser shading of landscapes [8]. Another contributing factor of microclimate is Vegetation cover, which is an assemblage of plant species and the ground cover they provide [9,10]. The vegetation changes microclimates and the consumption of energy of buildings by reducing temperatures of air and surface, also increasing relative air humidity. Plants can also control air pollution, filter the dust and reduce noise pollution levels.

Indoor simulations are still isolated from a major component of microclimate civic areas like civic trees. The main benefit of urban trees is that they produce shade as a bioclimatic reaction element, while their main disadvantage is that they block the wind [11]. Moreover, cultivating a specific type of civic tree around buildings influences their solar access and heat interchanges [12].

3.2 Shading and other techniques of solar control

Solar radiation extends to the outer surface of buildings and penetrates inside buildings from the transparent windows in different forms; these forms are direct, diffuse and reflective. Generally, solar radiation changes with many parameters such as latitude and altitude, sky clearance, the day of each year and the daytime. Solar radiation changes with the surface direction and angle to the horizontal surface for a certain surface.

The entry of sunlight into the building's interior leads to problems like high indoor temperatures, thermic and optical inconvenience, and damage to sensitive items and furnishings. Therefore it is essential to establish control of the solar radiation. Solar control refers to the riddance of the solar radiation from building surfaces, whether full or partial, permanent or provisional. The following techniques can be used to reach solar control:

1. Windows apertures:

The window's apertures design combination of the orientation, size, and tilt for the various window openings in the building's envelope is of vital importance. This is because these parameters affect the surface's view of the sun and sky over the daily and monthly cycles. Mazria [13] identified the optimum direction for the building's solar energy rates, which receives the highest solar radiation in the winter and less in the summer. The energy efficiency requirements such as area and perimeter of the surface, the height of buildings and the ratio of the width to the height of buildings are taken into consideration during the design stage.

2. Windows glass:

The thermal and optical properties of the glass windows of the building affect the level of solar radiation penetration. The flow rate could be increased by 11–17% with double window glass. Otherwise, the inner surface of the southern wall can be isolated to avoid increasing temperate inside the building because of windows in the southern wall [14]. Window technologies were stimulated by the transition from Single-glass windows in low-emission window systems into low heat transmission, Evacuated Windows, Vacuum-insulated Glass, Electrochromic windows, thermotropic materials, silica aerogels and transparent insulation (TIM) materials [15,16].

3. Thermal insulation of buildings:

One of the important factors in achieving thermal comfort for the occupants of buildings is buildings thermal insulation. Insulation reduces unwanted heat loss or gains. Hence, it reduces the energy requirements of cooling systems. Most popular insulation materials work through a slow, conductive flow of heat and convective heat. Materials for insulation include bulky fiber, glass, slag and rock, cellulose, natural fiber to smooth and thin foam panels. Substantial materials can withstand the conductive heat flow (in a smaller way) in the building cavity. Rigid foam panels pull air or gas to resist the conductive heat flow. Also, the radiant heat in the living spaces can be reflected using highly reflective foils [17].

4. Shading of buildings:

Primarily, the shading device is another connection between daylight performance and thermal perimeter. An integrated analysis should be conducted to consider the interactions of various parameters and achieve the optimum outcome. After all, with just a slight exception, integrated early facade analysis where critical decisions are of little economic impact can lead to significant energy savings throughout the building lifespan, while the interior conditions are being improved at the same time [18]. Moreover, it is crucial to establish research into balancing the different aspects of solar control, with consideration for natural ventilation, building façade, and other building components [19].

4 Techniques of modulation of heat gains (modification of heat gains)

There are two methods to implement the building's thermal mass. The building's thermal mass (usually contained in walls, floors, Parts-built from high heat capacity materials) absorbs daytime temperatures, regulates the extent of the temperature swings indoors, reduces the maximum cooling load and transfers part of the absorbed heat into the night to the environment. Passive cooling techniques can then cover the remaining cooling load. The second method is pre-cooled unoccupied buildings by ventilation during the night and transferring this coolness stored in the early hours of the next day, thus reducing energy consumption for cooling by close to 20% [20].

4.1 Thermal storage

The building's thermal mass is achieved either by using bulky building material or phase change material in the system of the building. Heat regulation by shifting the heat from the daytime to nighttime may be achieved through the following techniques.

– Thermal storage in the construction material.
– Thermal storage using PCM-based systems.

- PCM in Wallboards.
- PCM in roof & ceiling.
- PCM in glass windows.

4.2 Night cooling

The techniques for night cooling are founded on using fresh ambient air to reduce both inner air temperatures and building structure temperature. Night ventilation cooling efficiency is at most based on the relative variation between inner and outer nighttime temperatures, airflow rates, building thermal capacity and efficient flow of air and heat mass. Artmann et al. [21] evaluated the potential for passive cooling by nighttime ventilation through analysis of climatic data and excluding parameters which are building-specific. While, Finn et al. [22] investigated the design and operational parameters in a maritime type climate, in Ireland, for night ventilated library building. The parameters included ventilation duration, the mass of the building, internal gain and rates of ventilation. Many buildings use passive cooling techniques, especially in the countries of Europe, where night ventilation techniques have been successfully applied. Several studies have reported results of passive cooling monitoring in various construction types [23–26].

The performance of night ventilation is obviously dependent both on the environment climate conditions and on the building's physical parameters, for example, thermal and air exchange capacity storage. The validation of the night cooling and ventilation method in various weathers is therefore essential to examine. As stated earlier, many night ventilation studies have been carried out, however, experimental and theoretical research has been insufficiently documented on the proportionality of this method in the desert weather.

5 Techniques of heat dissipation (rejection of internal heat)

In several cases, heat gains can not be avoided nor modulated through controling the level of the internal temperature. The natural heat transfer processes include a more advanced refrigeration strategy for thermal sinks such as the upper atmosphere and the ambient sky. The design of the building is a major factor influencing the potential of natural cooling techniques. Natural cooling means using natural heatsinks to dispel heat excessively from the inner space such as natural ventilation, evaporative cooling, earth cooling, radiative cooling and the use of a free PCM-based cooling system.

5.1 Natural ventilation

The main technique of passive cooling and ventilation is natural ventilation. generally, ventilation of the buildings is also essential to preserve the necessary levels of oxygen in space and the quality of air. The requirements for ventilation have traditionally been met by natural means. The infiltration levels in the majority of older buildings offered considerable amounts of outdoor air, while the windows were opened to satisfy further requirements.

Modern architecture and a conscious energy design have minimized air infiltration in an effort to reduce its impact on cooling or heating loads. The result of better construction was the outdoor sealing of buildings. The building with large windows that do not open windows prevents possible usage of natural ventilation to provide clean indoor air. For a naturally ventilated building to be successful, it is necessary to understand its airflow patterns and the effects of the neighboring buildings. The goal is to ventilate as much of the indoor space as possible. This objective is achieved depending on the location of the window, the interior design, and the wind.

Piselli et al. [27] proposed and investigated the improvement of PCM's performance to be used for the passive cooling of buildings through efficient natural ventilation. Their research was focused on the climate conditions of Italy, and utilized the coupled dynamic simulation and optimization analysis. The investigation encompassed the assessment of the effect of different natural ventilation strategies on the cycle of charging and discharging of PCMs. Different scenario were considered for different climates, these scenarios ranged from the conventional, standard building, to the optimum scenario, with integration of PCM in the building envelope. Other scenarios included (i) the best for nighttime ventilation, (ii) optimum PCM for nighttime ventilation, and (iii) optimum PCM with temperature controlled nighttime ventilation. The study concludes that in all considered climates, the optimum performance is obtained when using both PCMs and natural ventilation controlled by indoor or outdoor temperature difference. The findings suggest a remarkable saving in cooling, of up to 300 kWh/year, that is achieved when incorporating PCM's into building envelopes. Other solutions include the use of photovoltaic thermal collector with PCM for building power generation, heating and natural ventilation collectively. Such research was carried out by Gan and Xiang [28], where different sizes of PCM were considered. The incorporation of PCM with a thickness and phase change temperature of 30 mm and 25 °C allowed for maintaining PV module temperature under 45 °C, enhanced its conversion efficiency by 10% for approximately 3.5 h at an insolation of 600 W/m^2. Moreover, the system was found to generated a ventilation rate of 15 L/s within a vertical duct (1100 mm wide, 1200 mm high, 100 mm deep) when metling, and up to 20 L/s when solidifying.

Tian et al. [29] focused on the air ventilation and thermal environments in buildings with fabric membrane structures. The research was done by (i) evaluating the impact of solar radiation and outdoor air temperature on the indoor thermal environment, (ii) modelling and simulation the natural ventilation using computational fluid dynamics (CFD) to understand the effects of air vents height and different areas of ventilation on the indoor thermal environment. Three different cases were considered, each with its own inlet air vent area and height, and area of outlet air vent. Cases 1, 2 and 3 exhibits 6 inlet air vent areas, 6 outlet air vent area and 6 inlet vent heights, respectively. Interestingly, the findings shows that peak air temperature and average indoor air temperature were around 34.7 °C and 38.2 °C, respectively, for the condition

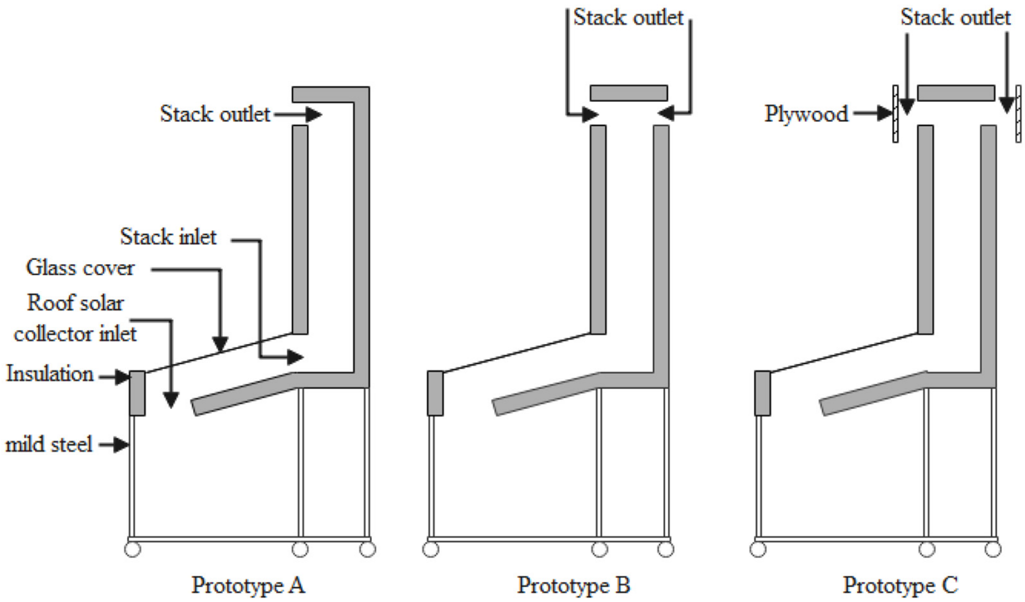

Fig. 2. Roof solar collector and vertical stack Prototype device A, B and C [38].

where the inlet and outlet vent areas are between 819 m^2 and 1092 m^2, in addition to the height of inlet vent being half a meter above ground. CFD was also used by Wu et al. [30]. However, the simulation was performed using the direct forcing approach which allows for simulation the dynamic window operations. This approach predicts, accurately, the volume flow rates through window apertures. The approach provides a band of cells corresponding to the windows angle of opening and employs an ad-hoc body force to the equations of momentum, thus avoiding issues such as (i) the skewness of the conformed cells near the surface of the window, and (ii) the requirement for a moving mesh to accommodate the change in the window's opening angle.

5.2 Natural cooling

Natural cooling includes the use of certain well-known physics laws which deprive bodies of heat. The following are those physical phenomena:

1. Evaporative cooling

Evaporative cooling is a method that capitalizes on the relationship of water and the heat in the air. In essence, sensible heat is extracted from the air by water in order for the water, which converts it into latent heat, to evaporate. The quantity of sensible heat absorbed depends on how much water can still be evaporated. Evaporative cooling is an extremely ancient process that originated in ancient Egypt and Persia some thousand years ago. Prototypes constructed in the USA at the beginning of the 1900s are the basis of modern evaporative coolers.

Direct passive systems involve the application of Evaporative vegetation, using saturated sources of water like ponds and swimming pools, sprays and using porous medium materials. Hence, moisture is transpired by trees and other plants in order to reject their sensible heat. The plant evapotranspiration theoretical function analysis demonstrates that one tree evapotranspiration can economize between 250 and 650 kWh of air conditioning electricity each year by Orosa JA and Oliveria AC [31]. On a sunny day, more than 50 GJ heat can transfer from 0.405 hectares of grass, whilst wet grass can be evaporated to reduce the ground temperature by about 6-8 °C lower than the average bare ground surface temperature.

2. Earth cooling

The earth cooling concept is founded on transferring the waste heat of a building into the earth because of the earth's temperature is lower than the outdoor air temperature. The earth cooling can be done either directly by touching a large part of the building surrounded by land or by injecting air, which has already been circulated underground to ventilate heat exchangers.

3. Radial cooling

Radial cooling is due to heat loss from one body to a lower-temperature body through the long-wave radiation emission that takes the heat sink's role. With regard to buildings, the outter surfaces of the building are cooled by the sky (heat sink) because it's temperature is lower than the outter surface temperature of the building. Thus, it is the principle that enables the earth to waste the heat received by the sun in order to maintain its heat balance. In buildings, radial cooling is implemented in different ways: passive cooling, direct cooling, and hybrid cooling. First, the roof of the building irradiate into the sky then becomes cool, causing the building's internal heat loss. Second, the heat sink is usually a metal platform, not a building envelope. This radiator is operated on the opposite side of an air-plate solar panel and before it is injected into the building previously, the air is cooled through circulation under the metal plate.

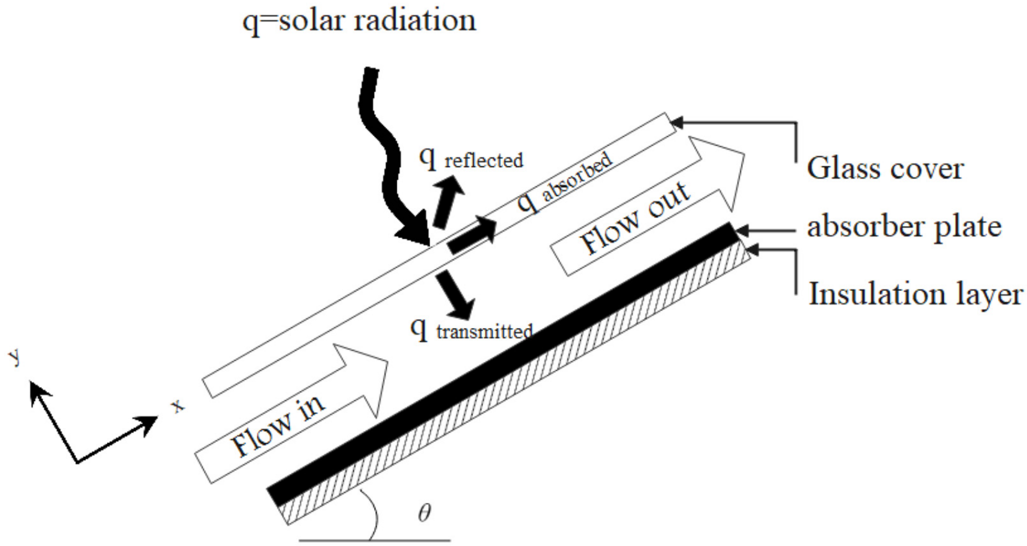

Fig. 3. Solar chimney [39].

6 History of previous research on buoyancy driven ventilation

Natural ventilation consists of using natural forces to drive airflow through space. As mentioned in the earlier section, the importance of using natural ventilation techniques for the indoor building is to ensure improving the indoor air quality of the building and to reduce energy requirements for cooling to then maximize the thermal comfort for the occupants using the building. Two natural forces can be used to drive air through a building, these forces are wind and buoyancy, which lead, respectively, to two main natural ventilation strategies: wind-driven cross ventilation and buoyancy-driven stack ventilation.

Many studies [32–37] were conducted to examine the natural ventilation system performance that uses buoyancy force to drive the air. This section will show many important studies that researched this topic. To improve the ventilation of the stack, Yusoff et al. [38] used the induced ventilation of the solar system as shown in Figure 2. This study includes the implementation of a solar roof collector and a vertical stack to increase the performance of stack ventilation in the warm and humid climate. In half-clear sky conditions and cloudy sky conditions, the highest difference in the air temperature between air within the stack and ambient air is around 9.9 and 6.2 °C, respectively.

Imran [39] induced the flow for ventilation and cooling by solar chimney (Fig. 3). It is observed that solar chimney induces ventilation to 50–425 m^3/h for a room of 12 m^3. Furthermore, the air flux increases linearly as the solar radiation increases and the gap between the absorber and the glass cover increases.

The new trombone wall as shown in Figure 4, combined with the solar chimney and the water pumping system in the desert climate of Yazd, has been researched by Rabani [40] experimentally in a test chamber. The results show that the energy supplied by the Trombe wall in non-sunny periods plays a key role in the air ventilation and the water spray system improves the heat efficiency by some 30%.

The performance of a hybrid system as shown in Figure 5 is investigated by Al Touma et al. [41], which combines passive evaporative cooling principles with a natural buoyant flow in the solar chimney, applied to glazed surfaces for reducing cooling load and asymmetries. The designed model was validated by testing of ambient air temperature, moisture and solar radiation conditions in a double climatic chamber. In spatial with fencing ratios of 40% in the case of clear double panel windows, a total load of 19.8% was then applied to an office area in Riyadh. Furthermore, because of radiation asymmetry, the system could reduce the sensation of thermal discomfort in relation to an occupant sitting 1 meter away from the window. When the system in Jeddah was applied, energy savings of 13.1% was found. The use of the suggested system was limited by the relative humidity in the outdoors, which limits its advantages in wet conditions.

The performance of the solar chimney is assessed by Asadi et al. [42] in the southern, southwestern and east-southern part of the building as shown in Figure 6. EnergyPlus software was used to simulate the performance of solar chimney connected to a typical seven-story office building located in Isfahan. The solar chimney performance can then be summarized in these 7 models as follows: Model 1: south-facing solar chimney with three-sided radiation; Model 2: solar chemistry linked to the building's southwest; Model 3: solar chimney linked to the building southwest; Model 4: solar chimney in the vertical channel plan center; Model 5: solar chimney in the plan center without wall; Model 6: solar chimney connected to the south of construction without any wall; Model 7: South-connected solar chimney with one-side radiation from the construction.

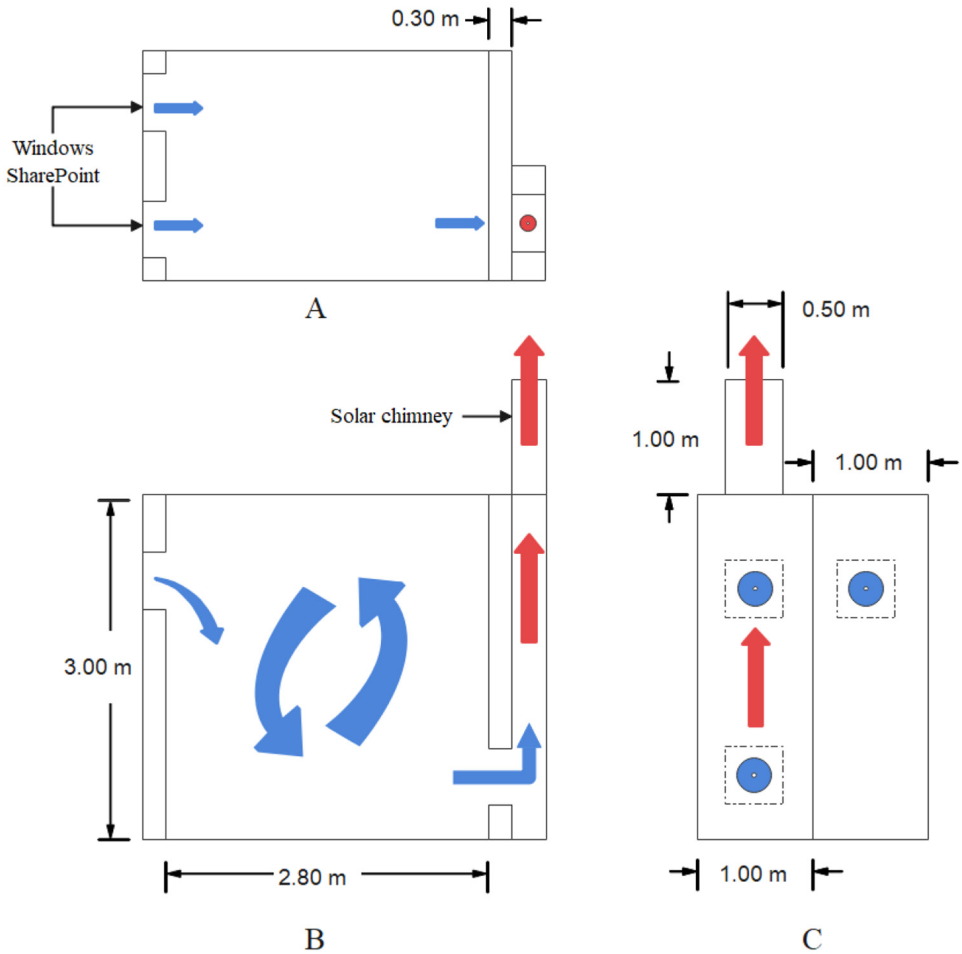

Fig. 4. Trombe wall with solar chimney and water spraying system: A. Top view. B. Front view. C. Side view [40].

The results indicate that the position of the solar chimney in the eastern and southern section of the building offers maximum ventilation because of the radiation maximum and 2 side walls. Every solar chimney has also been found to provide the necessary ventilation speed in its attached areas.

Mathematical model was developed to simulate the performance of the designed Solar Chimney in Figure 7, by Hosien and Selim [43]. The design considered the geometrical and operational parameters. These parameters includes solar irradiance, wind speed, environmental temperature, and Solar chimney dimensions of height, width and gap. In addition, various materials for solar chimney were examined. A computer program has been designed to simultaneously resolve the governing energy and conservation equations. The model results were compared to the published information available. The current study looked at solar chimney performance under certain weather conditions in Cairo. The results demonstrated that the air hourly rate of change (ACH) increased by increasing the height, the gap and the width of the chimney. In comparison to other geometrical parameters, however, the gap of the chimney had a very important impact on ACH. Increasing the chimney dimensions doubled afflicted positively on the mass flow rate of approximately 18% for height, 78% for gap and 63% for width. Thus, larger chimneys improved slightly in the mass flow rates but it was not sufficiently significant to be economical. The results indicated that the ACH was above

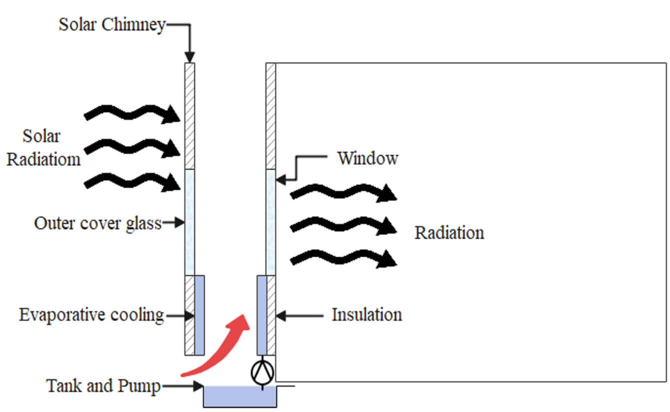

Fig. 5. Hybrid system [41].

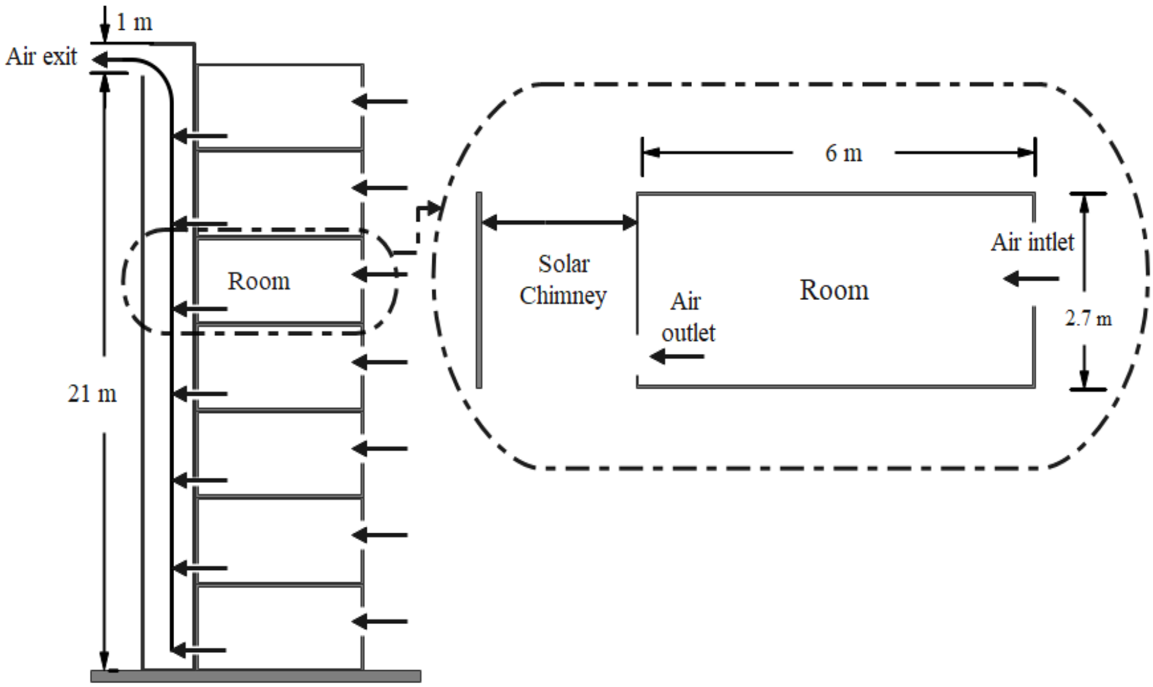

Fig. 6. Path of air movement [42].

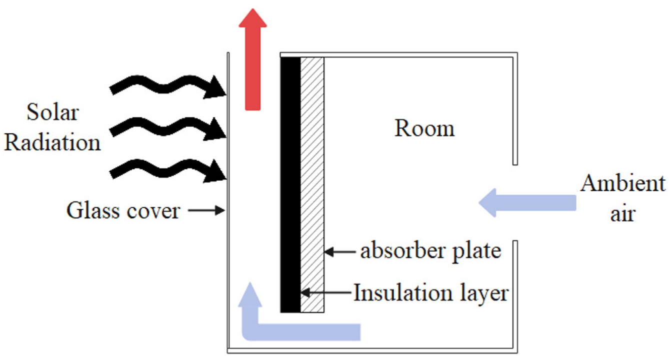

Fig. 7. Solar chimney configurations [43].

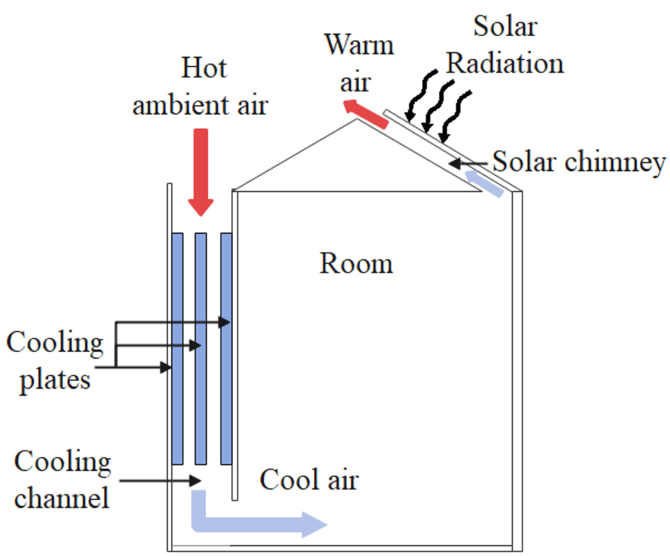

Fig. 8. Schematic representation of the room [44].

the desired level of ventilation throughout the year. Using non-glass materials to construct the exterior cover of the chimney, the ACH is found to be higher than the standard. In addition, both the cost and safety of the building are reduced.

Jafari and Haghighi Poshtiri [44] proposed a novel passive cooling system for buildings as shown in Figure 8. The system is theoretically simulated with an assessment considering room temperature, relative moisture and ACH. A cooling channel, a solar chimney, and solar-powered adsorption chiller were proposed for the buoyancy-driven air to flow into the building; due to the solar chimney. Hence, when heat transfers, as it flows, through the cooling channel with plates supplied by chilled water from the adsorption chilies, the hot ambient air temperature is then decreased. The performance of the system was examined under various environmental and geometric conditions. Adopting 3 cooling plates in the channel also indicates lowest room temperature, with the use of three plates reducing room temperature by 26.8% instead of a single one. The use of an airgap depth of 0.05 m was suggested in order to reduce room temperature. The maximum requirements for air refresher, with an air gap depth of 0.05 m and 0.1 m, were raised from 4000 W to 6000 W in Tehran, which were in accordance with ISO 7730. In addition, the ambient temperature and ACH rose insignificantly with an increase

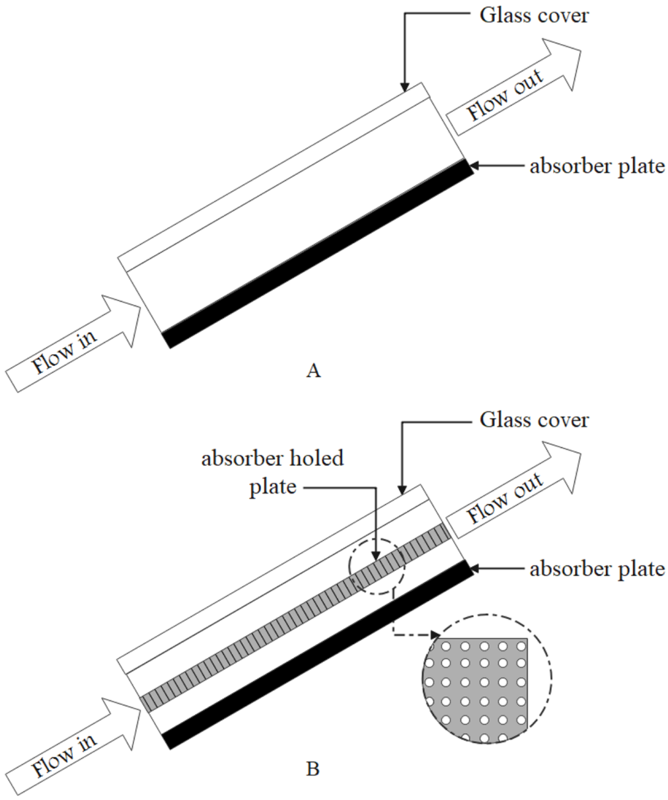

Fig. 9. Sketch of the optimized and traditional roof solar chimney (A) traditional chimney; (B) optimized chimney [45].

in the chimney's length. Finally, comparing it to a divided inverter air conditioner with the same cooling power, the proposed air conditioner is found to consume approximately 37% less electrical energy.

Lei et al. [45] proposed an optimized roof of the solar chimney equipped with a perforated absorber plate to augment the natural ventilation for the conservation of the building's energy. The perforated plate divides the roof solar chimney into two channels, increasing the pressure head and warming the air in the solar chimney on the chimney roof. The ventilation performance of the new roof solar chimney at several inclination angles (30°, 45°, and 60°) and depth widths (0.3 m, 0.4 m, 0.5 m) was studied through a three-dimensional numerical analysis. The design is shown in Figure 9. In comparison to the traditional roof solar chimney with the inclination angle of 60° and depth width of 0.5 m, the optimized roof solar chimney mass flow rates were shown to rise by 35.0% to 39.7%. The results showed that the increase of ventilation through the use of the perforated absorber plate is more relevant to the large-depth Solar Roof Chimney. This means that for the solar chimney roof the optimized configuration has a greater effect than for that with a smaller depth of width.

Saleem et al. [46] developed a steady-state mathematical model to derive the optimal design of the solar chimney, which achieves the best flow rate of air in accordance with international standards. The designed model is the cable

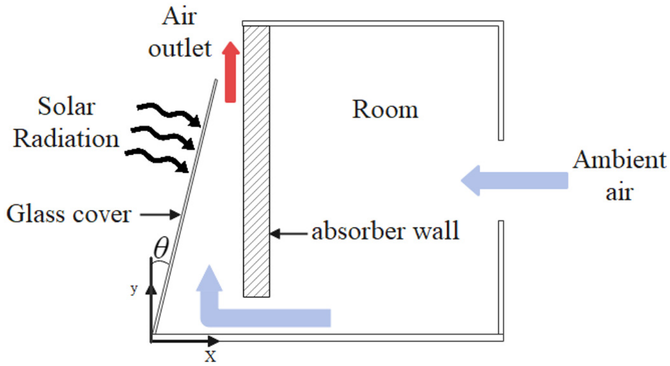

Fig. 10. Schematic of a two-dimensional solar chimney (IPWSC) attached to a room [47].

for a large range of variables for predicting airflow rates. The template also predicts glazing temperatures, the black painted absorber and the airspeed out of the chimney. The results from the analysis show an optimal flow rate of 0.019 into 0.033 m^3/s during the daytime of 88.2%, where the dimensions of the solar chimney proposed are 45^0 inclined angle, 1.4 m in length, 0.6 m in width and 0.20 m in air gauge. Furthermore, computerized fluid dynamics (CFD), used in software design builders, based on the EnergyPlus simulation program, to predict the pattern of space flow using the CFD Module. For the resolution of mass and energy equations within the solar chimney, the model of the Renormalization Group (RNG) k-ε has been used. The validity of this model is described by comparisons of the model predictions with CFD calculations and bibliographical experiments.

Khanal et al. [47] examined a numerical study of the buoyancy induced turbulent airflow in the inclinde passive wall (IPWSC) solar chimney, as shown in Figure 10, which is connected to a ventilation room (ventilated space) with various control parameters. The study extends previous research to the full-turbulent flow system that is more relevant to practical applications on the IPWSC design than the laminar flow regime. The standard k-ε turbulence model was used to model air turbulence on the solar chimney system. These numerical findings have shown the efficiency of the IPWSC design in the improvement of natural ventilation at a great height (more than 1 m). The results show that the independent model overestimates the mass flow in comparison with the annexed model. The average mass flow difference of the predicted standalone model to the attached model is around 10%, with inclination angles of 0–6°.

Shi et al. [48] introduced a solar chimney that is designed to save energy and provide fire safety for a real building. The proposed designs were simulated numerical and validated through experiments. The chimney's purpose is ventilation and thus the airflow rate through the chimney's cavity was the focus of the study, in this case it was considered to be the inlet air's air flowrate. The study considered two types of air supply which are (i) the bottom door and (ii) the top vent. Various parameters were considered to optimize the chimney design, these parameters included the location of the chimney and solar radiation, the area of air supply through the bottom door and top vent, in addition to chimney height and cavity gap. In addition, multiple scenarios were taken into consideration for the numerical simulations. Type (i) was preferred due to its high efficiency, while the top vent, type (ii), is faulted for sometimes functioning as an exhaust vent, which was observable for the smoke exhaustion scenarios. Similarly, in a study by Kong [49], a CFD numerical simulation was implemented to determine the solar chimney's roof-top optimum angle of inclination to maximize the ventilation performance. The size of the chimney was characterized as small scale, with lengths of 500 mm and 40 mm for the absorber wall and air gap, respectively. Moreover, the inclination angle was varied from 30° to 90° and subjected to various heat fluxes. The study then associated the solar irradiance with chimney performance corresponding to the inclination angle, then imported data for three different cities in Australia (different latitudes) to view the optimum angle. The angle was found to range between 45° and 60°, which is dependent on both latitude and season. The impact of the season on the chimney performance was also studied by Jimenez-Xaman et al. [50] who studied a rooftop SC attached to a single room considering both Summer and winter conditions in Merida, Mexico.

In other cases, researchers investigated solar chimnies with other system components for improved performance or multifunctionality, where Serageldin et al. [51] combined the chimney with an earth-to-air heat exchanger, Moosavi [52] coupled the chimney to a windcatcher, which was the north façade of the building, and Wang [53] who used CFD to investigate the performance of a solar chimney and a water wall for thermal comfort and ventilation purposes.

7 PCM integrated Trombe walls

Trombe walls are well-established methods for passive solar heating of buildings. These walls store the solar energy when received during peak sunshine hours to then release it during peak demand of heat. In such way, it reduces the heat during the day, maximise it during the night, or as designed, allowing for a cheap thermal comfort in winter seasons. Classifical designs of these walls are low-cost and require minimal maintenance, however, to achieve a better heat storage it is required to increase the volume and weight of these walls. This change leads to an increase in the "building's dead load". Hence, alternative strategies are utilized, mainly the incorporation of phase change material.

Omara and Abuelnuor [54] reviewed the implementation of Tromb walls with PCMs. The review led the authors to conclude that the low-thermal resistance of the tromb wall could be mitigated through the incorporation of PCM, which exhibit high storage capacity, and hence the heat dissipation can be reduce and solar radiation gain could be better controlled. However, the use of PCM is associated with a number of challenges such as finding the exact quantity suitable for the application, a little amount is not enough to achieve the desired performance, while too much of it can lead to an increase in the thermal gains, beyond desirable amounts, which is the not the target of thermal comfort. Moreover, the quantity will affect the weight and associated costs. In addition to the need to find the optimum thickness of the used PCM. Other challenges include findings the optimum phase change temperature for the Trombe wall incorporated PCMs. Meanwhile, the issues of high humidity could be mitigated using a new type of PCM, which is referred to as "phase change humidity control materials", which can both regulate humidity and indoor temperature. However, further researcher is required on such topic.

Szyszka et al. [55] proposed and experimentally tested an innovative tromb wall for heating spaces in cold weathers, that the authors named "Thermo-diode Trombe wall" which was specifically designs to increase solar gains and reduce thermal losses, this being achieved by improving the insulation of the building's envelope. The proposed solution consisted of a glazing system, black steel absorber, vent, internal wall, PCM containers to store thermal energy, lower and upper insulations and an internal wall. The experiments were run for three months and focused on observing the climatic conditions and thermal parameters associated with the proposed tromb wall. The researchers found in their study that the "thermo-diode Trombe wall" led to higher temperatures in the air cavity, exceeding 35 °C in the upper section when the external air temperature being close to 0 °C.

Oluah et al. [56] investigated the optimum PCM for Trombe wall by employing two methods, (i) entropy weight method, which the researchers used to determine the weight of the various criteria, and (ii) the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology, which was used to rank the different types of PCM. The methodology considered four criteira, namely (i) heat of fusion, (ii) thermal conductivity, (iii) density and (iv) cost. The highest weight was assigned to the thermal conductivity, with around 72.12%. TOPSIS was carried out by assigning scores, to each PCM, in a range interval of with the ideal PCM being the closest to 1.0. The findings suggest that the best PCM, among the 11 tested types in the study which exhibited phase change temperatures ranging from 18 to 28 °C, was the eutectic mixture of capric acid and palmitic acid.

In a systematic review and meta analysis, Wang et al. [57] showcased the classifications of Trombe walls and provided the hybrid types of trombe walls as follows: (i) composite trombe wall with PCM, (ii) PV trombe wall with PCM, (iii) Transwall, and (iv) Trombe wall with translucent insulation material (TIM) and PCM. Type (i) differs from the classic trombe wall in that it incorporates both thermal storage wall along with greenhouse effect, from outside air channel, for solar energy collection, while the inside air channel is utilized for heating. Hence, the process of heat-collection is saperated from that of room-heating, thus effectively reducing the influence of external environment. Furthermore, the integration of an insulation layer allows for an improved wall thermal resistance which can consequently lowers thermal losses during night time. Type (ii) utilizes both photovoltaic (PV) technology and PCM material. The addition of PV modules allows for power generation to be part of the process. Altought the heating process is reduced due to PV absorping the solar radiation, the PV is beneficial in mitigating over-heating during the summer period, and is useful in producing electricity which can be used for different purposes. Type (iv) is introduced to replace the conventional single/multiple glazed covers because TIM exhibits a good acoustic insulation and is characterized to be light-weight. While type (iii) is a water trombe wall with TIM, which, during the daytime, provides improved direct-heat gain and indoor lighting, in addition to its high aesthetic value as it provides visual access to indoor space; all because of the material's transparency.

8 Critical review

To critically review the literature, a sample from the literature is summarized and explained in terms of cooling technique, approach and application across time is provided in Table 1.

The risk of overheating in populated buildings with limited space is a contemprory issue. Sustained elevated temperatures during the summer season are major causes to this problem. Hence, it is crucial to establish passive cooling methods to target overheating. The adoption to existing buildings can be made by the use of Phase Change Material (PCM), as done by [58–64].

On the other hand, the use of radiant panels which can utilize a cooling medium such as water, which could also be passively cooled, is effective [65]. However, the problem remains to be the use of water pumps, unless they can dually serve another purpose. Hence, in the form provided by Baharun [65] it is a combination of active and passive cooling.

From Table 1, the following topics for discussion are to be highlighted:
– The storage capacity per unit volume of PCM material is high and hence they are easier to employ with retrofit project.
– The implemented ventilation strategy strongly influence the success of PCM in passive cooling. This point is supported both by the work done by Zavrl [61].
– Nighttime cooling is a necessity to purge the stored thermal energy; to improve the efficacy of the thermal energy storage system.
– Innovative designs and mechanisms, as provide by Gracia [59], are presented in the literature where PCM layer can be rotated corresponding to melting and solidification; nighttime it is shifted outward to cooldown and daytime it is shifted inword to absorber internal heat. However, the shifting process itself require mechanical actuation; which mainly is done through passive elements.
– The importance of Global Energy Balance (GEB) model in the prediction of the dynamic behavior of a solar chimney passive cooling system was highlighted by Jimenez-Xaman [60].

The use of solar chiney assisted means of room conditioning [66] was found to provide daytime cooling and to avoid the risks of temperature stratification; an issue for the occupants. The topic was further expanded by employing a novel trombe wall [67]. The topics covered in the literature are recent, i.e. 2018–2019, and state-of-the-art. The work in PCM-TES systems is growing and the potential for further development on material aspect is promising.

9 Innovation in natural ventilation research

The research on passive cooling through natural ventilation has went through many developments in the last 10 years, a summary of some of the studies on natural ventilation is provided in Table 2. Saber et al. [72] conducted a review on control system for natural ventilation as a strategy in the United Kingdom (UK) for passive cooling of buildings. The study reviewed design features for natural ventilation, considering cross ventilation, or double sided, as well as single sided/single opening and single sided/double openings indoor spaces. Moreover, the authors stated that design of natural ventilation is highly dependent on the climate types, which in terms affects the appropriateness of design features and control strategies. Moreover, different intelligent systems and controls are reviewed, listing Artificial Intelligence (AI), Artificial Neural Networks (ANN), Genetic Algorithms (GA), Fuzzy Logic Controllers (FLC), etc. The authors recommended testing proposed control systems in an experimental setup or an actual case study. Abd Rahman et al. [73] reviewed naturally ventilated public hospital wards in tropical climates, focusing on the Malaysian climate. The review covered energy management aspects such as energy efficiency and renewable energy, as well as thermal comfort aspects such as patient thermal comfort and staff thermal comfort. The review showcases that Photovoltaic thermal (PV/T) heat pump systems and PV heat pump system are excellent renewable energy options to establish the target thermal comfort and improve energy saving of the public hospital ward. In a later work published by Abd Rahman et al. [74], the authors investigated the thermal comfort conditions in a public hospital ward that was naturally ventilated using field surveys, objective measurements and a computer simulation to ensure obtaining accurate. The results of the objective measurements and predicted simulations were very similar, the predicted mean vote ranged between 1.0 and 1.6, while the survey showed that 82% of the hospital's occupants were dissatisfied. This study shows a good approach to acquire accurate results. Bayoumi et al. [75] studied the improvement of wind-driven air exchange of classrooms using different methods. These exchangers are implemented to improve the indoor environmental quality in warm climates. The authors investigated different alternatives, or scenarios, using CFD analysis with considerations of thermal sensation, air velocity, air change rate and pressure distribution. The findings indicate that each façade in the building requires special treatment and that unifying the opening scenario for all facades is undesirable. Among the parameters used to assess the indoor air quality is the air change rate (ACH) which can determine if the supplied fesh air is sufficient or not. Haw et al. [76] also used ACH to assess the performance of a wind-induced natural ventilation tower, and compare it to other wind ventilators. Figure 11 shows the average daily

Table 1. Summary of some references in the literature.

References	Year	Cooling technique	Approach	Application
[58]	2018	Passive Cooling Thermal Energy Storage (TES) system	Exposed thermal mass was injected into the building's interior	Improving the quality of indoor environment for occupied spaces in UK.
[65]	2018	Modular radiant cooling panel coupled with night cooled water	(1) water stored in HDPE tank is cooled at night, (2) indoor test room cooled during day	Improving thermal comfort of buildings in Malaysia.
[59]	2019	Passive Cooling Thermal Energy Storage (TES) system	PCM layer position variation with respect to insulating layer of building envelope	Use as thermal barrier and a cooling supplier system.
[68]	2019	Solar chimney	STPV panels are utilized as the collector roof of the solar chimney	Semi-transparent PV plant cooled using solar chimney.
[60]	2019	Solar chimney and PCM	Review designs using CFD and GEB approaches	Solar Chimney & PCM for ventilation and passive cooling in buildings
[66]	2019	solar chimney and a water spraying system	Four titled absorbers were placed for the solar chimney, symmetrically facing south-north direction, with a Water spraying system	Air conditioning of a room under arid climate
[67]	2019	Trombe walls with solar chimney & water spraying system	The novel trombe wall can receive the solar intensity from three directions as apposed to one direction for normal trombe wall	Air conditioning of a room under arid climate
[61]	2018	Passive cooling thermal energy storage system	A wall installed – lightweight timber envelope containing layer of PCM	Envelop with layer of PCM for Lightweight Prefabricated Houses
[62]	2019	Passive cooling thermal energy storage system	(1) PCM layer attached at the ceiling in contact with the indoor space, (2) PCM layer integrated inside a suspended ceiling	Analysis of two cases for PCM application for dwelling in a multi-family building
[69]	2019	passive design structure with natural ventilation	Use of Shavadan: An ungergound natural ventilation system	Ventilation for Iranian underground living space
[63]	2019	Passive cooling thermal energy storage system	Reviewed solar & heat protection, heat modulation, free cooling and closure	Passive cooling techniques for buildings
[70]	2019	Wall-mounted attached night ventilation	Enhanced convective cooling via downward air jet flowing over internal surface of the wall	Ventilation for buildings at night time
[64]	2019	Passive cooling thermal energy storage system	Room Integrated PCM Wallboards	Passive cooling for office rooms in Germany
[71]	2019	Passive cooling Vertical ventilation system	house incorporated with vertical ventilation, measurements for each floor	Natural ventilation for a house in Indonesia

Table 2. Summary of research studies on natural ventilation for passive cooling applications [72–75,77].

References	Year	Type of study	Topic and application	Approach
[72]	2021	Review	Control systems for naturally ventilated buildings	A systematic review approach to identify the most effective intelligent control system for natural ventilation design features.
[73]	2021	Review	Natural ventilation in public hospital and thermal comfort conditions	Literature review to cover the published literature on naturally ventilated public hospitals, thermal comfort and energy saving.
[74]	2022	Original	Natural ventilation in public hospital and thermal comfort conditions	The authors used computer simulations, objective measurements and field surveys to determine the thermal comfort conditions.
[75]	2021	Original	Single-sided ventilation and cross ventilation for classrooms	Numerical simulation using Computational Fluid Dynamics (CFD)
[77]	2022	Original	Microencapsulated PCM plates cooling system	Experimental testing chamber of two separate units: one that is PCM modified and one as a reference unit.

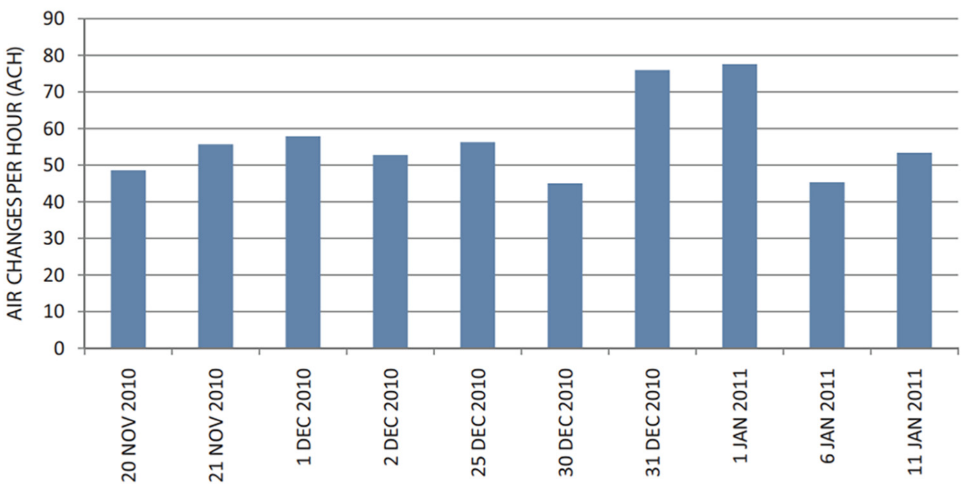

Fig. 11. Daily averaged air change rates induced by the wind-induced natural ventilation tower [76].

ACH across different days in November, December and January in 2010, for the proposed ventilation tower. Finally, Zavrl et al. [77] investigated a system that is comprised of two units, each representing an office and are equipped with a ventilation inlet and outlet, the inlet is at the bottom of the wall while the outlet is at the middle of the ceiling. One of the units was PCM modified while the other was used as a reference. The macroencapsulated PCM plates were installed on the internal walls and ceiling. The system was found to provide indoor space cooling during daytime as the PCM is melting. At cooler indoor temperatures, 26 °C, no external cooling is required, only passive, while at higher temperature, 30 and 35 °C, external cooling sources are required. Moreover, they found that a complete solidification of the PCM plates can be achieved within 12 h (nighttime cycle), when average inlet air temperature is 15 °C and at a flowrate of 500 m^3/h.

10 Conclusions

Many scientists and designers have been interested in the modern method of passive cooling, where they begin to change the current mechanical cooling practice. It should be noted that, where the climatic conditions are different, a suitable concept for one location may not be suited for another. Therefore the choice of various passive cooling techniques and buildings and related materials selection must be highly located specifically depending on the area's weather. The passive cooling concept for Buoyancy air-driven ventilation in this review paper will be helpful for designers and architects to develop several ideas for a certain site and to make energy-efficient building designs. The following recommendations provide multiple topics for investigation related to research in passive cooling:

- Passive cooling design can also provide thermal comfort to building integrated Photovoltaic (BIPV) systems. This cooling leads to increase in the electrical energy generation of the PV system. Further investigation into optimum passive cooling technique corresponding to BIPV systems are important, especially in hot and dry climates.
- To investigate the performance of nano-enhanced Phase Change Material, such as nano-enhanced paraffin wax or other organic PCM, as medium for passive cooling to establish thermal comfort.
- PCM tube designs are to be investigated in terms of optimum PCM peak melting temperatures, design strategy and supporting elements.
- To incorporate different methods to identify thermal comfort inside buildings such as numerical, objective measurements and surveys to obtain results with a higher accuracy.

The route to utilizing phase change material and natural means of ventilation seem to present interesting results and good cooling rate. The quest for achieving hybrid designs of thermal energy storage and natural ventilation system can reflect positively on future development in the field of passive cooling of buildings.

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