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A review on the application of Trombe wall system in buildings

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ABSTRACT

A major portion of the total primary energy consumed by today's buildings is used in heating, ventilating, and air-conditioning (HVAC). Conventional heating and cooling systems are having an impact on operational cost, energy requirement and carbon dioxide emission. In this regard, Trombe walls are receiving considerable attention because of their potential ability for addressing the environmental and energy crisis. This paper reviews the most pertinent contents of studies on Trombe walls that have been carried out in the recent 15 years. According to utilizing functions of Trombe walls, they are divided into two major types: a heating-based type and a cooling-based type. In terms of content, we emphasize the introduction of three groups of parameters that be considered when designing Trombe walls: the 'Trombe wall' parameters, the 'building' parameters and the 'site' parameters. Then different evaluation indicators on Trombe walls have been summarized from three points of view: energy, environment and economic. We hope that this review is useful to academic researchers and can provide a reference for architects or related engineering designers in the field of passive design.

1. Introduction

Parallel to the global population growth, energy consumption and environmental issues are today an increasing and global concern. According to the World Energy Council, primary energy demand will double by 2050 [1]. The building sector is the majority of energy consumption in the world and most of the energy is used for heating, ventilation and air condition systems (HVAC). They are indoor climate controls that regulate humidity and temperature to provide thermal comfort and indoor air quality [2]. For these reasons, the buildings we find today are expected to achieve both energy efficient and environmental-friendly design, using renewable energy partly or completely instead of fossil energy for heating and cooling, particularly solar energy that utilize cost-free solar radiation from the sun. In this direction, the integration of passive solar systems in buildings is one strategy for sustainable development and increasingly encouraged by international regulations. Passive solar techniques can reduce annual heating demand up to 25% [3]. Various architectural devices, such as solar chimneys [4], solar roofs [5], Trombe walls, etc., are used in construction. Among these devices, Trombe walls [6,7], which are known as storage walls and solar heating walls (SHW) [7,8], can harmonize the relationship between humans and the natural environment and are widely used because of advantages such as simple configuration, high efficiency, zero running cost and so on. In addition to being environmentally friendly, using a Trombe wall in building can reduce a building's energy consumption up to 30% [9]. A similar result was presented in Ref. [6]: energy heating savings of 16.36% was achieved if a Trombe wall was added to the building envelope.

The objective of this paper is to review the development on Trombe wall system for space heating and cooling. The academic research on Trombe wall is extensive, but this review is necessarily limited. Therefore, only the most pertinent scientific studies carried out in the recent 15 years is discussed in this review. Fig. 1 illustrates the journal papers distribution per year on the field of Trombe wall. We hope that the present information could provide a reference for architectural designers or related engineering designers.

2. Classification

Over time, modifications have been made to Trombe walls in order to improve their efficiency. Based on the major utilizing functions of Trombe walls, they are classified into two types: a heating-based type of Trombe wall and a cooling-based type of Trombe wall. Seven different configurations of heating-based types of Trombe wall will be described:

Abbreviations: HVAC, Heating, ventilation and air condition; SHW, Solar heating walls; CTW, Classic Trombe wall; TMW, Trombe–Michel wall; WTW, Water Trombe wall; ZTW, Zigzag Trombe wall; SCTW, Trombe wall in combination with solar chimney; HTF, Heat transfer fluid; LCA, Life cycle assessment; LCC, Life Cycle Cost; ACH, Air change per hour; PCM, Phase change material; FTW, Fluidized Trombe wall; PVTW, Photovoltaic Trombe wall; CECW, Ceramic evaporative cooing wall; HTF, Heat transfer fluid

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Nomenclature

Q	Heat gain (J)
α	The percentage of Trombe wall area to the total south wall area
η	Thermal efficiency
$\dot{m}$	Mass flow rate (Kg/s)

(1) a classic Trombe wall (CTW); (2) a composite Trombe wall or Trombe–Michel wall (TMW); (3) a water Trombe wall (WTW); (4) a zigzag Trombe wall (ZTW); (5) a solar trans-wall (STW); (6) a fluidized Trombe wall (FTW); and (7) a photovoltaic Trombe wall (PVTW). Three different configurations of cooling-based types of Trombe wall will be introduced: (1) a ceramic evaporative cooing wall (CECW); (2) a classic Trombe wall and photovoltaic Trombe wall for cooling operation mode; and (3) a new designed Trombe wall in combination with solar chimney (SCTW). Fig. 2 illustrates the general classification. Each configuration of Trombe wall is discussed in detail in Sections 2.1 and 2.2, with their main advantages and disadvantages.

2.1. A heating-based type of Trombe wall

The concept of Trombe wall was patented by E.S. Morse in the 19th century and developed and popularized in 1957 by Félix Trombe and Jacques Michel. In 1967, in Odeillo, France, they built the first house using a Trombe wall. This wall is a simple configuration and designed to accumulate the solar heat and provide the interior space heating, which is known as classic or standard Trombe wall [10–12]. The exterior surface of the wall is colored black to increase the absorption rate and the surface of the classic Trombe wall is glazed. The channel is left between the wall and glass [13]. Fig. 3 shows the operating modes of a classic Trombe wall for winter heating.

The classic Trombe wall can catch solar radiation exploiting greenhouse effect created in a glazed cavity, and absorb and store heat using a massive wall. Part of the energy is transferred into the indoor of the building (the room) through the wall by conduction. Meanwhile, the lower temperature air enters the cavity from the room through the lower vent of the wall, heated up by the wall and flows upward due to buoyancy effect. The heated air then returns to the room through the upper vent of the wall. Whereby, heat exchange of Trombe wall with the indoor environment is partly by transmission through the wall and partly by ventilation through the vents. This simple configuration of Trombe wall suffer from the following shortcomings.

(1) Low thermal resistance. during the night or prolonged cloudy periods, some heat flux is transferred from the inside to the outside, which results in excessive heat loss from the building [11].
(2) Inverse thermo-siphon phenomena. when the storage wall is colder than the air in the ventilated layer, the air is cooled and re-injected into the room through the lower vent, particularly during the night in the cold season and hence decrease the room temperature [14].
(3) Low aesthetic value [15].

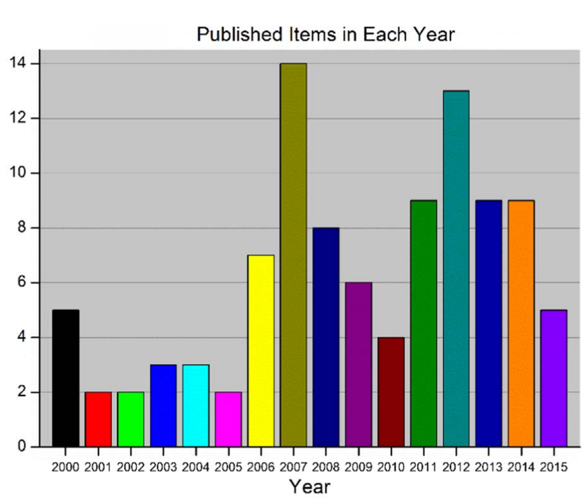

Fig. 1. Number of papers per year on the field of Trombe walls.

To increase the thermal resistance of the classic Trombe wall and control supplies, another heating-based type of Trombe wall, which is known as composite Trombe wall or Trombe–Michel wall [11,12], is developed. The composite Trombe wall consists of several different layers. These layers comprise a transparent outer cover, an enclosed air layer, a storage wall, a ventilated air layer, and finally an insulation layer (see Fig. 4). It works as follows. The first layer, which is transparent, dispatches the majority of the gained solar beams. Consequently, the storage wall absorbs part of the solar energy and heats up by greenhouse effect. The thermal energy can be transferred from outside to the interior air layer by conduction through the massive wall. Then it can be transferred by convection while using the thermo-circulation phenomenon of air between the massive wall and the insulating wall. In addition, a small portion of the energy is transmitted by conduction from the wall into the room. Therefore, nearly all the supply is provided to the building by means of the ventilated air layer. Due to greater thermal resistance of this design (the existence of the insulation layer and the air layers), there is little thermal flux that going from indoor to outdoor. Moreover, users can control the rate of heating at all times by adjusting the air circulation. While this type of Trombe wall can't avoid the reverse thermo-circulation of a classic Trombe wall and requires a mechanism to prevent it.

Another approach to reduce the heat loss of the classic Trombe wall is that using water for the heat storage instead of building materials, such as concrete, bricks, adobe, and stone. In this direction, the water Trombe wall is invented (see Fig. 5) [16,17]. Because the specific heat of water is higher than that of the building materials, the water's surface temperature does not rise as high as that of the masonry. Therefore, less heat is reflected back through the glazing. However, containing the water is much more difficult than containing solid materials such as masonry [18], which limited its spread.

Another heating-based type of Trombe wall is a zigzag Trombe wall, which is designed to reduce the excessive heating gain and also glare of sunny days [10]. As shown in Fig. 6, the wall consists of three sections. One section faces south. While the two other sections are angled inward forming a V-shaped wall. The section that faces southeast has a window that provides heat and light in the morning cold when immediate heating is required. Opposite the V shape is a classic Trombe wall, which stores heat for redistribution in the cold night hours.

Another innovative heating-based type of Trombe wall is a trans-wall (as shown in Fig. 7). It is a transparent modular wall that provides both heating and illumination of the dwelling space [19]. Therefore, a trans-wall plays an aesthetic role by providing visual access to a building's interior. These walls are comprised of water enclosed between two parallel glass panes supported in a metal frame. A semi-transparent absorbing plate is positioned between the parallel glass panes. The incident solar radiation is partially absorbed by the water and semi-transparent glass plate, the rest of the transmitted radiation

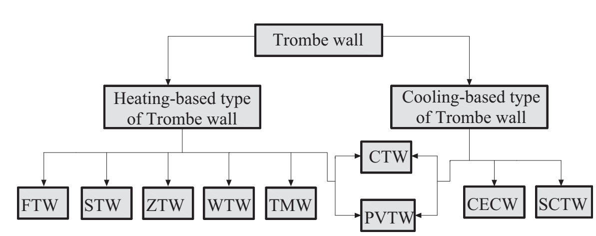

Fig. 2. Trombe wall classification.

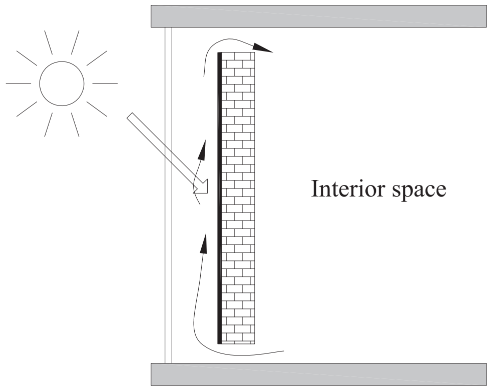

Fig. 3. A classic Trombe wall for winter heating.

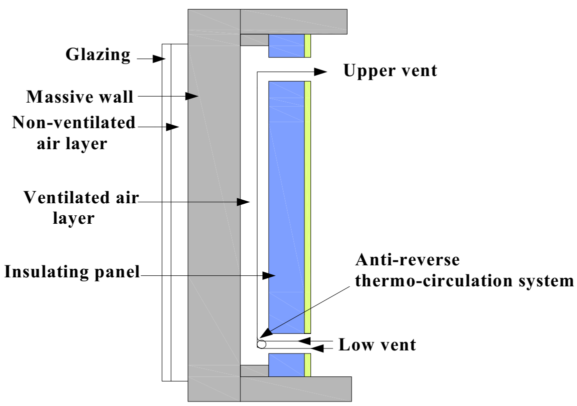

Fig. 4. A composite Trombe wall.

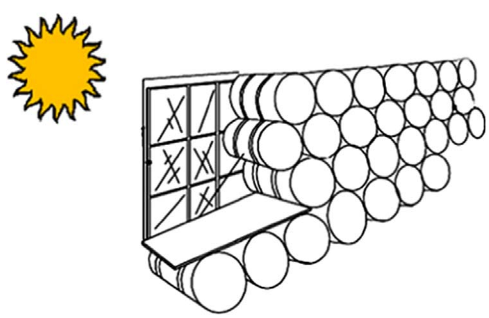

Fig. 5. A sketch of water wall [10].

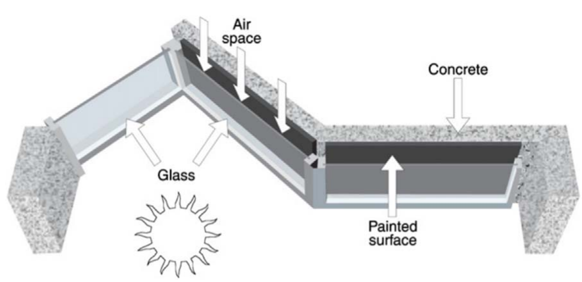

Fig. 6. A zigzag Trombe wall [10].

causes both heating and illumination that are required by the indoor space. Therefore, this type of wall uses the direct and indirect gain systems and is suitable for locations where daytime temperature is high [20]. Its main drawback is the existence of convective heat transfer in a trans-wall. However, installing transparent baffles overcomes this deficiency.

A novel concept of fluidized Trombe wall system is developed, which is also a heating-based type of Trombe wall and based on the classic Trombe wall but where the gap between the Trombe wall and the glass cover is filled with highly absorbing, low-density particles [21]. The solar energy gained by these highly absorptive particles is transferred to the indoors through fan-circulated air. Two filters at the top and bottom of the air channel prevent the fluidized particles from entering the indoor space [22]. The fluidized Trombe wall are far more efficient than classical Trombe walls as the air (heat transfer fluid (HTF)) is in directly contact with the fluidized particles (see Fig. 8).

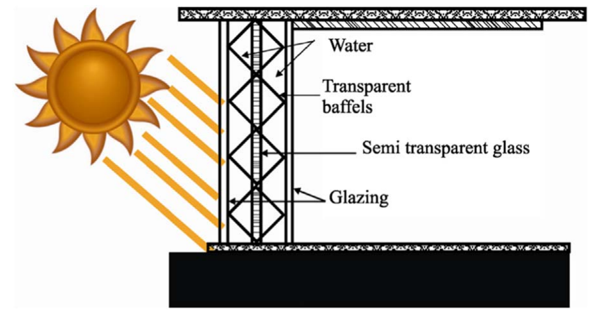

Fig. 7. A cross-sectional view of Trans-wall system [10].

Another heating-based type of Trombe wall is invented by incorporating solar cells with classic Trombe wall, which is known as photovoltaic (PV) Trombe wall (see Figs. 9 and 10). The PV-Trombe wall not only provides space heating, but also generates electricity; meanwhile it brings more aesthetic value. PV coverage on the glazing reduces the solar heating ability of the Trombe wall, however, this type of Trombe wall generates electricity, which is of high quality compared with the thermal energy [23–25].

2.2. A cooling-based type of Trombe wall

According to Sodha et al. [26], passive cooling concepts for the buildings are as follows.

(1) Reduction of solar and convective heat input
    Orientation, shading by neighboring building, shading by vegetation, shading by overhangs textured facades, reflecting surfaces, and shelter against hot winds.
(2) Reduction of heat transmission
    Thermal insulation, air cavities.
(3) Increase of heat loss by radiation
    Enlarged surface area, movable elements.
(4) Increase of heat loss by convection
    Outdoor wind management, indoor natural ventilation, Indoor

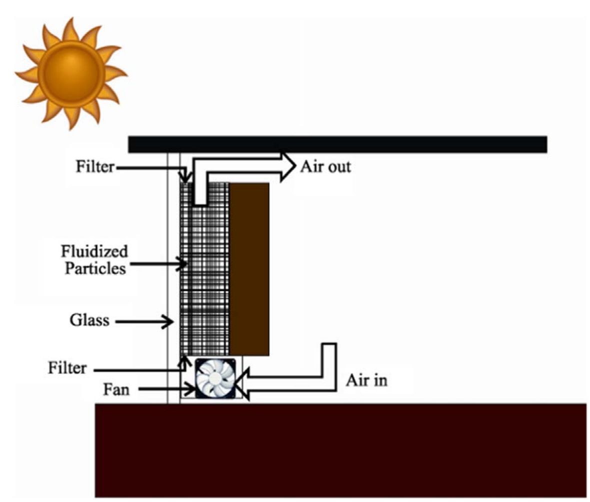

Fig. 8. A cross-sectional view of fluidized Trombe wall system [22].

Fig. 9. Graphic representation of the PV-Trombe wall assisted with DC [25].

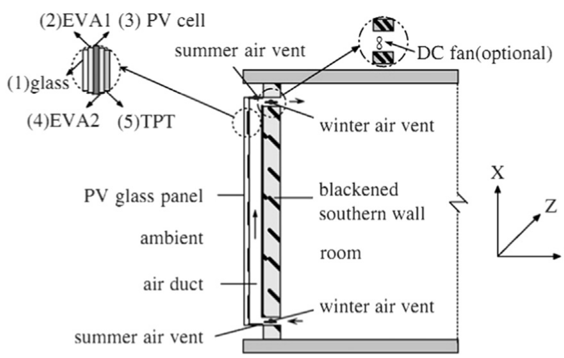

Fig. 10. PV-Trombe wall with DC fan for winter heating [25].

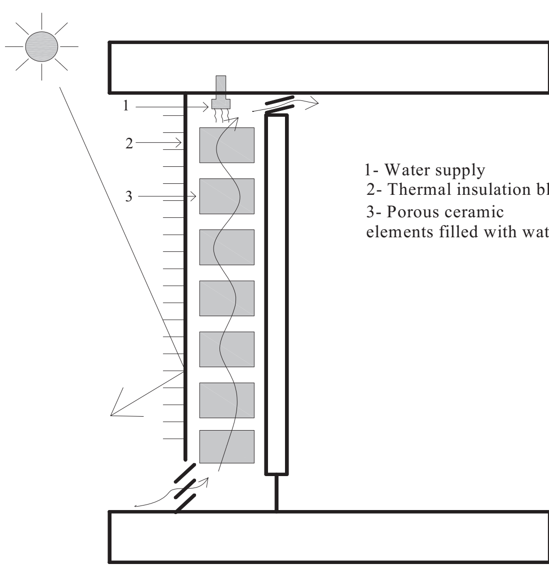

Fig. 11. Ceramic evaporative cooling wall [27].

forced ventilation,

Earth air tunnel flowing water.

(5) Increase of heat loss by evaporation

Outdoor and indoor air-cooling, building surface cooling.

According to the concepts (1) and (5), the first cooling-based type of Trombe wall is the ceramic evaporative cooing wall [27] (Fig. 11). The wall employs an external reflective thermal insulation blinds to avoid direct solar gain. In particular, the porous ceramic element filled with clean water is used in the interior wall. The outside air intake is through slots in the lower part of the gap and the outtake is through the upper part of it, to the inside room. In hot summer, the gap is function as a cooling chamber to cool down the outside air temperature due to the direct evaporative cooling phenomenon [27].

The second cooling-based type of Trombe wall is developed based on the solar chimney [2]. Strictly speaking, this type of Trombe wall is not a new invention and is only another operation modes of the heating-based type of Trombe wall. For moderate climate, when the outdoor temperature is lower than the indoor temperature, the cooling-based type of Trombe wall is functioned as natural ventilation (Fig. 12(a)). However, for hot climate, when the outdoor temperature is higher than the indoor, it operates as thermal insulation to reduce heat gain of the room (Fig. 12(b)). According to the concept (2) and (4), both of the two operation modes can provide passive cooling for the inside space. Nonetheless, this cooling–based type of Trombe wall is not architectural attractive in term of aesthetics aspect. Moreover, it has the risk of overheating in hot summer due to the lack of control over the energy supply by the storage wall. To satisfy the thermal comfort and aesthetic value, PV panel and shading device incorporate with the second cooling-based type of Trombe wall hybrid, which is another operation mode of PV-Trombe wall in summer [15,28] (Fig. 13).

A recent study carried out by Rabani et al. in hot and dry cities [29] presents a new designed Trombe wall (see Fig. 14), which is the combination of Trombe wall and solar chimney. This innovative design eliminates the major defects of the two systems: Trombe wall's uselessness in half of the year and solar chimney's incapability to create air flow in the late hours of the day. Moreover, contrary to the classic Trombe walls where the absorber receives solar radiation from one direction, the new design in Trombe wall channel enables the absorber to receive solar radiation from three directions (east, south and west) that causes the channel temperature and the mass flow rate inside the channel to increase. Furthermore, to reduce the air temperature and increase the humidity inside the room, two incoming fresh air ports equipped with water spraying system have been employed. According to the experimental results [29], use of water spraying system enhances the thermal efficiency of the system by approximately 30% (see Fig. 15).

3. Factors that be considered when designing Trombe wall

Trombe walls are regarded as a sustainable architectural technology using solar energy for heating and cooling in various climatic regions [30]. To achieve a high efficiency, some influencing factors must be considered when designing Trombe wall system in building, including Trombe wall design parameter (outer skin glazing properties, Trombe wall's area, channel depth, massive wall properties, shading devices), building parameters (construction materials, window effects), site parameters (solar radiation and orientation, wind speed and direction). Table 1 groups the parameters evaluated in this section and summaries main findings of the selected literature reviews of Trombe wall. In the following section, the above-described parameters will be discussed in detail.

3.1. Trombe wall design parameters

3.1.1. Glazing properties

Glazing properties, such as the materials, the thickness and the number of glazing layers not only influence the amount of solar radiation that is either reflected, absorbed or transmitted but also affect the heat loss between the inter-space and outside environment [31]. Therefore, considering the influence of different glazing properties is of importance in Trombe wall design phase. During the cooling season, the favorable number of glazing layers design for a Trombe wall depends on the climate conditions of the building site. According to Yilmaz et al. [32], in Turkey, single glass improved Trombe wall

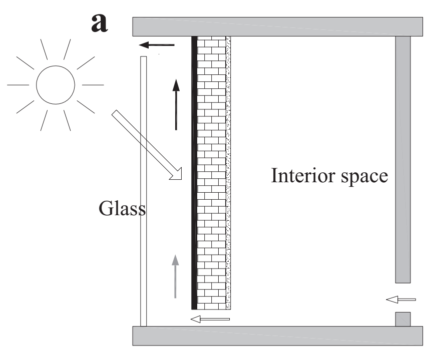

Fig. 12. The second cooling-based type of Trombe wall operation mode (a) natural ventilation mode (b) thermal insulation model.

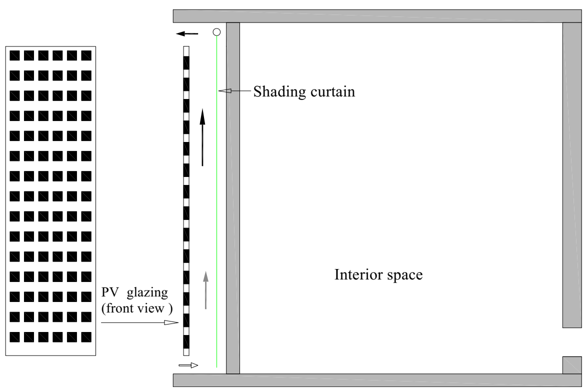

Fig. 13. PV-Trombe wall for cooling operation mode.

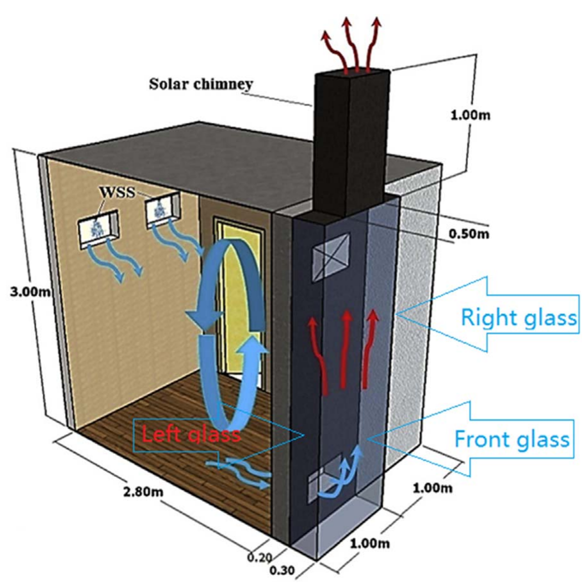

Fig. 14. Schematic of airflow circulation for the cooling performance of the system [29].

performance during day time due to having higher solar radiation transmissivity. However, in Italy, according to Stazi et al. [31,33], the installation of double glazing allowed more reduction in winter heating energy need because the double glass determined lower heat losses and did not affect significantly solar heat gains. Similarly, Irshad et al. proposed that the application of double glass filled with argon PV-TW in Malaysia climatic condition was economically viable from the point of view of saving in cooling energy cost and CO_2 emission [34].

In terms of glazing materials, Richman and Pressnail [35] introduced a low-e coating on the spandrel glass to minimize the radiative losses to the exterior during heating season. In addition, a simulation was conducted by Zalewski et al. in Trappes (longitude: 2°01´, latitude: 48°46´) and Carpentras (longitude: 5°03´, latitude: 44°08´) to study the impact of materials on the Trombe-wall performance. The results showed that use of low-e double glazing collected more solar energy contrary to the a standard double glazing [14]. The comparison of energy collected during a heating season for different type of Trombe wall varying the glazing materials was shown in Figs. 16 and 17. The results also revealed that Trappes show more significant changes compared with Carpentras when changing the glazing material [14].

3.1.2. Trombe wall area

A simulation study using TRNSYS software was conducted in Tunisia by Abbassi et al. [1]. The study aimed to evaluate the impact of Trombe wall area on energetic performance. The annual heating energy saving for different Trombe wall areas were presented in Fig. 18. The results seem that the increase in Trombe wall area provided the decrease in heating energy demand, while we must also not forget that we are limited by the total south wall area of the building. Jaber et al. [36] performed another simulation study on a typical Jordanian residence, which was equipped with Trombe wall system. In this study, they investigated the effect of variable Trombe wall ratio (α), the percentage of Trombe wall area to the total south wall area, on building heating from thermal and economic points of view by using Life Cycle Cost (LCC) criterion. They found that the percentage of heating energy savings increased with the increasing of Trombe area ratio (α) firstly, as shown in Fig. 19. When (α)=20%, about 22.3% of heating auxiliary energy was saved annually. However, when α exceeded the value of 37%, the percentage of heating energy savings kept at nearly steady values. Therefore, the optimum Trombe wall area ratio was 37%, which corresponded to 32.1% of heating auxiliary energy savings (see Fig. 19).

3.1.3. Massive wall properties

A group of Algerian scholars have concluded that the massive wall is the most crucial component of a Trombe wall [7]. Massive wall parameters discussed in this review include the thickness, materials and insulation level. With respect to wall thickness, Briga-Sá et al. [6] used a calculation methodology for the Trombe wall based on ISO 13790:2008(E), to study its behavior for the thicknesses of 15 cm, 20 cm, 25 cm, 30 cm, 35 cm and 40 cm. The obtained results indicated that for the heating season, if the Trombe wall was ventilated, the heat gains increased with the increasing of the massive wall thickness. However, in the case of the non-ventilated Trombe wall, the heat gains decreased when the thickness increased (see Fig. 20). The thicker the wall is, the longer it takes the heat to reach the interior. This situation results in the thermal discomfort for the building occupants. While insufficient thickness wall caused the wide range room temperature fluctuation [37,38]. In this direction, Agrawal and Tiwari have proposed an optimal thickness of 30–40 cm for a concrete Trombe wall [39], which is similar to Stazi et al. [31] (around 35 cm for clay brick wall) and Fang et al. [40] (37 cm for brick; 35–40 cm for low concrete walls and 40–45 cm for high concrete walls).

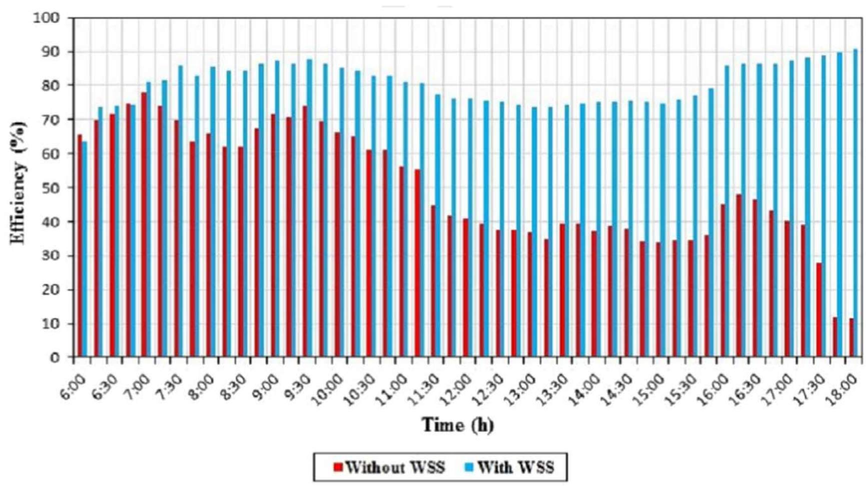

Fig. 15. Variation of hour average efficiency with and without WSS for 29–30 June 2014 [29].

In terms of the selection of Trombe wall materials, a study was carried out by Stazi et al. [31] during both the pre-use phase and use phase of Trombe wall on three wall materials: concrete, brick and aerated concrete. Considering both pre-use and use phases, the best overall performance was obtained using the wall with aerated concrete blocks that combines a production cycle with low environmental impacts and high energy performances in the use phase [31]. Boji´c et al. dealt with an optimization of massive wall materials of the two Trombe walls used at the south side of a “Mozart” house located in Lyon, France. They concluded that the concrete core in Trombe wall yielded lower use of the annualized life cycle energy than that of clay brick core for the same thickness. In addition, Hassanain et al. [41] examined the effects of various adobe materials on the efficiency of Trombe walls and found that different adobe materials resulted in different efficiency.

Increasing the weight and volume of Trombe walls can increase their heat storage capacity. However, this increase a building’s dead load, which is considered a problem by structural engineers. To address this problem, one of the possibilities is to use the phase change material (PCM) as the thermal storage media [42–46]. PCM was first time used to Trombe wall in 1978 by Telkes at al. [47]. The PCM can store more energy in a relatively small volume and are also lighter than normal building materials [48]. Moreover, the stored energy in PCM can transfer to the room faster compared to that in concrete wall based on the experimental study by Zalewski et al. [49]. The results indicated that for the brick containing hydrated salts, the solar gains was restituted to the room with a delay of 2 h 40 min that was more than twice shorter than a 15 cm thick concrete wall. This may be an inconvenient if the wall is devoted to be installed in an inhabited dwelling to take advantage of gains at the end of the day. While this undesirable phenomenon seem not boring due to the lager amount of stored energy for PCM. According to the simulation study performed by Rabani et al. [50] on the time duration of room heating during the non-sunny periods for different materials of the Trombe wall. The results showed that the Trombe wall made of paraffin wax could keep the room more warm in comparison with other materials for about 9 h (see Table 2). Similarly, Liu et al. [51] found that the application of PCM can extend the duration of the utilization of the solar chimney particularly at night-time.

Different types of PCM showed different heat reaction on a Trombe wall. A numerical study was conducted by Khalifa and Abbas in Baghdad, Iraq, for a zone heated by a south-facing Trombe wall with different storage materials (concrete, paraffin wax and the hydrated salt $CaCl_2{\cdot}6H_2O$) [52]. The two types of PCM (paraffin wax and the hydrated salt $CaCl_2{\cdot}6H_2O$) were encapsulated in copper capsules with length to diameter ratio of 0.76. The results indicated that an 8 cm thick hydrated salt storage wall gave the least variation where the room temperature fluctuated around the comfort temperature of around 20 °C compared with the 5 cm thick paraffin wax [52] (see Table 3). In Japan, a group of scientists confirmed the results [53]. In addition, variations of PCM position in the external envelope affect the Trombe wall efficiency differently. Francesco Fiorito [48] defined the suitable position for five different climatic zones. In addition, the materials used to coat the massive wall should be noticeable, which is seen as a heat transfer enhancement technique on the absorption and storage capacity of the Trombe wall [54,55]. Finally, thermal insulation on massive wall is considered a remedy for the deficiency of a classic Trombe wall: low thermal resistance and heat loss at night [56,57]. According to Ji et al. thermal insulation in both winter and summer improves the efficiency of PV-Trombe wall [15]. In addition, they carried out a numerical study on an improved type of composite Trombe wall with insulated internal and cavity wall [58]. The study revealed that the insulation increased the efficiency of a composite Trombe wall.

3.1.4. Shading devices

Heat loss in winter night and excessive heat gains in hot summer are the two shortcomings that restrict the application of Trombe wall. Shading devices are regarded as a simple technique to address these unfavorable problems [59], such as shading curtain [15,60], roller shutter [33,61,62], venetian blinds [63] and overhang [61,64]. Stazi et al. pointed out that using a Trombe wall without solar screening in hot summer is strongly not recommended [33]. In addition, they demonstrated the combined use of overhangs and roller shutters can achieve the optimal Trombe wall efficiency in hot summer [61]. Moreover, an experimental study that was conducted by Chen et al. in a winter night demonstrated that the use of shading in the channel is an effective way to improve thermal performance of the Trombe wall [60].

The use of shading devices during the different seasons of the year should be adjusted. During the cooling season. The shading devices should be removed in the daytime to make more solar radiation strike the Trombe walls. While, in hot summer, the operation is the opposite. A simulation study was carried out by Soussi et al. [64] on Trombe walls implemented in the building. Each southwest Trombe wall was supposed to integrate a 1.5 m solar overhang. The solar overhangs were assumed to be movable: they were applied during the hot season and removed in winter. The results of the simulations illustrated an important reduction in the annual required cooling energy (see Fig. 21).

Recently, a Trombe wall with venetian blind structure is studied by He et al. in Hefei, China [65]. This shading avoids the additional operation during the different seasons. Moreover, the two sides of

Table 1
Summary of some of the selected previous researches.

Category	Parameter	Author/Year	Location	Variation	Evaluation Indicators	Major findings	Refs.
Trombe wall design parameters	*Glazing properties*	Basak Kundakci Koyunbaba/2012	Izmir, Turkey	Single, double and PV panels	Electrical power rate and thermal gain	1. Single glass provides higher solar radiation gain for the thermal wall during day time. 1. Double glass has higher insulation character during nighttime and the evening.	[32]
		Stazi et al./2012	Ancona, Italy	Single and double glass	Heating/cooling load savings	1. A significant improvement of the solar wall's performances with double glass.	[31,33]
		Irshad et al./2014	Perak, Malaysia	PV single, double glazing and double glazing filled with Argon	Cooling load savings and CO_2 emission	1. The application of double glass filled with argon PV-TW was economically viable.	[34]
		Zalewski et al./2009	Trappes and Carpentras	Double glazing emissivity	Heat gain	1. The use of low-emittance double-glazing increased the collected energy.	[35]
	Trombe wall area	Abbassi et al./2014	Borj Cedria, Tunisia	0, 1, 2, 3, 4, 5, 8, 12, 16 and 18 m^2	Heating load savings	1. The increase in Trombe wall area provided the decrease in heating energy demand.	[1]
		Jaber et al./2011	Mediterranean region	Trombe wall ratio	Life Cycle Cost (LCC)	1. The optimum Trombe wall area ratio (the percentage of Trombe wall area to the total south wall area) was 37%.	[36]
Trombe wall design parameters	*Massive wall properties*	Briga-Sá et al./2014	Portuguese	Massive wall thickness (15, 20, 25, 30, 35 and 40 cm)	Heat gains	1. With the increasing of the massive wall thickness, heat gains increased for the ventilated Trombe wall and decreased for the non-ventilated Trombe wall.	[6]
		Fang et al./2000	Not specified	Wall thickness (25–45 cm)	Room temperature	■ 37 cm for brick; 35–40 cm for low concrete walls and 40–45 cm for high concrete walls.	[40]
		Stazi et al./2012	Not specified	Wall materials: concrete, brick and aerated concrete	Environmental performance: CO_2 emissions and energy demand	1. Considering both pre-use and use phases, the best overall performance was obtained using the wall with aerated concrete blocks.	[31]
		Zalewski et al./2012	France	Phase change material (PCM)	Wall temperature and heat gains	1. Solar gains were released to the room with a time lag for A PCM Trombe wall.	[49]
		Rabani et al./2013	Not specified	Wall materials: concrete, brick, Hydrated salt and Paraffin wax walls	Room temperature (the time duration of room heating)	1. The Trombe wall made of paraffin wax could keep the room more warm in comparison with other materials.	[50]
		Khalifa et al./2009	Baghdad, Iraq	Types of PCM	Room temperature fluctuation	1. Hydrated salt storage wall gave the least variation than the paraffin wax wall.	[52]
		Ji et al./2007	Hefei, China	Massive wall with thermal insulation	Heat gains and room temperature	1. Thermal insulation in both winter and summer improved the efficiency of PV-Trombe wall.	[15,58]
		Francesco Fiorito/2012	Five Australian cities	PCM position	PCM temperature and heat gains	1. The suitable position for five different climatic zones.	[48]
Trombe wall design parameters	*Shading devices*	Stazi et al./2012	Ancona, Italy	Overhangs and roller shutters	Cooling load savings	1. The combined use of overhangs and roller shutters can achieve the optimal Trombe wall efficiency in hot summer.	[61]
		Chen et al./2006	Dalian, China	Position in the cavity	Air temperature in the cavity	1. Using shading can decrease heat loss. 1. Different shading fixed locations have different heat preservation effect.	[60]
		Soussi et al./2013	Tunisia	Time of using overhang	Cooling load savings	1. Shading devices should be removed in the cooling season. While, in hot summer, the operation is the opposite.	[64]
		He et ai./2015	Hefei, China	Position of venetian blind in the cavity	Thermal efficiency and heat gains	1. The distance of 0.09 m between venetian blind and the glass for an air duct of 0.14 m width was recommend.	[63,65]
	Channel depth	Liping and Angui/2006	Not specified	0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m	Mass flow rate	1. With the increase of air gap width, the mass flow rate is increasing. 1. The optimum ratio of channel depth to height is about 1/10 in most cases	[68,69]
		Peng et al./2013	Hong Kong, China	5–25 cm	Heat gains	■ 0.06 m could be the optimal thickness for the air gap of the south-facing PV wall.	[28]
		Yilmaz et al./2008	Izmir, Turkey	0.05, 0.10 and 0.15 m	Room temperature and heat gains	1. Changing the inter-space distance didn't affect the inside air and inner surface temperatures much for the unvented Trombe wall.	[70]
Building parameters	*Construction materials*	Abbassi et al./2014	Tunisia	Composition and heat transmission coefficient of	Heating load savings	1. High thermal inertia walls and thermal insulated walls can greatly decrease the heating needs.	[1]

(continued on next page)

Table 1 (*continued*)

Category	Parameter	Author/Year	Location	Variation	Evaluation Indicators	Major findings	Refs.
				walls			
		Stazi et al./2012	Ancona, Italy	Types of building envelopes	Cooling load savings	1. The overall energy performance increased at the increasing of insulation level.	[33]
	Window effects	Ji et al./2011	Hefei, China	with or without window	Electrical and thermal efficiency	■ The mean diurnal efficiencies were 21.4% and 15.7% for the PVTW on the building without and with window, respectively.	[23,24]
Site parameters	*Solar radiation and orientation*	Li and Liu/2014	Not specified	Solar radiation: 500, 600 and 700 W/m^2	Thermal efficiencies, air flow rate and economic feasibility	■ Air flow rate for heat flux of 700 W/m^2 is slightly higher than those for the other two heat fluxes.■ The largest thermal efficiency is under the heat flux of 500 W/m^2.	[51]
		Soussi et al./2013	Borj Cedria, Tunisia	Trombe wall orientations: due west, southwest and northwest	Heating load savings	■ Trombe wall for southwest orientation gives the greatest contribution in reducing heating energy needs amongst the three orientations.	[64]
	Wind speed and direction	Lambic et al./2011	Cacak, Serbia	Wind speed: 0, 2.5, 5 and 7.5 m/s	Thermal efficiency	■ Thermal efficiency increases with the increasing of wind speed. ■ For a wind velocity greater than 5 m/s efficiency has very close values.	[66]

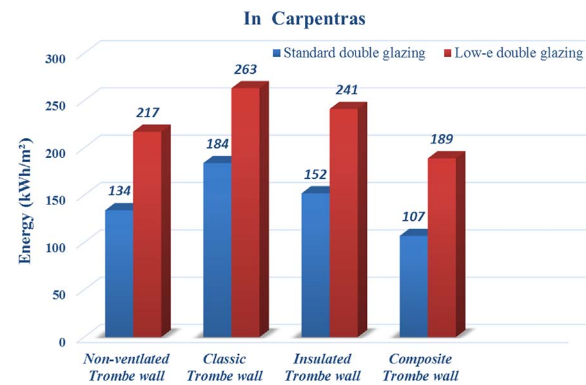

Fig. 16. Energy collected per m^2 in Carpentras.

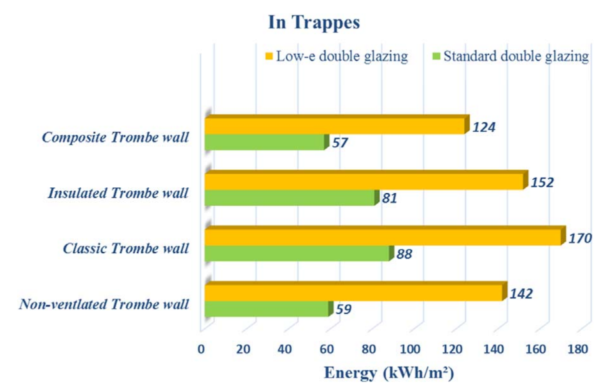

Fig. 17. Energy collected per m^2 in Trappes.

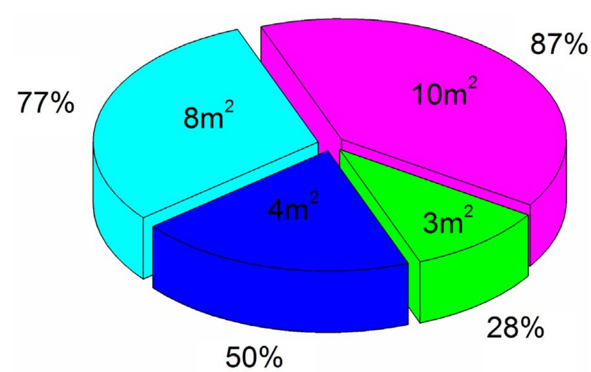

Fig. 18. Trombe wall area effect on annual heating energy saving.

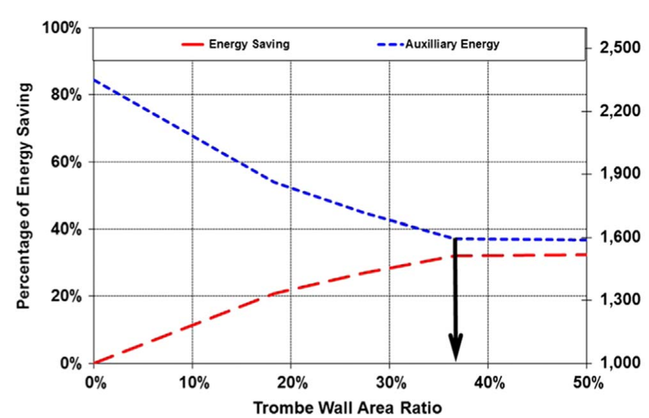

Fig. 19. Annual auxiliary energy saving for variable Trombe wall area ratio [36].

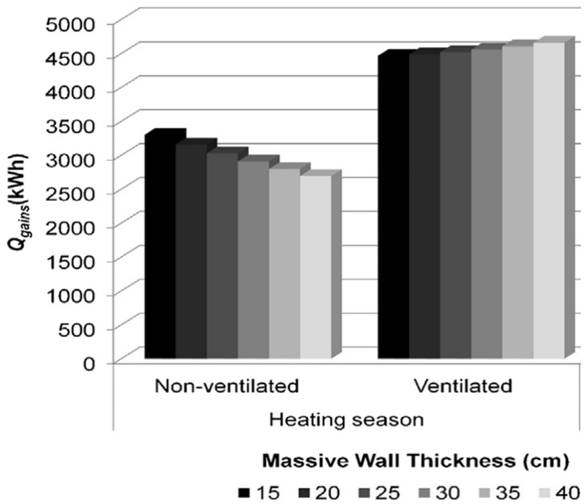

Fig. 20. Trombe wall global heat gains depending on the thickness of the concrete massive wall [6].

Table 2
The time duration that stored energy can heat the room during the sunset.

Type of wall	Time (h)
Concrete wall	7 h 12 min
Brick wall	8 h 11 min
Hydrated salt wall	8 h 30 min
Paraffin wax wall	8 h 55 min

Table 3
A comparison of concrete, hydrate salt and paraffin wax.

Types of thermal storage wall	Concrete	Hydrated salt	Paraffin wax
Room temperature range (°C)	15–25	18–22	15–25
Variation of temperature in the storage wall at night (°C)	1–3	4–6	3–7
Variation of temperature in the storage wall at night (°C)	7–15	10–18	10–22
Thermal storage wall thickness (cm)	20	8	5

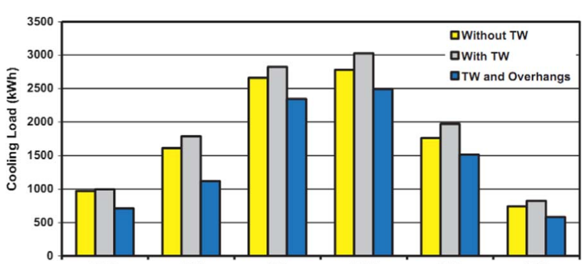

Fig. 21. Cooling energy savings using solar overhangs [64].

venetian blind are covered with selective coating. In hot summer, the side covered with high reflectivity coating is overturned outward to prevent overheating problem. While, in winter turning the other side covered with high absorptivity coating outward, which results in absorbing an amount of solar radiation striking on the slats. The absorbed solar irradiance can be controlled by controlling the slat angle of the venetian blind. In their study, comparisons of Trombe wall with and without venetian blind were made by the simulation study. They determined that the Trombe wall with venetian blind achieve a more comfortable condition for building compared to a classic Trombe wall. Simultaneously, the simulation study indicated that the Trombe wall with venetian blind is more suitable for the structures that are occupied during the day, such as shopping malls, schools and office buildings in winter [65]. In addition, they performed a parametric study on Trombe wall [63]. One of objective of this study was to determine the optimal fixed location of venetian blind. The distance of 0.09 m between venetian blind and the glass for an air duct of 0.14 m width was recommend [63].

3.1.5. Channel depth

When considering a Trombe wall design, consideration of channel that lies between the glazing cover and external massive wall is inevitable [66]. With the increase of channel depth, the friction pressure losses are decreasing, thereby the flow resistance is decreasing and the mass flow rate is increasing [67]. When the depth is increasing to a certain value, air flow status will change from the limited space flow to unlimited space flow, simultaneously, the average air temperature in the channel is decreasing during this process. Then backflow will occur around the outlet of Trombe wall. In addition, an excessive depth of channel will results in an insufficient thickness of massive wall, and then causes the problem of structural security [63].

Wang et al. pointed out that the effect of the depth of channel on mass flow rate was complicated [68]. It was not only related to height of Trombe wall but also dependent on the dimension of inlet and outlet, which influenced the entrance and exit losses. For instance, for a fixed inlet and outlet size of 0.1 m in width, the flow rate was almost unaffected by the depth of channel [68,69]. Finally, they concluded that the optimum ratio of channel depth to height is about 1/10 in most cases [68]. Peng et al. conducted a dynamic simulation to investigate the annual thermal performance of a PV wall [28]. In this study, they discussed the impact of channel depth. The results illustrated that the depth of the channel not only affected the cooling load in summer and the heating load in winter, but also contributed to the temperature of PV modules. Simultaneously, they found that the optimal depth for the channel of south-facing PV wall could be 0.06 m in Hong Kong in terms of the height of 3.6 m PV-Trombe wall [28]. It seems that the impact of channel depth on an unvented Trombe wall is not significantly effective. Yilmaz et al. conducted a study on an existing building that was renovated by the combination of unvented Trombe walls with direct gain windows [70]. They investigated three different inter–space distances between the existing exterior wall and glass, which were 0.05, 0.10 and 0.15 m. The results showed that changing the inter-space distance didn't affect the inside air and inner surface temperatures much.

3.2. Building parameters

3.2.1. Construction materials

One of the parameters that influence the thermal behavior of a building with Trombe wall is the construction materials used in the building envelope. One common option for building envelope is to use materials with high thermal inertia and insulation level. A group of researchers in Tunisia undertook a simulation study to evaluate the performance of Trombe wall for different building envelope [1]. The study concluded that using a Trombe wall in an insulated building

Table 4
Annual heating energy for different building envelope types.

Wall type	U (W/m^2 K)	Heating energy saving % (Trombe wall area of 6 m^2)
RW	1.906	65.95
SW	2.035	75.93
DW no insulation	1.508	79.14
DWI-2.5	0.768	94.90
DWI-5	0.516	97.20
DWI-7.5	0.388	97.49

could greatly decrease the heating needs (see Table 4). Another numerical study that was undertaken in Ancona, Italy by Stazi et al. aimed to analyze and optimize the Trombe wall's behavior varying building envelope insulation [33]. The simulation results showed that the overall energy performance increased at the increasing of insulation level. The sum of seasonal heating and cooling energy needs was approximately 38 (kW h/m^2) for the conventional envelope and 29 (kW h/m^2) for the super-insulated envelope.

3.2.2. *Window effects*

The thermo-siphon induces the indoor air flow from the top down, however, as a window is designed, the solar radiation can strike the indoor floor or its adjacent walls directly. Then these walls are heated up, and an air flow from the bottom up occurs. Consequently, the air flow in the room is changed compared to without the window. According to the simulation study that was operated by Ji et al. in Hefei, China, with or without a window on building south facade affected the thermal efficiency of a PV-TW [23,24]. The obtained results showed that the mean diurnal efficiencies were 21.4% and 15.7% for the PVTW on the building without and with window, respectively. This means with the window the thermal efficiency was reduced by relative 27% [23]. Although the results suggest that without a window can achieve a higher efficiency, windows provide not only direct sunlight but also beneficial daylight and visual contact with the outside. In addition, the above-described study cannot refer to the window area and position effects in detail. Therefore, the impact of windows on Trombe wall will need future investigations.

3.3. *Site parameters*

3.3.1. *Solar radiation and orientation*

Solar radiation level have been identified by Li and Liu [51] and Dragicevic et al. [71]as one of the most important factors in generating air movement in a Trombe wall channel. Study by Yongcai Li and Shuli Liu [51] on the effect of different levels of solar radiation to Trombe wall indicated that the air flow rate for heat flux of 700 W/m^2 was slightly higher than those for the heat fluxes of 600 W/m^2 and 500 W/m^2. Similarly, experimental investigation conducted by Burek and Habeb into heat transfer and mass flow in a Trombe wall varying the heat inputs confirmed that the mass flow rate through the channel was a function of the heat inputs [72]. Generally, Trombe wall efficiency increases with increasing of solar radiation level.

The Trombe wall efficiency is not only related to solar radiation level, but it is also affected by the orientation. In the north hemisphere, the sun rises and sets slightly south of east and west in the winter, and slightly north of east and west in the summer. This slight angle depends on the time of year and the observer's distance from the equator. In the southern hemisphere, all of these directions are reversed. Therefore, in the north hemisphere the most favorable orientation for Trombe walls is due south, southeast, and southwest. While it is due north, northeast and northwest in the south hemisphere [56]. For instance, Soussi et al. conducted a simulation study in a solar-cooled office building located at Borj Cedria, Tunisia (in the north hemisphere) and investigated three orientations for Trombe wall design [64]: due west, southwest and northwest. The study showed that the total heating needs inside the building for the southwest orientation were estimated to approximately 469.6 kW h while they reach 1364 kW h for northwest orientation and exceed 1800 kW h for the northwest orientation [64]. Furthermore, in Trombe wall design phase, attention should be paid to the solar shading created by surrounding environment and the building itself in highly dense cities.

3.3.2. *Wind speed and direction*

In addition to solar radiation, wind is a key natural stimulus to the thermal and air flow behavior of the Trombe wall, such as wind speed and direction. Generally, the heat loss coefficient of glazing and wind pressure is associated to wind speed and direction, which mainly affects the thermal efficiency and ventilated rate of Trombe wall. According to Lambic et al. for the same solar radiation, the thermal efficiency of Trombe wall system increased with increasing of wind speed varying the wind speed from 0 to 5 m/s, while the value of efficiency was very close for a wind velocity greater than 5 m/s [66]. The obtained conclusion were close to the result given for Trombe wall by Bhandari and Bansal [73]. The influence of wind speed and direction on ventilated rate of Trombe wall is little investigated. Tan and Wong investigated influence of ambient air speed on performance of a similar Trombe wall (solar chimney) in the tropics. Solar chimney was recommended to be employed under zero ambient air speed [74]. In this direction, comprehensive studies on the impact of wind speed and direction on Trombe wall performance should be investigated further.

4. Evaluation indicators

To assess Trombe wall system performance under different operation conditions, many indicators are monitored or calculated. Generally, they can be classified from three points of view: energy (room temperature [75–80], heating/cooling load savings [28,61,64,75], thermal efficiency [23,51,63,80] and air change per hour (ACH)/mass flow rate [51,81–83]), environment (CO_2 emissions) and economic (payback period [84]). For a based-heating type of Trombe wall, it is obvious that the larger value of room temperature, the more effective for Trombe wall. So is heating/cooling load savings. For the concept of thermal efficiency of a Trombe wall, many kinds of definition can be found in precedent studies. According to Rabani et al. [29] and Li and Liu [51], thermal efficiency is an important measure of the useful energy gained by the air flows through the air channel:

$$Q_o = \dot{m}C_p(T_o - T_i) \tag{1}$$

$$\eta = \frac{Q_o}{Q_o + Q_r} \tag{2}$$

where η is the thermal efficiency, Q_r is radiation heat gained by the glass.

Sun et al. [23] and He et al. [63] gave the similar definition of thermal efficiency except the total heat energy input, which was evaluated as:

$$Q_t = A_g G \tag{3}$$

The thermal efficiency was calculated as:

$$\eta = \frac{Q_o}{Q_t} \tag{4}$$

For the cooling-based type of Trombe wall (see Fig. 12(a)), the air change per hour (ACH) or the mass flow rate ($\dot{m}$) is an important index from the perspective of energy conservation, which was given using the following equations [29,30,81]:

$$\dot{m} = \rho V_o A_o \tag{5}$$

$$\dot{V} = \frac{\dot{m}}{\rho} \tag{6}$$

$$ACH = \frac{\dot{V} \times 3600}{room \quad total \quad volume} \tag{7}$$

Design of sustainable Trombe walls requires the analysis of environmental performances in every stage of their life cycle. The environmental performance was calculated in terms of the amount of CO_2 emissions in the production phase and operational phase with the method of life cycle assessment (LCA) [31,36].

5. Conclusion

Trombe walls are receiving considerable attention and proven to be highly useful and significant in current environment protection and energy conservation. In the present study, a detailed literature survey of the important contributions of Trombe wall related studies carried out during the last 15 years has been performed. Based on the major utilizing functions of Trombe wall, it reviewed in this article is divided into two major types: a heating-based type of Trombe wall and a cooling-base type of Trombe wall. Each type of Trombe wall includes various Trombe wall configurations, which range from those that incorporate new elements into a classic Trombe wall to those that use modified components Trombe wall components. Then emphasis is placed on the introduction of factors that be considered when designing Trombe wall, which have been classified and grouped according to 'Trombe wall', 'building' and 'site' parameters. The main deductions applicable to the Trombe wall design from this review are:

(1) The larger Trombe wall area, the more high efficiency. However, it is limited the total south wall area, that is, it is related to (α), the ratio of the Trombe wall's area to the total wall' area. The optimal size is (α)=37%.
(2) Massive wall materials and thickness contribute importantly to the efficiency of the wall's heat storage and release capacity. Any material characterized by high storage capacity can be used to construct Trombe walls. However, the use of lightweight materials with high storage capacity in a relatively small volume is more preferable, such as PCM. With regard to the wall thickness, 30–40 cm concrete Trombe walls have performed well in many geographical locations. In addition, thermal insulation on massive wall is considered a remedy for the deficiency of a classic Trombe wall.
(3) Glazing properties, such as the materials and the number of glazing layers significantly affect the performance of Trombe walls. However, the selection of glazing depends on many variables including the longitude and latitude of the project. Normally, low-e double glazing is recommended.
(4) Channel depth mainly contributes to the flow resistance. It is not only related to height of Trombe wall but also depend on the dimension of inlet and outlet. In addition, the structural safety should be considered when design the channel depth because an excessive depth of channel will results in an insufficient thickness of massive wall. Shading devices, such as: overhang, roller shutter and venetian blinds can control the performance of Trombe wall and address some of the shortcomings: overheating in hot summer and heat loss in winter night.
(5) Similar to thermal insulation on massive wall, proper insulation of building envelope have perform well. Due to solar radiation can strike the indoor floor or its adjacent walls directly through a window, therefore the design of windows should be considered including the size and position (relative to the Trombe wall).
(6) Solar radiation level have an important influence in generating air movement in a Trombe wall channel. Generally, Trombe wall efficiency increases with increasing of solar radiation. Moreover, for a building with Trombe walls located in the north hemisphere, the south facing facade (with 45° variations) seems to be the most effective orientation in capturing the solar gain.
(7) The wind speed and direction are related to the heat loss coefficient and wind pressure. The Trombe wall tends to perform better if the wind speed is small, and in this direction, further investigation should be carried out in the future.

Finally, to assess the performance of Trombe walls, many indicators are developed from the perspective of energy, environment and economic. We should chose a proper indicator to evaluate a Trombe wall performance according to the purpose of using the Trombe wall, and also make corresponding adjustment for the index based on the type of Trombe wall.

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