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Classification, experimental assessment, modeling methods and evaluation metrics of Trombe walls

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Abstract:

Solar energy building applications are attracting increasing attention from researchers, engineers, businessmen and officials due to their significant benefits in sustainable development, such as energy saving, cost reduction and environmental protection. Trombe wall, as a classical passive solar heating technique, has been studied for many years. A variety of concepts, methodologies and experiences have been developed during relevant research. Especially in recent years, numerous studies on Trombe wall have been published, which implies a rising attention to this technique. This review focuses on the classification, experimental assessment, modeling methods, and evaluation metrics for Trombe wall. In detail, nine types of Trombe walls are introduced according to their materials, structures and functions. Four experimental methods and two modeling methods of Trombe wall are discussed based on their functions, advantages, disadvantages, and applicability. Three aspects of evaluation metrics for Trombe wall are summarized in terms of technique, economy and environment. Moreover, the current and future research of Trombe wall are discussed at the end. The authors consider this article would be useful for their peers and can facilitate the technical development of Trombe wall.

Keywords: Trombe wall; classification; experimental assessment; modeling methods; evaluation metrics

1. Introduction

Building is the base for human production and living. About 20-40% of the world's total energy consumption is related to the building sector [1–5], wherein, 33-55% of the building energy supply is consumed by HVAC to maintain a comfortable indoor environment [6–10]. Therefore, the reduction of

HVAC energy consumption is always a main focus for building energy conservation. One of the best approaches to achieve this goal is by using a passive system (e.g. passive solar heating), which can reduce the building heating demand by up to 87% [11].

Among numerous passive technologies, Trombe wall, is one of the classical passive solar heating methods which has the features of simple construction, high efficiency, and zero operation cost [12]. It can achieve up to 30% reduction of the building energy consumption [13]. Therefore, it has attracted increasing attention from scholars and engineers. Several scientific studies on Trombe wall have been carried out with regard to structure retrofit [14], modeling method [15], design method [12], optimization [16] and engineering practice [17]. These studies have provided significant support for the development and applications of Trombe wall. Numerous review articles on passive solar heating [18], solar chimney [19], opaque solar facades [20], passive building [21], passive wall [22], and bionic green architecture [23], have introduced this development and application of Trombe wall. Moreover, specific review articles [12,24] have also been published on the classification, influence factors, design parameters and evaluation indexes of Trombe wall.

However, the following research aspects are insufficient and still need to be completed so as to supplement the current reviews on Trombe wall:

- Few of the current reports have thoroughly reviewed the experimental methods and modeling methods for Trombe wall, which are essential for relevant research and development. A summary of these is needed and useful.
- Only a brief introduction on evaluation indexes of Trombe wall is given in current review articles [12,24]. A detailed summary on evaluation indexes for Trombe wall as well as data statistics are necessary, which can provide complete information on the evaluation references for research and

development.

- As a number of innovative modifications on Trombe wall have been proposed in recent years, e.g. air-purification Trombe wall [25–32] and electrochromic Trombe wall [33], a new review of Trombe wall classification is necessary as well.

In this paper, an overview of Trombe wall research is provided with regard to classification, experimental assessment, modeling methods, and evaluation metrics. In Section 2, the methodology of this Trombe wall review is described. In Section 3, the classification of Trombe wall into nine different types is introduced. In Section 4, four experimental methods for testing Trombe wall performance are summarized. In Section 5, two modeling methods for Trombe wall research are presented. In Section 6, evaluation metrics for Trombe wall in terms of technique, economy and environment are summarized. In Section 7, the discussion for the current and future research of Trombe wall as well as the suggestions are provided. In Section 8, the main conclusions from this review of Trombe wall are presented.

2. Methodology

This review on Trombe wall covers the English research articles from 2001 to 2019. Its review process follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method which contains the procedures of identification, screening, eligibility check, and inclusion [34,35]. The detailed process of this review is as follows (Fig. 1):

(1) In the field of building and renewable energy, academic journals are commonly published by Elsevier, Springer, Taylor & Francis, Sage, Wiley, and MDPI. Therefore, ScienceDirect, SpringerLink, Taylor & Francis Online, SAGE Journals, Wiley Online Library, and MDPI are chosen as the search engines in this review. Moreover, as Trombe wall is a famous passive solar

technology and it is sometimes named by solar wall, “Trombe” and “solar wall” are used as the keywords to search articles. After duplicates removed, the obtained records are merged finally.

(2) The records searched are screened by their titles and abstracts. Those having clear relationship with Trombe wall are kept. Furthermore, the scope of solar façade (e.g. solar wall, solar chimney) and passive technology (e.g. passive heating, passive house) are also considered as the screening criterion to select the records, because Trombe wall lies in the field of solar façade and passive technology.

(3) The screened records are assessed for eligibility through full text. The articles which are most related to Trombe wall are remained.

(4) According to the topics of this review, all the selected articles are summarized and analyzed in terms of classification, experimental assessment, modeling method, and evaluation metric. In addition, the statistical analysis for the research quantity and performance data of Trombe wall are provided based on the selected articles.

Fig. 1 Methodology of Trombe wall review

3. Classification of Trombe wall

Trombe wall was initially developed as a simple architectural component, which absorbs solar radiation to heat the circulating air in the channel and stores the heat in the wall mass for indoor heating. However, further research provided many new modified versions of Trombe wall. In this review, in terms of its structures, materials and function, Trombe wall is classified in the following major types: (1) Classical Trombe wall; (2) Composite Trombe wall; (3) Phase change material (PCM) Trombe wall;

(4) Photovoltaic (PV) Trombe wall; (5) Water Trombe wall; (6) Fluidized Trombe wall; (7) Air-purification Trombe wall; (8) Electrochromic Trombe wall; and (9) Trombe wall with translucent insulation material (TIM). Fig. 2 provides an overview of Trombe wall classification and Fig. 3 illustrates a summary of Trombe wall studies since 2001.

Fig. 2 Overview of Trombe wall classification (PCM - Phase change material; PV - Photovoltaic; TIM - Translucent insulation material; TC - Thermal-catalytic-oxidation; PC - Photocatalytic-oxidation; PTC - Photocatalytic-thermal-catalytic).

Fig. 3 Summary of Trombe wall research in ScienceDirect, SpringerLink, Taylor & Francis Online, SAGE Journals, Wiley Online Library, and MDPI.

3.1. Classical Trombe wall

Classical Trombe wall is the most basic and simplest type in the classification mentioned above. It was invented in 1881 by the American engineer, Edward Morse, who patented it [24]. However, this kind of wall was named as Trombe wall due to the promotion by Felix Trombe and Jacque Michel (a French engineer and a French architect) [24], who applied this technique to a building for the first time in Odeillo, France in 1967 [12].

The classical Trombe wall mainly consists of four parts: glass, air channel, thermal storage wall and vents (in some cases, there are no vents) (Fig. 4a). The thermal storage wall is constructed with materials of high thermal capacity so that the absorbed solar radiation can be stored for a long time. The wall surface is commonly coated with a black color paint to achieve higher solar absorptivity. The glass is used to transmit the light and create greenhouse effect in the air channel. A space heating cycle is then created due to the air-density difference between the hot channel and the cold room, as presented in Fig. 4a. In general, the vents are operated with panels, which turn off to prevent the inverse thermo-siphon phenomena during the night when the outside temperature is low and no solar radiation exists.

Fig. 4 (a) A classical Trombe wall and its retrofits with (b) roller shade, (c) venetian blind, (d) internal thermal fins [14] or (e) water spraying system [36].

To improve the performance of the classical Trombe wall, many scholars have proposed a series of modifications to its structure. For example, a roller shade [37–39] or a venetian blind [40–47] can be added to prevent overheating from the sun in summer (Fig. 4b and c). Additionally, thermal fins can be attached to the internal wall surface to improve the heat transfer during winter [14] (Fig. 4d). Furthermore, a water spraying system can be installed in the vents on the opposite wall to provide cooling through water evaporation, when Trombe wall functions as a solar chimney during summer [36] (Fig. 4e). Moreover, a zigzag Trombe wall, which is a spatial arrangement of classical Trombe wall and normal wall can be employed to improve solar heating during cold mornings and avoid overheating during the day [12,24]. In addition, Long et al. [48] presented a new Trombe wall which included a solar collector and reflection layer to increase the thermal insulation of the wall in summer by storing excess absorbed solar energy into a water tank and preventing solar radiation from reaching the massive wall.

3.2. Composite Trombe wall

Due to the low thermal resistance of a classical Trombe wall, the indoor room is easily affected by the outside environment and there is substantial thermal loss. To overcome these drawbacks, a composite Trombe wall, which is also known as Trombe-Michel wall, was developed as illustrated in Fig. 5a. This wall consists of six components: glass, non-ventilated air channel, thermal storage wall, ventilated air channel, insulation layer and vents. Different from a classical Trombe wall, this configuration uses thermal storage wall and greenhouse effect of outside air channel to collect solar energy, and inside air channel to heat the room through air cycle. As the room-heating process is separate from the outside heat-collection process, the influence of external environment can be reduced with this modification. Moreover, the insulation layer increases the overall thermal resistance of the wall system as well, which can reduce the thermal loss during the night in cooperation with the panels.

Different from the above-mentioned composite Trombe wall, Chen et al. [49,50] proposed a new type of composite Trombe wall with porous absorber (Fig. 5b). In this type of wall, the added porous absorber works as a heat storage buffer that initially absorbs solar heat and then distributes it to the air in the channel or the thermal storage wall. Moreover, this porous component can also function as a semi-thermal insulator to increase the thermal resistance of Trombe wall and prevent heat loss on cloudy days or at night when solar radiation is not available [49].

Fig. 5 (a) A composite Trombe wall and (b) a new composite Trombe wall with porous absorber

3.3. PCM Trombe wall

In classical Trombe wall, thermal storage wall stores energy in the form of sensible heat, so the thermal storage capacity is generally limited. To increase the storage capacity, phase change materials

(PCM), have been introduced into Trombe wall for latent heat storage [51–74]. A PCM Trombe wall with a PCM layer attached to the outside surface of an insulation wall is illustrated in Fig. 6a. Its working process is identical to that of the classical Trombe wall, except for the latent heat storage. A PCM layer can also be installed in the middle of the air channel [55,69,74], which results in a style similar to a composite Trombe wall (except that the thermal storage wall is made by PCM). Consequently, this type of Trombe wall combines the advantages of a composite Trombe wall and a PCM Trombe wall, and can be regarded as a hybrid type.

Fig. 6 (a) A PCM Trombe wall and its retrofits with (b) delta winglet vortex generators in wall surface [72] or (c) NTG.

Some retrofits have also been made on the PCM Trombe wall to improve its performance. For example, Zhou et al. [72] installed many miniature delta winglet vortex generators on the outside wall surface to enhance the heat transfer into the air flow by increasing turbulence (Fig. 6b). Kara et al. [59] created a novel triple glass (NTG) consisting of an ordinary glass, a Prismasolar glass, and a low-e glass, to reflect the radiation with high incidence angle during summer (to prevent overheating) and to transmit the radiation with low incidence angle in winter (to collect heat) (Fig. 6c).

3.4. PV Trombe wall

This is a type of Trombe wall integrated with PV technology which can provide both heating and power supply simultaneously. Fig. 7 presents a PV Trombe wall with PV cells installed in the outside glass (PVGTW), wall surface (PVMTW) and venetian blinds (PVBTW), respectively. The heating operation of this wall is identical to that of a classical one, but the PV cells also share part of the solar energy for electricity generation. This means that the heating performance of PV Trombe wall is worse than that of a classical Trombe wall. However, there are two advantages of PV Trombe wall. One is that the electricity can be used for other purposes, such as domestic appliances. The other advantage is that overheating can be alleviated in summer since the solar energy is partly converted into electricity. Therefore, considering the multifunctional demands of heating and electricity as well as the comprehensive benefits of power-supply and overheating-prevention, many studies on Trombe wall have focused on this PV type [75–95]. Hu et al. [82,83], compared the above three types - PVGTW, PVMTW, and PVBTW - by both experiment and simulation. The results indicated that for annual heating load reduction, the best performance was exhibited by PVBTW, then PVMTW, and then PVGTW. For annual electricity generation, PVBTW performed similar to PVGTW but better than PVMTW. For total annual electricity saving, PVBTW performed best, while PVGTW and PVMTW were similar. Ahmed et al. [75] used a porous medium to fill up the air channel of a PV Trombe wall. By combining with DC fan, the thermal and electrical efficiencies were increased of 20% and 0.5%, respectively, compared to a PV Trombe wall without porous medium.

Fig. 7 PV Trombe wall with PV cells integrated in (a) outside glass, (b) wall surface or (c) venetian blinds

3.5. Water Trombe wall

Similar to the purpose of introducing PCM into Trombe wall, water is also employed for the thermal storage of Trombe wall, due to its better thermal capacity compared to ordinary wall materials. A schematic of water Trombe wall is illustrated in Fig. 8. Except that some water tanks constitute the thermal storage wall, the rest of the components are similar to a classical Trombe wall. However, a main problem of water Trombe wall is the construction for water tanks in the thermal storage part, which is more difficult than constructing the ordinary Trombe walls [12,24].

Fig. 8 A water Trombe wall

3.6. Fluidized Trombe wall

The air channel of this kind of Trombe wall is filled with many small-scale, low-density and high-absorption particles that form a porous structure [96] (Fig. 9). Solar heat is initially collected by the fluidized particles and subsequently transferred into the air. Due to the increased contact area within the porous structure, the circulated air is intensively heated and carries large amounts of energy into the indoor room for space heating. It has been reported [96] that the heating performance is improved by using fluidized particles when compared to a classical Trombe wall. To prevent the small particles carried by the circulated air, from entering the internal room and polluting the indoor environment, two filters are respectively installed at the top and bottom of the air channel.

Fig. 9 A fluidized Trombe wall

3.7. Air-purification Trombe wall

Air-purification Trombe wall is a new type of Trombe wall that has been developed recently [25–32]. It is helpful to reduce the indoor formaldehyde (especially in a new-built house) in many developing regions where building materials containing formaldehyde are still used due to economic and technical limitation. This Trombe wall integrates the idea of air purification into the conventional heating process, which extends the functions of classical Trombe wall. It can also be divided into two sub-types according to the degradation principle: thermal-catalytic-oxidation Trombe wall (TC-Trombe wall) [27,28] and photocatalytic-oxidation Trombe wall (PC-Trombe wall) [25,26,29,31] (Fig. 10). Recently, these two sub-types were also combined to form a photocatalytic-thermal-catalytic-Trombe wall (PTC-Trombe wall) [30]. However, regardless of their differences, the main operation process of these sub-types is identical: during the heating process, polluted indoor air passes through the degradation modules, wherein the contaminants, e.g. formaldehyde, can be converted into harmless substances by the catalytic reaction. Then, the purified air is supplied to the indoor room.

Fig. 10 (a) A TC-Trombe wall [27] and (b) a PC-Trombe wall [25]

3.8. Electrochromic Trombe wall

This type of Trombe wall is almost identical to a classical Trombe wall except that the outside glass is replaced by an electrochromic glass [33]. Due to its electrochromic property, the outside glass also provides shade to avoid overheating and reduce cooling load during summer. This function is similar to that of roller shade or venetian blinds, but can be achieved easily by changing the electric field without any mechanical motion. Pittaluga [33] has simulated the annual energy consumption of this electrochromic Trombe wall in DesignBuilder software. The results show that an annual energy saving of 29.5% (cooling and heating load) can be achieved when compared to a classical Trombe wall.

3.9. Trombe wall with translucent insulation material

Due to its light weight feature and good acoustic insulation, translucent insulation material (TIM) has been used to replace single or multiple glazed covers. Many studies on TIM were conducted during the 1980s and 1990s by the Fraunhofer Institute for Solar Energy Systems in Germany [97] under the International Energy Agency's Solar Heating and Cooling Program Task 20. The world's largest TIM Trombe wall was installed at Strathclyde University in the UK [98]. Three years of monitoring showed that the building uses 40% less energy than official "good" category buildings in the UK, and the south facade has a monthly net heat gain into the building even in the middle of winter in Glasgow.

The most advanced TIM is aerogel insulation which is the only known solid with high transmittance and low thermal conductivity. It could achieve 0.1 W/m^2K U-values and allow 90% of light to pass through [99,100]. Fricke et al. [101–103] and Riffat [104] have explored the potential building applications of the aerogel TIM.

Granular silica aerogel TIM was integrated with PCM by Berthou et al. [105] in France in 2015. A 4.41 m^2 full-scale TIM-PCM wall was tested on a light weight building in southern France. The results show that the TIM-PCM wall has great potential for energy saving in buildings in winter and shoulder seasons with sunny weather conditions. Moreover, Souayfane et al. [106,107] investigated this TIM-PCM wall with regard to thermal comfort in summer and economy. The results show that TIM-PCM wall faces a major problem of indoor overheating in summer and may be economically attractive in polar and subarctic climates.

A new version of Trombe wall, which consists of PCM, insulating aerogel and a textured surface, was recently proposed by Delft University of Technology under its DoubleFace 2.0 project [108]. It was found that the lightweight, translucent, and adjustable Trombe wall could reduce the energy demand for heating of a typical Dutch household by 25-30% [108].

TIM has also been employed in water Trombe wall, resulting in the development of a hybrid type of Trombe wall, namely Transwall [109–112] (Fig. 11). In addition to the properties of water Trombe wall, this type of wall can also improve the indoor lighting and the direct heat gain during daytime due to the transparency of the materials. Moreover, the aesthetic value can be increased by providing visual access to the indoor space [24].

Fig. 11 A Transwall with air gap

4. Experimental assessment of Trombe wall research

Experiment is the most effective method to test and understand the actual performance of a Trombe wall. In this paper, the existing experimental methods for Trombe wall are divided into four types: reduced-scale thermal box, full-scale thermal box, stand-alone Trombe wall module, and actual testing house. Table 1 offers a comparison between each set-up type and Fig. 12 provides a graphic example for them.

Table 1 Comparison between each experimental method

Fig. 12 Different experimental methods for Trombe wall: (a) a reduced-scale thermal box [14]; (b) a full-size thermal box [113]; (c) a stand-alone Trombe wall module [83]; (d) an actual testing house [114].

4.1. Reduced-scale thermal box

This method involves constructing a reduced scale thermal box to simulate thermal performance of an ordinary building in which a Trombe wall is installed. This experimental set-up has the advantages of space saving, flexible arrangement and cost saving. In addition to measurements under actual climate condition, this device may also be placed in a climatic chamber for a repetitive test of Trombe wall, to obtain more comparable and diverse results under controllable environment. However, if the similarity law is ignored in the reduced-scale design,, the reduced-scale experimental results of a Trombe wall may be greatly different from the actual performance of a full-scale Trombe wall. Therefore, it is important to consider the similarity law in the reduced-scale experiment. Table 2 provides some references for reduced-scale thermal box used in current Trombe wall studies. It should be noted that no clear description with regard to the similarity design has ever been reported in reduced-scale experiments. This limitation should be addressed in the future studies.

Table 2 References for reduced-scale thermal box used in Trombe wall studies

4.2. Full-scale thermal box

Compared to reduced-scale thermal box, the full-scale thermal box is used to simulate a building which has an absolutely or approximately real size. The tested Trombe wall in this experimental model is also full scale. This method can obtain more reasonable results compared to the reduced-scale method. Nevertheless, space limitation and increased cost are the disadvantages of this method. Table 3 provides some references for full-scale thermal box used in current Trombe wall studies.

Table 3 References for full-scale thermal box used in Trombe wall studies

4.3. Stand-alone Trombe wall module

In this method, only a testing Trombe wall is fabricated and measured, without an adjacent parts to simulate a room. This method requires less expenses and space compared to the full-scale thermal box. If the size is appropriate, this stand-alone module can also be placed into a climatic chamber for more diverse experiments.

However, the inlet and outlet of stand-alone Trombe wall module are directly connected with the ambient environment, while an actual Trombe wall is connected with an indoor room. Due to the great difference between the indoor and ambient environments, the experimental results obtained from this stand-alone Trombe wall module cannot accurately reflect its operation performance in a real application. In other words, this method can only reflect the independent performance of the tested Trombe wall. Nevertheless, this method is suitable for a comparative research of different Trombe walls, because only the same outside condition is required regardless of whether it is an indoor room or ambient environment.

Table 4 provides some references for stand-alone Trombe wall module used in current Trombe wall studies.

Table 4 References for stand-alone Trombe wall module used in Trombe wall studies

4.4. Actual testing house

This Trombe wall experiment is based on a real house or a simplified house. It can be carried out through two ways: (1) by adding a testing Trombe wall in existing rooms (room retrofit); (2) by building a new test house with a testing Trombe wall (newly built house).

For the former approach, as building retrofit is necessary, the selection for an existing house should consider the feasibility for structural retrofit and the suitability for experimental requirements. Space saving can be achieved in this way since no extra space is occupied. However, it is uncertain whether cost saving is achieved compared to the above-mentioned experimental methods, because the cost for demolishing or modifying an existing wall should be taken into consideration as well.

In the second method, the technical restriction for a Trombe wall experiment is small because a new house can be freely designed according to any experimental requirement. However, it would result in a great cost for space, money and time. If a complete test house is considered for a series of technical experiments and not just for a Trombe wall experiment, the shared cost for Trombe wall may be small. Therefore, this method is generally suitable for a comprehensive experimental cluster of which one purpose is a Trombe wall experiment.

The Trombe wall experiment in an actual testing house is similar to that in a full-scale thermal box. However, it can include more actual factors of a buildings, such as architectural construction, building materials, human behaviors or appliance behaviors. Therefore, the testing results in an actual testing house can provide more actual and practical information for engineering applications.

Table 5 provides some references for actual testing house used in current Trombe wall studies.

Table 5 References for actual testing house used in Trombe wall studies

5. Modeling methods of Trombe wall research

Simulation is a cost-space-time-saving approach to predict the performance of a Trombe wall. It is also the basis for computer-based optimization for a Trombe wall. The general modeling for a Trombe wall includes glass modeling, airflow modeling and mass-wall modeling. Since the flow problem is generally very complex, the airflow modeling is the most significant step for Trombe wall modeling. In this paper, according to the complexity of airflow assumption, the modeling methods for a Trombe wall are divided into two types: flow-simplified model and CFD model. Table 6 offers a comparison between both types.

Table 6 Comparison between different types of modeling method

5.1. Flow-simplified model

The main assumption in this kind of model is that the airflow in a Trombe wall is an ideal unidirectional plug flow and no turbulence exists. The thermodynamic property of the channel-air at the same height can be considered identical and uniform. Based on this assumption, a flow-simplified Trombe wall model can be built by combining different methods of glass modeling, airflow modeling, and mass-wall modeling. Fig. 13 provides a summary of available methods for flow-simplified Trombe wall modeling, including three methods for glass modeling, two methods for airflow modeling, and two methods for mass-wall modeling.

Fig. 13 Method summary for flow-simplified Trombe wall modeling

The glass modeling can be carried out by uniform assumption, one-dimension assumption or two-dimension assumption. The uniform assumption means that the whole glass is considered uniform and its temperature can be represented by one uniform value (Fig. 13a1). According to the one-dimension assumption, the glass temperature only varies along the height and it is a function of the height (Fig. 13a2). In the two-dimension assumption, the glass temperature varies along both the height and the width, and it is a function of the height and the width (Fig. 13a3). As the glass thickness is usually thin enough, the glass temperature is considered constant along the thickness. For an ordinary glass, the temperature generally varies very little along the width, so the uniform assumption and the one-dimension assumption are commonly used in the modeling [15,30,75,87]. However, for a particular glass, e.g. PV-integrated glass [79,91–93], if its materials are inhomogeneous, the two-dimension assumption is preferable.

The airflow can be modeled by either uniform assumption or one-dimension assumption. For the former, the heat transfer within the air channel is calculated based on one uniform temperature (average temperature) (Fig. 13b1). Although this method can reduce computation, it is necessary to know the temperature regularity with the height or the relationship between uniform temperature and inlet-outlet temperature in advance [139,163]. For the latter method, the air temperature changes along the height and the heat transfer is calculated separately within the air-node at each height (Fig. 13b2). This is a more general method because it needs less temperature information compared to the former one.

The mass-wall modeling can be performed by either steady assumption or one-dimension assumption. In the steady assumption, the heat transfer within the mass wall is considered a steady conduction and it can be calculated by Fourier's law (Fig. 13c1). This method is only suitable for a steady calculation or a mass wall of small thermal capacity. In the one-dimension assumption, the wall temperature only changes along the thickness (Fig. 13c2). This method is closer to actual conditions for a mass wall of thermal storage, so it is used commonly.

The heat transfer coefficient for heat convection on each surface is determined by empirical correlation. For multi-layer structure of glass, channel, and wall, the modeling method can refer to the above assumptions. Note that the high-dimension model undoubtedly has high accuracy but does not mean a great increase in accuracy. In other words, the low-dimension model can be also useful if the accuracy is high enough. Moreover, the computation time can be reduced by the low-dimension model.

As the most complex fluid problem is simplified, the flow-simplified model can be quickly solved through computer programming. Therefore, this model is suitable for long-term simulation of a Trombe wall. However, the simplification also leads to missing information for detailed airflow areas, which makes the flow-simplified model unsuitable for structure optimization of a Trombe wall.

The flow-simplified model of Trombe wall can be built by numerous programming tools, e.g. Matlab [46,82], Matlab/Simulink [77], and FORTRAN [14,80,91]. Moreover, TRNSYS provides a complete model for Trombe wall by assuming uniform glass, uniform airflow, and one-dimension wall [164]. EnergyPlus [165], IESVE [166], ESP-r [167], and IDA ICE [168] provide indirect conditions for Trombe wall modeling.

Table 7 provides some references for flow-simplified model used in current Trombe wall studies.

Table 7 References for flow-simplified model used in Trombe wall studies

5.2. CFD model

A CFD model for Trombe wall can be also regarded as a detailed model for Trombe wall. It is built mainly based on Navier-Stokes equations. As the Navier-Stokes equations consider many fluidic-factors (compressibility, stress, dissipation), a CFD model can provide detailed information with regard to the temperature-, velocity-, and pressure-field within any part of a Trombe wall. Therefore, this method is suitable for structure optimization of a Trombe wall. However, the complexity of CFD model also leads to considerable computation as well as time-consumption, which limits the simulation duration for a Trombe wall.

A Trombe wall modeling with CFD method includes geometric modeling, meshing, governing-equation selection, boundary-condition decision, and solution-method selection. k–ε turbulence model is often used to handle a Trombe wall problem [122,134,182,183]. A few studies have also used laminar model [69,184] or k−ω turbulence model [185,186] for this purpose. Boussinesq approximation is generally adopted to handle the buoyancy force so as to simplify the solution [31,121,134,183].

CFD model of a Trombe wall can be built by numerous commercial software. e.g. Fluent [44,115,126,187] (within ANSYS at present), ANSYS CFX [78,81], Solidworks Flow Simulation [188], and CFD Flex [189].

Table 8 provides some references for CFD model used in current Trombe wall studies.

Table 8 References for CFD model used in Trombe wall studies

6. Evaluation metrics of Trombe wall

6.1. Technical performance

6.1.1. Temperature

Temperature is the most common parameter used for Trombe wall evaluation [33,58,142,158,189,196–203]. It is also the calculation base for the other evaluation indexes of Trombe wall. A general temperature-measurement includes the temperatures of the outside and inside glaze-surfaces, the channel air, the outside and inside wall-surfaces, the inlet and outlet vents, and the indoor room. The performance of a Trombe wall can be reflected by the different temperatures in different aspects. For example, the high temperature of channel air and outlet vent can indirectly indicate high efficiency of Trombe wall. The high indoor temperature during winter can reflect a low heating load or a good thermal environment.

In addition, there are some formalized evaluation indexes for Trombe wall performance in terms of temperature fluctuation.

Thermal load leveling (TLL): This index is equal to the difference between the maximum and minimum of indoor temperature ($T_{r\,max}$ and $T_{r\,min}$) divided by their sum [94]:

$$TLL = \frac{T_{r\,max} - T_{r\,min}}{T_{r\,max} + T_{r\,min}} \tag{1}$$

In this equation, the numerator represents the degree of the indoor temperature fluctuation and the denominator reflects the basic value of such variation. A greater numerator and a smaller denominator indicate more fluctuation. Hence, TLL indicates the stability of the indoor temperature.

Decrement factor (f): It is defined as the ratio of temperature amplitude at the inside wall-surface to that at the outside wall-surface [94]:

$$f = \frac{T_{w\,inside\,max} - T_{w\,inside\,min}}{T_{w\,outside\,max} - T_{w\,outside\,min}} \tag{2}$$

where $T_{w\,inside\,max}$, $T_{w\,inside\,min}$, $T_{w\,outside\,max}$, $T_{w\,outside\,min}$ are the maximum- and minimum-temperature of inside and outside wall-surface, respectively. This index represents the temperature attenuation by the wall.

Relative fluctuation number (V): The fluctuation of indoor temperature is dependent on that of outdoor temperature. V is defined as the ratio of indoor temperature variation coefficient (T_{vi}) to outdoor temperature variation coefficient (T_{vo}) [114]:

$$V = T_{vi}/T_{vo} \tag{3}$$

$$T_v = T_\sigma/T_\mu \tag{4}$$

where T_v equals the temperature variation coefficient, T_σ is the standard deviation of the temperature distribution, and T_μ is the mean temperature. A lower value of V indicates more stable indoor thermal environment [114]. Besides, T_v can be used to evaluate the temperature fluctuation intensity [114].

6.1.2. Energy

An energy evaluation of a Trombe wall can be carried out in terms of either energy supply or energy demand. Although energy supply and energy demand are usually related, they provide two opposite viewpoints to evaluate a Trombe wall.

Energy gain (Q_{gain}): This is an evaluation index from the aspect of energy supply by Trombe wall. In terms of thermal energy, energy gain can be calculated by the sum of the heat gain through air circulation (Q_{air}) and thermal storage wall (Q_{wall}):

$$Q_{gain} = Q_{air} + Q_{wall} \tag{5}$$

For a PV Trombe wall, the electricity generation is also evaluated as one aspect of energy gain [82,89].

Energy load: This is also regarded as energy demand or energy consumption for maintaining an indoor thermal environment after using a Trombe wall. It includes heating load and cooling load for winter and summer, respectively. Building energy simulation can be used to obtain this energy load.

Solar fraction (SF): This index contains the information of energy gain and energy load. It indicates the level of solar energy used for room heating. It can be expressed as the ratio of effective solar heating to total heating demand [59,153]:

$$SF = \frac{Q_{gain}}{Q_{gain} + Q_{heating}} \; or \; \frac{Q_{heating,without\ TW} - Q_{heating}}{Q_{heating,without\ TW}} \tag{6}$$

where $Q_{heating}$ and $Q_{heating,without\ TW}$ are the heating load of a building with and without a Trombe wall, respectively.

New degree days ($NDDs$): This index is a variation of a widely used index - Degree days [151]. It equals the accumulation of the absolute difference between the indoor temperature T_r and the limits of the comfortable temperature T_{comf} [151]:

$$NDDs = \begin{cases} \sum\left[T_r - \left(T_{comf} + \Delta T\right)\right], & T_r > T_{comf} + \Delta T \\ 0, \quad T_{comf} - \Delta T \le T_r \le T_{comf} + \Delta T \\ \sum\left[\left(T_{comf} - \Delta T\right) - T_r\right], & T_r < T_{comf} - \Delta T \end{cases} \tag{7}$$

where $T_{comf} \pm \Delta T$ is the variation limit for acceptable room temperature. As the increased deviation of T_r from $T_{comf} \pm \Delta T$, leads to increased energy consumption for cooling and heating, $NDDs$ can indicate the performance of a Trombe wall in terms of energy demand.

Energy payback time for the use of embodied energy (EPT): This index considers the energy consumption not only during operation, but also during production, transportation, installation, and scrap disposal (the latter four are considered the embodied energy) [177]. It is given as follows [177]:

$$EPT = \frac{year \cdot \left(AEE_{TW} - AEE_{ref}\right)}{E_{pry,ref} - E_{pry,TW}} \tag{8}$$

where $E_{pry,ref}$, $E_{pry,TW}$ are the annual primary operating energy used by the house without or with Trombe wall respectively, AEE_{ref}, AEE_{TW} are the annualized embodied energy of the normal wall and Trombe wall respectively, and $year$ is the life cycle time. EPT indicates the periods when the additional invested embodied energy by using a Trombe wall can be recovered by the primary operating energy savings [177].

6.1.3. Efficiency

Since efficiency is a frequently used evaluation parameter for Trombe wall, it is described in detail in this section.

Thermal efficiency (η_{th}): Since heating represents the major function of Trombe wall, this index is often adopted to analyze the Trombe wall performance [27,53,59,204,205]. It can be expressed as the ratio of the thermal energy supplied by Trombe wall, to the solar radiation falling on Trombe wall surface (Q_{sol}):

$$\eta_{th} = \frac{Q_{gain}}{Q_{sol}} \tag{9}$$

Absorption-storing efficiency (η_{A-S}) and **dissipation efficiency** (η_D): These two indexes convey opposite meaning. They respectively indicate the ability of a Trombe wall to absorb and store the heat from solar radiation during daytime, and to discharge this heat for the indoor room during night [116]. They are expressed as [116]:

$$\eta_{A-S} = \frac{m_{wall} c_p \,\Delta T/t}{Q_{sol}} \tag{10}$$

$$\eta_D = \frac{t_{discharge}}{t_{night}} \tag{11}$$

where m_{wall} is the mass of the thermal storage wall, c_p is its thermal capacity, ΔT is the temperature rise during the time t, $t_{discharge}$ is the total discharging time of the stored heat in Trombe wall, t_{night} is the duration of the night time.

Load reduction efficiency (η_{load}): Since the air circulation driven by Trombe wall via the upper and lower vents causes an air stratification in the indoor space, only a part of the entire heat gain from Trombe wall can be directly used to reduce the heating load [53]. Therefore, to reflect the effectiveness of the heat supply from a Trombe wall, the load reduction efficiency parameter is used [53]:

$$\eta_{load} = \frac{Q_{load,reduction}}{Q_{gain}} \tag{12}$$

where $Q_{load,reduction}$ is the energy saving brought by a Trombe wall.

Exergy efficiency (η_{ex}): Different from energy analysis, exergy analysis can provide information on the energy quality and the maximum work potential [179]. Therefore, some scholars have adopted exergy analysis for Trombe wall research [179,204]. Exergy efficiency can be expressed by the ratio of the gained exergy (Ex_{gain}) and the solar radiation exergy (Ex_{sol}) [179,204]:

$$\eta_{ex} = \frac{Ex_{gain}}{Ex_{sol}} \tag{13}$$

Electrical efficiency (η_e): This parameter is specially used for PV Trombe wall [77,80,83,93,95]. It is usually defined by the following two equations [77,83]:

$$\eta_e = \frac{Q_{elc}}{Q_{sol}} \; or \; \frac{Q_{elc}}{\varepsilon Q_{sol}} \tag{14}$$

where Q_{elc} is the electricity generated by PV Trombe wall, and ε is the ratio of PV cell coverage. In the former equation, the PV cells are regarded as the parts of Trombe wall and the result is related to the performance of whole wall. In the latter equation, the result concerns the performance of the PV cells themselves and it is affected by the thermal effect of Trombe wall. To investigate the comprehensive efficiency of PV Trombe wall, the total efficiency is used which is a combination of the electrical efficiency and thermal efficiency and is given as follows [77,83]:

$$\eta_{total,th,e} = \eta_{th} + \eta_e \; or \; \eta_{th} + \eta_e/\eta_{power} \tag{15}$$

The former equation directly represents the efficiency considering the total energy quantity. The latter equation considers the quality difference of electric energy and thermal energy, and it is converted into the same by a standard fuel electric plant efficiency - η_{power} [83].

Formaldehyde degradation efficiency (η_{HCHO}): This parameter is specially used for a TC Trombe wall and it can reflect the indoor formaldehyde-removal ability. This index was developed to integrate the degradation performance with the thermal performance [27]. Actually, the formaldehyde removal efficiency can be reflected in the thermal storage performance of the catalyst layer, because the thermal catalytic oxidation reaction is initiated when the catalyst layer reaches the start-off temperature after absorbing sufficient solar radiation [27]. Thus, the index is defined by [27]:

$$\eta_{HCHO} = \frac{Q_{HCHO}}{Q_{sol}} \tag{16}$$

where Q_{HCHO} is the formaldehyde-degradation heat consumption which can be calculated by the equivalent electricity consumption of an electric heater that heats the catalyst layer to achieve the same formaldehyde degradation as by solar energy. Subsequently, the total efficiency which integrates the formaldehyde degradation efficiency with the thermal efficiency is given by [27]:

$$\eta_{total,th,e} = \eta_{th} + \eta_{HCHO} \tag{17}$$

It should be highlighted that Equation (16) and (17) can be extended to evaluate other types of air-purification Trombe walls, by varying some terms through the similar analysis as described above.

6.2. Economic analysis

6.2.1. Auxiliary energy cost

Auxiliary energy cost is a direct evaluation index for the operation cost of a building with a Trombe wall, but it can also indirectly reflect the cost-saving performance of Trombe wall. This cost can be calculated by multiplying the consumed quantity of the auxiliary energy (e.g. electricity, gas, oil, biomass) by its unit price. A lower value implies more cost saved by Trombe wall. However, only a limited number of studies [56] have ever used this method.

6.2.2. Life cycle cost (LCC)

As a common economic analysis tool, LCC is often adopted to evaluate the cost of a building with Trombe wall [16,90,206]. A detailed LCC for Trombe wall can be expressed as follows [16]:

$$\begin{aligned} LCC = {} & C_{aux,heat}(a)\left[\left(1 + f_m PWF - f_{salv}\left(\frac{1+i}{1+r}\right)^N\right)\right] + C_{wall} + C_{TW}(a) \\ & + \left[(Q_{aux.heat} - Q(a))\frac{P_d}{\eta_{aux,heat}}PWF\right] \end{aligned} \tag{18}$$

where a is the Trombe wall area ratio, C_{wall} is the existing wall cost, $C_{TW}(a)$ is the cost of Trombe wall, $C_{aux,heat}(a)$ is the cost of auxiliary heating system, $Q(a)$ is the annual saved energy due to the Trombe wall, $Q_{aux.heat}$ is the annual auxiliary heating energy consumption without Trombe wall, f_m

is the operating and maintenance fraction, f_{salv} is the salvage fraction, i is the inflation rate, r is the interest rate (equivalent to discount rate), N is the years of investment, PWF is the Present Worth Factor, P_d is the thermal energy price, and $\eta_{aux,heat}$ is the auxiliary heating system efficiency.

6.2.3. Payback period (PP)

PP is also a common economic index used for Trombe wall analysis [107,173,206,207]. It represents the period when the accumulative operation-cost saving of Trombe wall can offset the additional investment of Trombe wall compared to a normal wall. A PP for Trombe wall can be expressed as:

$$PP = \frac{C_{TW,i} - C_{Ref,i}}{C_{Ref,o} - C_{TW,o}} \tag{19}$$

where $C_{TW,i}$, $C_{TW,o}$, $C_{Ref,i}$, $C_{Ref,o}$ are the investment and operation costs of a Trombe wall and a normal wall, respectively. If PP exceeds the acceptable time for consumers, there will be less value in adopting a Trombe wall.

6.3. Environment impact

6.3.1. Indoor environment

Indoor thermal comfort is a non-negligible aspect to evaluate the performance of a Trombe wall, because the major task of this wall is to maintain a suitable temperature for people indoor. Winter heating and summer overheating are both important issues with regard to the indoor thermal comfort for a Trombe wall. Some available methods for thermal comfort evaluation of a Trombe wall are listed in Table 9.

Table 9 Estimation methods for thermal comfort introduced in previous studies

Indoor air quality (IAQ) is another aspect which has been studied in recent years since the development of air-purification Trombe wall [25–27]. A relevant evaluation index for an air-purification Trombe wall is the pollutant-removal efficiency which is expressed by the ratio of the removed pollutant concentration to the initial pollutant concentration [27]. However, this index can only reflect an IAQ-improvement efficiency rather than an IAQ state, because it is related to the air-purification Trombe wall rather than the room. More attention should be paid to the evaluation of the room's IAQ if an air-purification Trombe wall is used in the building.

6.3.2. Outdoor environment

With regard to the outdoor environment impact of a Trombe wall, the life cycle assessment can provide a complete answer which includes the stages of fabrication, operation, and disposal. The available evaluation indexes are listed in Table 10. GWP, which is also called CO_2 emissions, is used more frequently than other indexes in the environmental assessment of a Trombe wall, not only for a life-cycle analysis [174,208–210] but also for an annual analysis [82,90,173,206]. GWP can be calculated by multiplying the quantity of energy consumption of a Trombe wall by its unit CO_2 emissions.

Table 10 Evaluation indexes available in the life cycle assessment for Trombe wall [208]

6.4. Statistical analysis

To display the ranges of Trombe wall performance reported in the literature, Fig. 14 provides the statistics for thermal efficiency, heating load reduction, energy saving, and solar fraction according to Trombe wall types. In terms of thermal efficiency, the average values are 49.3% (Classical Trombe wall), 51.6% (PCM Trombe wall), 35.6% (PV Trombe wall), 40.4% (Air-purification Trombe wall), and 35.2% (Trombe wall with TIM). In terms of heating load reduction, the average values are 50.0% (Classical Trombe wall), 63.1% (PCM Trombe wall), 54.1% (Water Trombe wall), and 50.3% (Trombe wall with TIM). In terms of energy saving, the average values are 34.1% (Classical Trombe wall) and 17.6% (Electrochromic Trombe wall). In terms of solar fraction, the average values are 60.7% (Classical Trombe wall), 70.0% (PCM Trombe wall), 57.4% (Water Trombe wall), and 62.4% (Trombe wall with TIM).

Fig. 14 Statistics for thermal efficiency [15,27,29–31,43,44,47,53,59,69,70,72,75–77,80,81,83,85,87,93,105,114,130–133,136,138,139,153,179,184,186,193,204,211–214], heating load reduction [16,53,61,107,114,117,123,148,169,175,177,206,215–217], energy saving [33,147,148,217], and solar fraction [59,153,213,216,218–220] of different types of Trombe wall.

7. Discussion and suggestions

7.1. Multifunctional development

As can be seen from Fig. 3, an increasing number of studies have considered a multifunctional Trombe wall, e.g. PV Trombe wall [75,76,83,87] and air-purification Trombe wall [25–32]. This reflects the trend for the future development of conventional Trombe wall. It is also an idea to solve the problems of the current heating-only Trombe wall. For example, besides the electricity generation for user, the PV Trombe wall has the potential to reduce summer overheating and increase aesthetic value. The new multifunctional walls can be created by combining the current Trombe wall with other functional demands of a building, e.g. sound insulation, natural lighting, CO_2 removal and O_2 supply (photosynthesis), and dehumidification or humidification.

7.2. Translucent insulation material application

Low thermal resistance is a typical problem for Trombe wall [12,24]. Some modifications of the Trombe wall have been proposed to solve this problem, e.g. composite Trombe wall [200]. However, this modification usually results in a complex wall structure (Fig. 5). With the development of translucent insulation material (TIM), especially aerogel insulation which can reach 0.1 W/(m^2K) U-values and allow 90% of light through [99,100], better thermal insulation can be realized for Trombe wall without a complex wall structure. Numerous studies have applied aerogel materials in Trombe wall in recent years and have observed good performance [105–108]. In addition, the aesthetic value of Trombe wall can also be improved by using TIM, e.g. Transwall [12]. Therefore, the TIM application in Trombe wall is also a future direction for Trombe wall development. It should be noted that overheating in summer by using TIM in Trombe wall needs to be carefully dealt with as well [106].

7.3. Reduced-scale experiment

Considering the flexible arrangement, space saving and cost saving, the reduced-scale experiment is a recommended experimental method for Trombe wall. It is worth popularizing this approach for Trombe wall research. Although the similarity design is the key for a reduced-scale experiment, the similarity principle is usually ignored in the current Trombe wall studies [14,74,75,117,118,121,122]. Therefore, the design and description of experimental similarity should be added in the future reduced-scale experiments for Trombe wall. In addition, the location for reduced-scale experiments should be carefully chosen because the ambient conditions can influence the experimental results and are different in different place. For example, wind velocity and air temperature are different at different heights, which may result in differences between the ambient conditions of reduced-scale experiment and full-scale one.

7.4. Modularized modeling

The flow-simplified model is a useful approach to simulate the long-term performance of a Trombe wall. Many commercial software (e.g. TRNSYS [164], EnergyPlus [165], IESVE [166], ESP-r [167], and IDA ICE [168]) have provided certain solutions for this type of modeling. However, they also lack flexibility to deal with a complex or new Trombe wall (e.g. Trombe wall with heterogeneous PV glass [91], PV Trombe wall with PCM [77], and Air-purification Trombe wall [32]). Numerous studies have built this type of model by programming (see Table 7). Although their research points are different, the modeling methods are similar. Fig. 13 provides a summary of flow-simplified Trombe wall modeling which includes glass modeling, airflow modeling, and mass-wall modeling. Obviously, a general modeling process and some common modeling methods exist for Trombe wall modeling. Therefore, it is possible to develop a modularized modeling tool which modularizes the modeling process for glass, airflow as well as mass-wall by encapsulating original mathematical formulas and empirical data. This tool can be helpful for scholars and engineers to simplify the modeling process and reduce the work load.

7.5. Aesthetic evaluation

The existing evaluation metrics for Trombe wall are mainly focused on technical, economic and environmental aspects. No aesthetic evaluation method for Trombe wall has been found to date. However, low aesthetic value is a problem for conventional Trombe wall [12,24], which is an underlying obstacle for its popularization. Therefore, aesthetic evaluation should also be considered for developing a new Trombe wall. One possible idea to evaluate the aesthetic value of a Trombe wall is to carry out comparative rating. For example, people can be asked to rank the pictures of different Trombe walls or different walls (including Trombe wall) by aesthetic feeling. Then the statistical data can be analyzed to give a representative aesthetic score. If more aesthetic evaluations are provided, a guideline for solving the aesthetic problem of Trombe wall can be summarized with some normal forms.

8. Conclusions

Trombe wall is an important type of passive solar heating technology. Numerous studies have been carried out in last two decades regarding the retrofits, experiments, modeling, and optimization of Trombe wall. In this review, the authors attempted to present a methodological overview of Trombe wall research and have summarized the classification, experimental assessment, modeling methods, and evaluation metrics of Trombe wall mentioned in current literature. The major conclusions are drawn as follows:

(1) Trombe wall can be classified into nine types which include classical Trombe wall, composite Trombe wall, PCM Trombe wall, PV Trombe wall, water Trombe wall, fluidized Trombe wall, air-purification Trombe wall, electrochromic Trombe wall, and Trombe wall with TIM. In recent years, a multifunctional tendency of Trombe wall is observed, e.g. PV Trombe wall and air-purification Trombe wall. Moreover, the use of TIM, especially aerogel material, is a good solution for improving the low thermal resistance and low aesthetic value of Trombe wall.

(2) The experimental methods for Trombe wall are divided into four types, including reduced-scale thermal box, full-scale thermal box, stand-alone Trombe wall module, and actual testing house. Reduced-scale thermal box is a good experimental approach due to its flexible arrangement, space saving, and cost saving features. However, the similarity principle and testing location should be considered in the experimental design. If different experiments (including Trombe wall testing) need to be conducted in an actual environment, then an actual testing house can be a good choice.

(3) The modeling methods for Trombe wall can be classified into two types which include flow-simplified model and CFD model. For a flow-simplified Trombe wall model, it is recommended to develop a modularized modeling tool so as to simplify the modeling process for glass, airflow, and mass-wall. If a structural optimization for a Trombe wall is needed, a CFD model is recommended.

(4) The evaluation of a Trombe wall can be carried out in terms of its technical performance, economic analysis and environmental performance. In addition, it is recommended to consider the aesthetic evaluation in future Trombe wall research. This can be helpful to improve the aesthetic value of current Trombe walls and eliminate the obstacle for their popularization.

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Fig. 1 Methodology of Trombe wall review

Fig. 2 Overview of Trombe wall classification (PCM - Phase change material; PV - Photovoltaic; TIM - Translucent insulation material; TC - Thermal-catalytic-oxidation; PC - Photocatalytic-oxidation; PTC - Photocatalytic-thermal-catalytic).

Fig. 3 Summary of Trombe wall research in ScienceDirect, SpringerLink, Taylor & Francis Online, SAGE Journals, Wiley Online Library, and MDPI.

Fig. 4 (a) A classical Trombe wall and its retrofits with (b) roller shade, (c) venetian blind, (d) internal thermal fins [14] or (e) water spraying system [36].

Fig. 5 (a) A composite Trombe wall and (b) a new composite Trombe wall with porous absorber

Fig. 6 (a) A PCM Trombe wall and its retrofits with (b) delta winglet vortex generators in wall surface [72] or (c) NTG.

Fig. 7 PV Trombe wall with PV cells integrated in (a) outside glass, (b) wall surface or (c) venetian blinds

Fig. 8 A water Trombe wall

Fig. 9 A fluidized Trombe wall

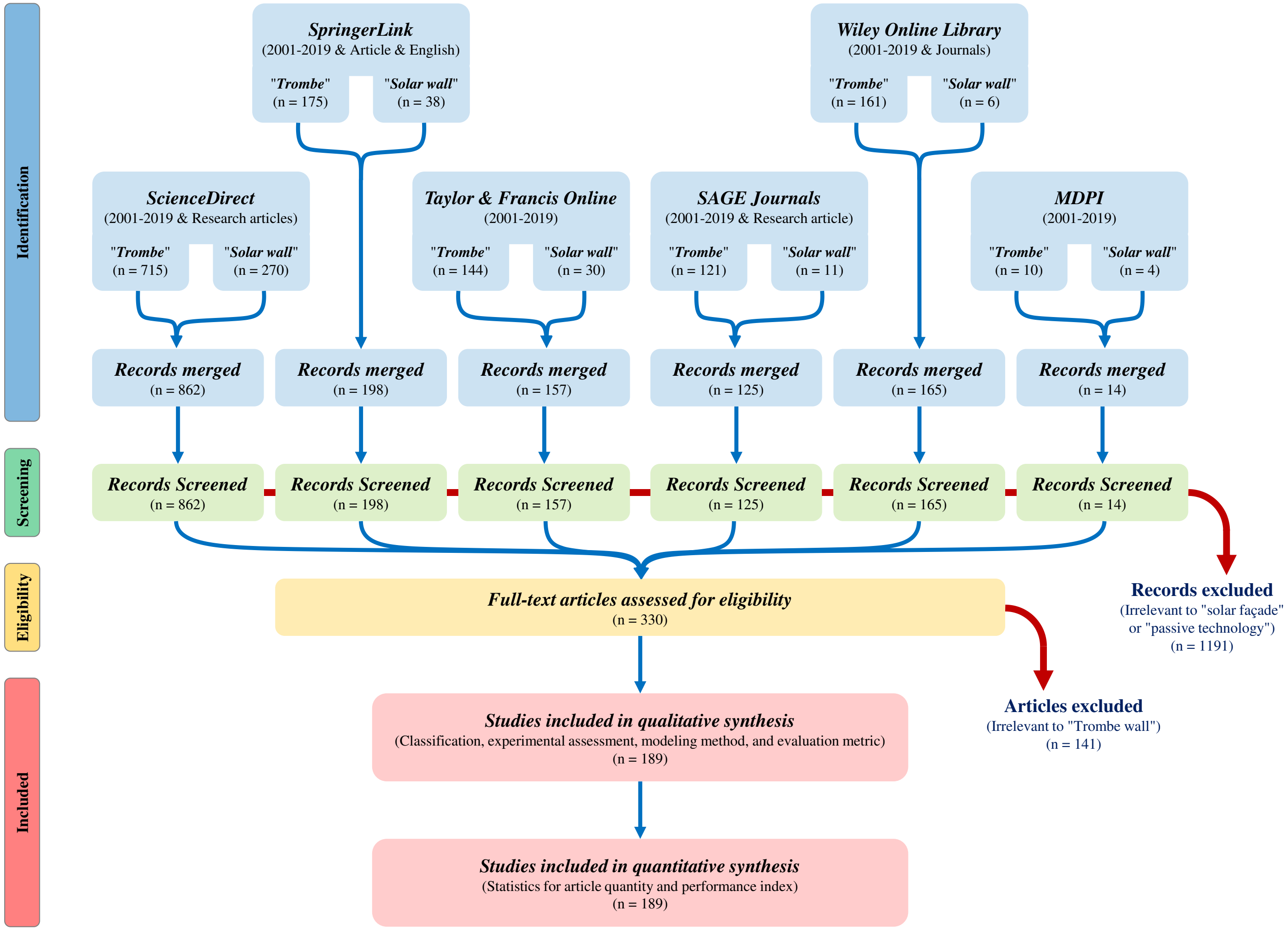
Fig. 10 (a) A TC-Trombe wall [27] and (b) a PC-Trombe wall [25]

Fig. 11 A Transwall with air gap

Fig. 12 Different experimental methods for Trombe wall: (a) a reduced-scale thermal box [14]; (b) a full-size thermal box [113]; (c) a stand-alone Trombe wall module [83]; (d) an actual testing house [114].

Fig. 13 Method summary for flow-simplified Trombe wall modeling

Fig. 14 Statistics for thermal efficiency [15,27,29–31,43,44,47,53,59,69,70,72,75–77,80,81,83,85,87,93,105,114,130–133,136,138,139,153,179,184,186,193,204,211–214], heating load reduction [16,53,61,107,114,117,123,148,169,175,177,206,215–217], energy saving [33,147,148,217], and solar fraction [59,153,213,216,218–220] of different types of Trombe wall.



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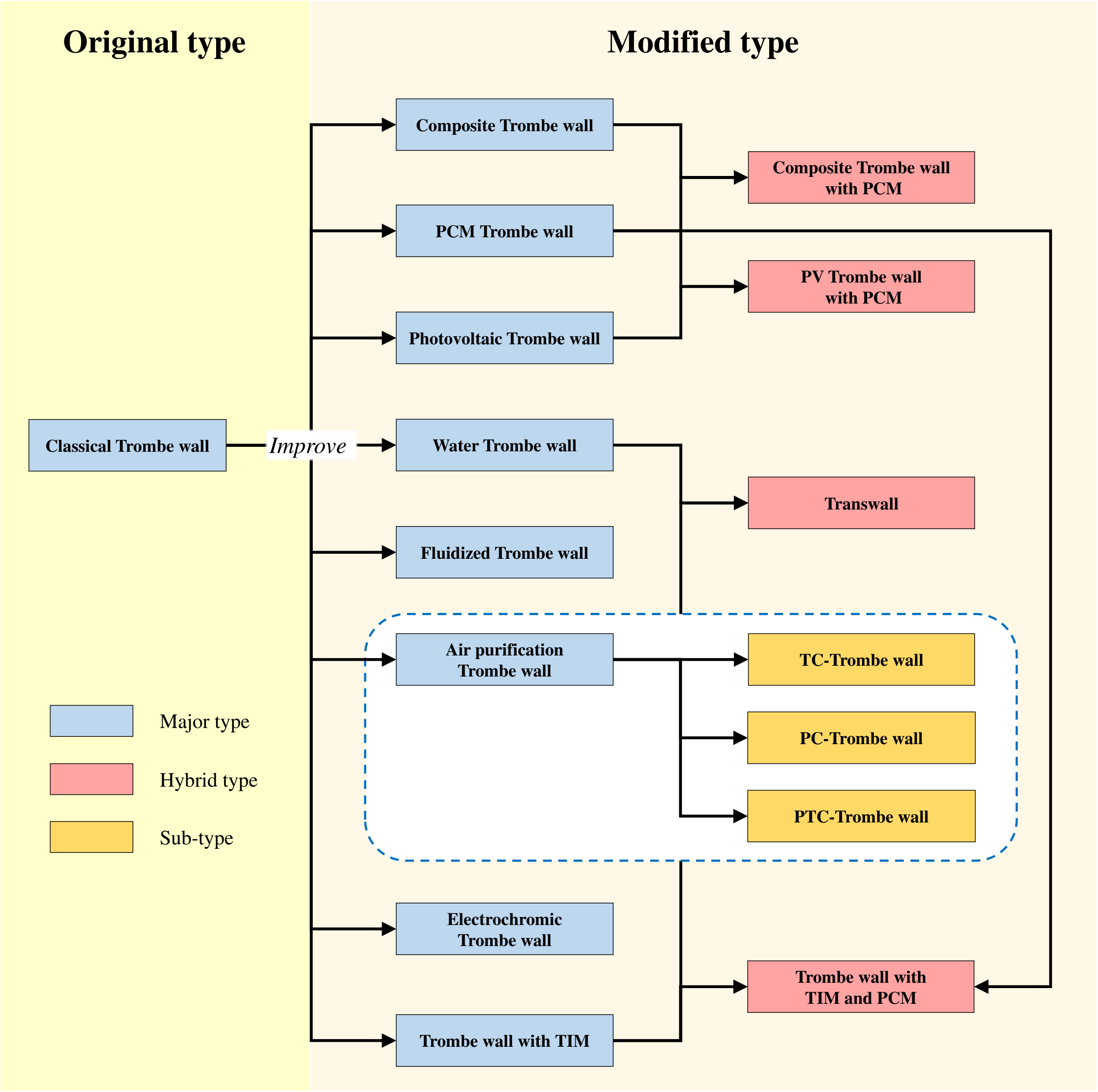

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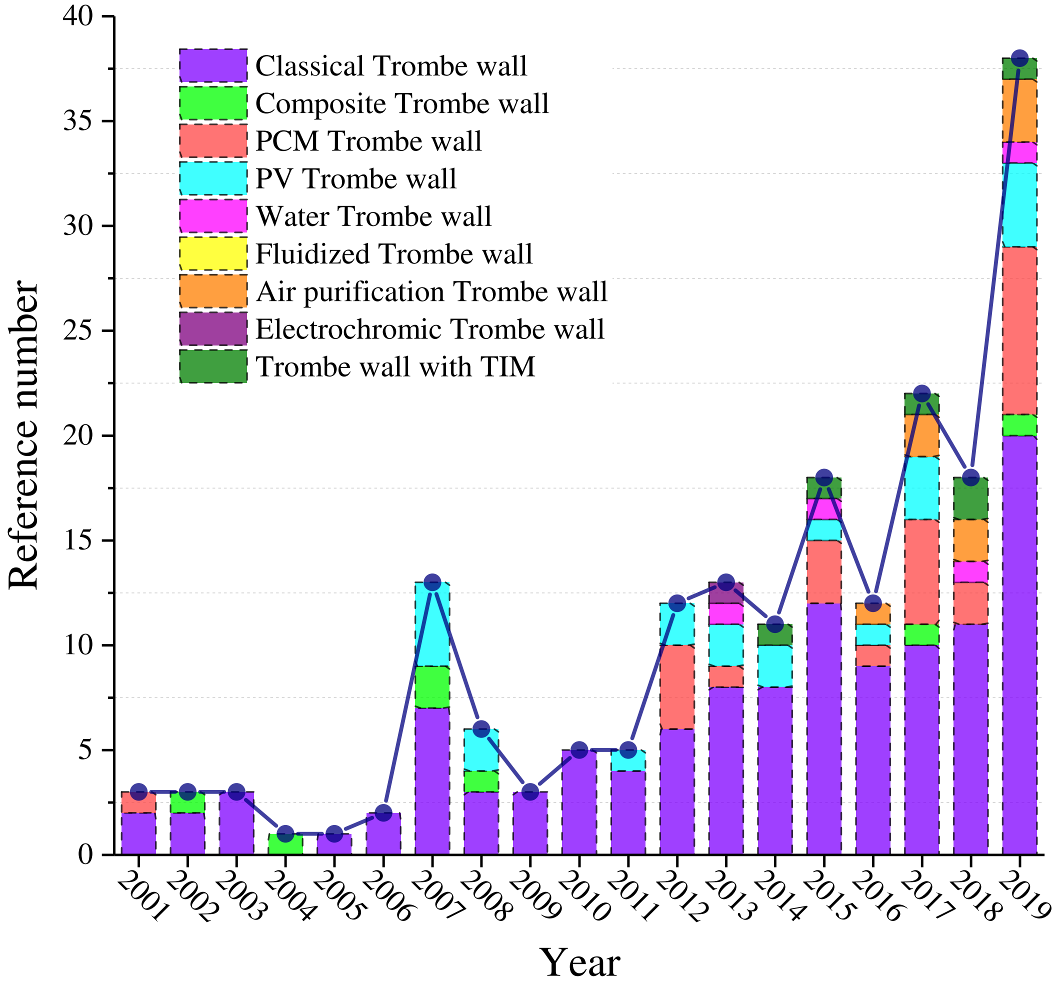

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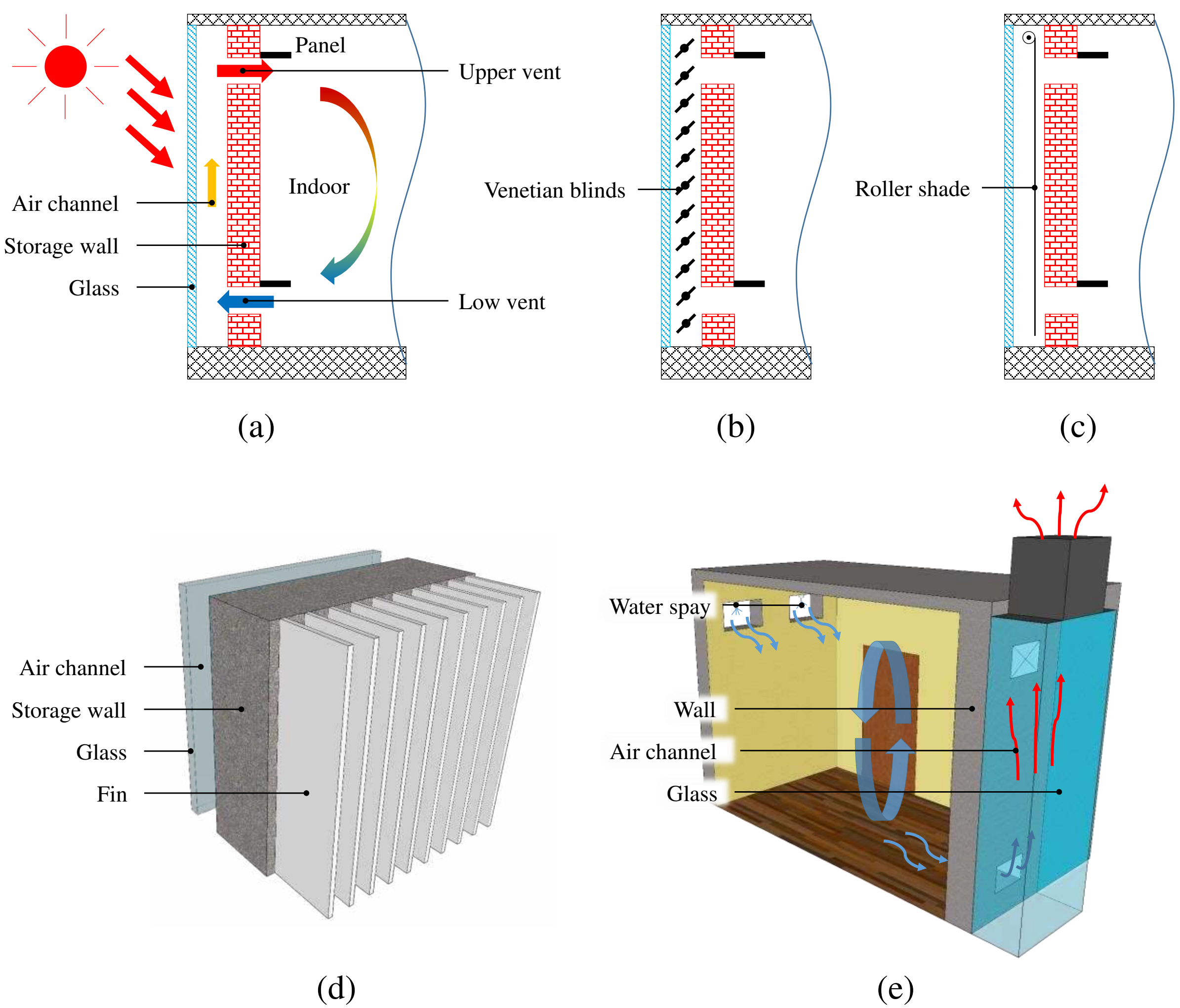
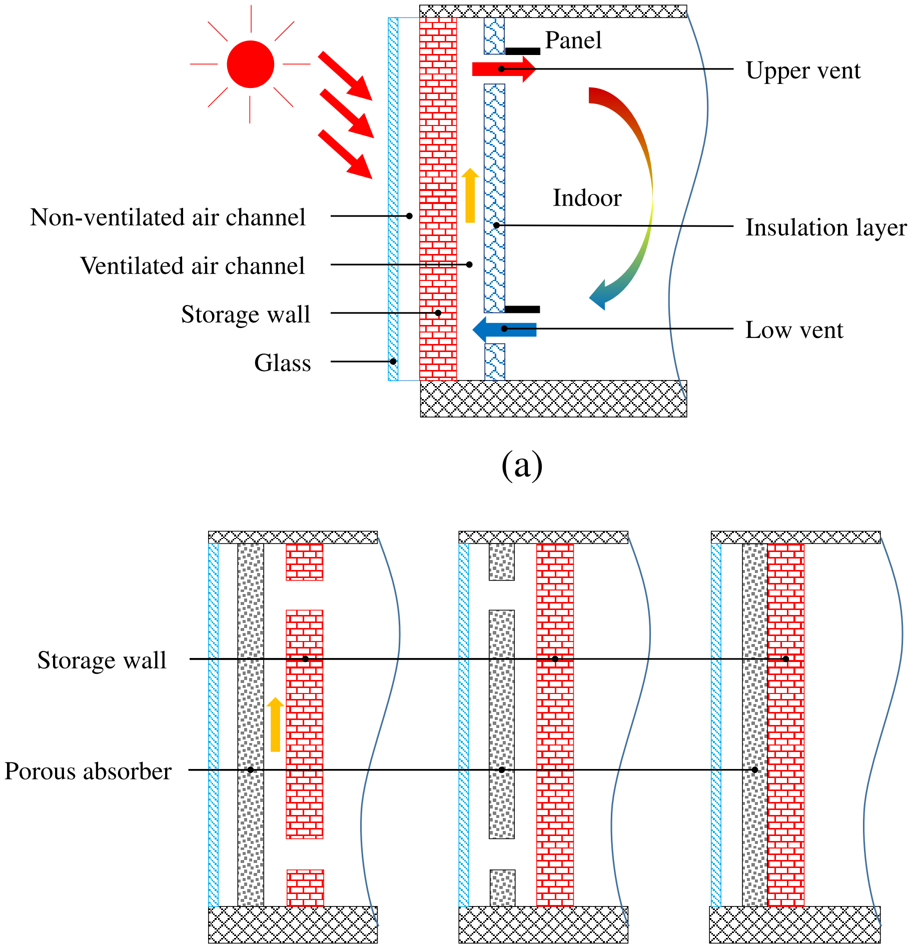


Fig. 4 (a) A classical Trombe wall and its retrofits with (b) roller shade, (c) venetian blind, (d) internal thermal fins [14] or (e) water spraying system [36].



(a)

(b)

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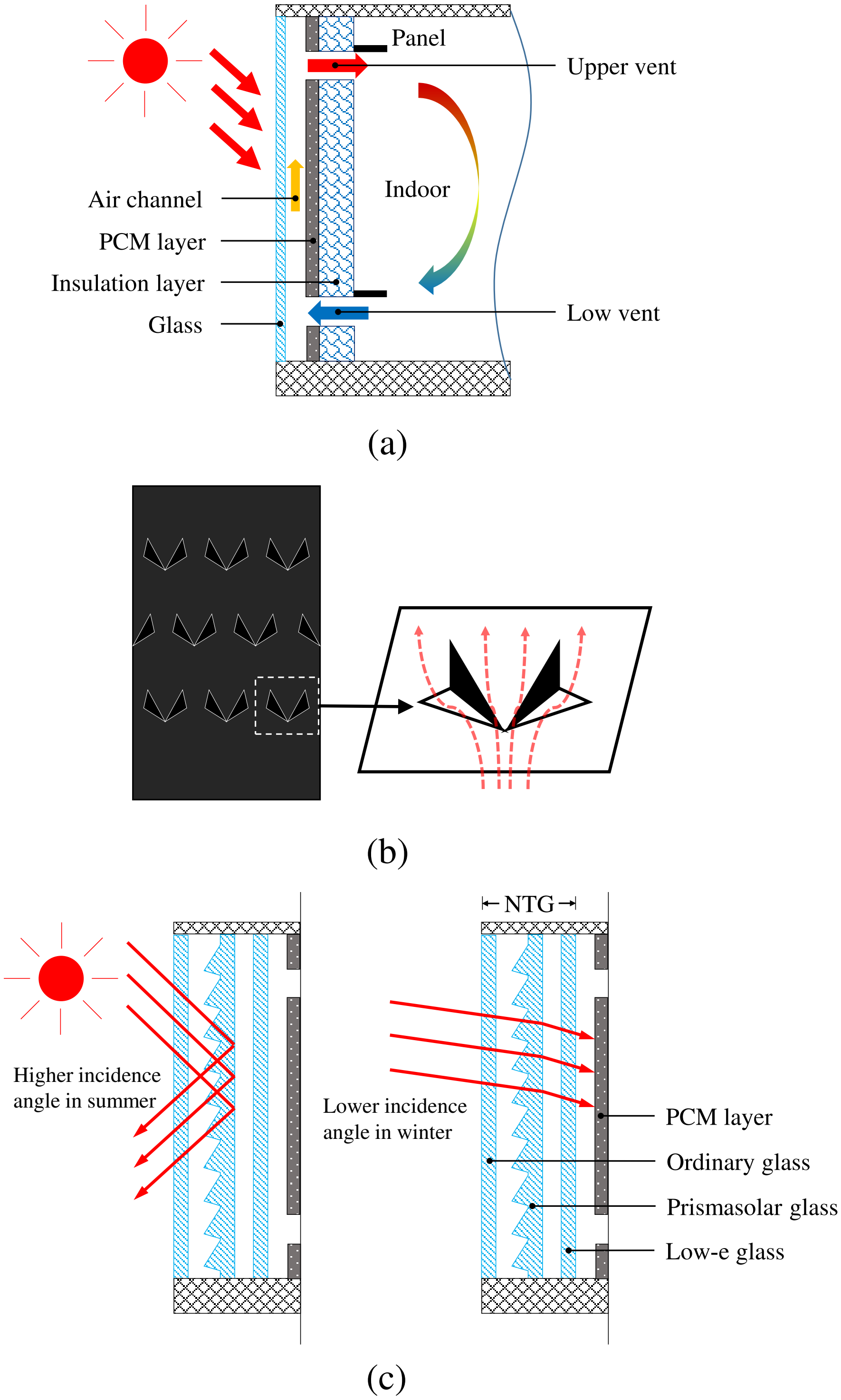

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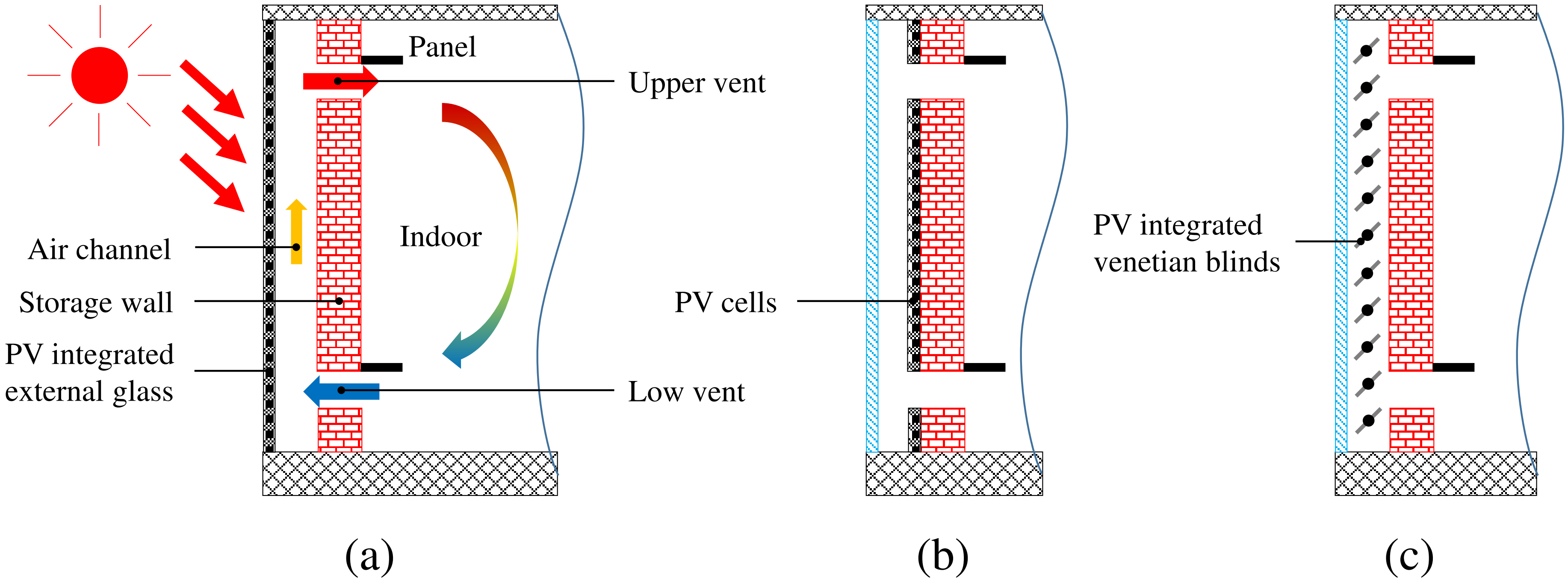

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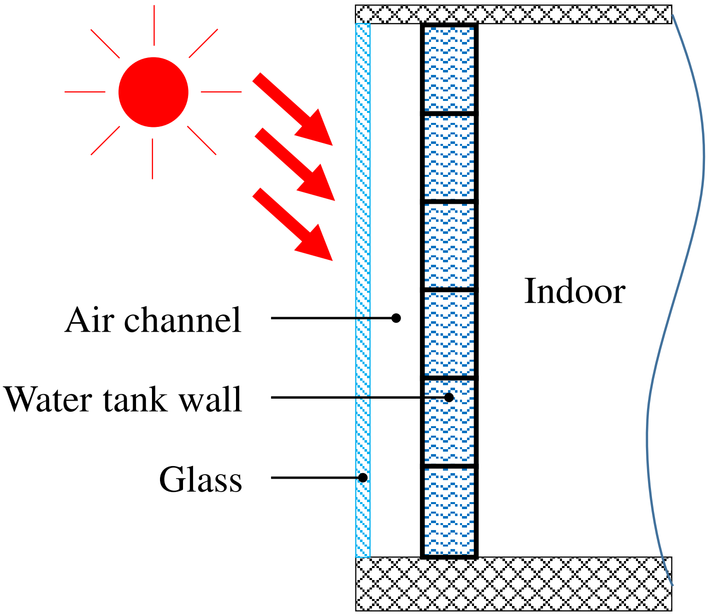


Fig. 8 A water Trombe wall

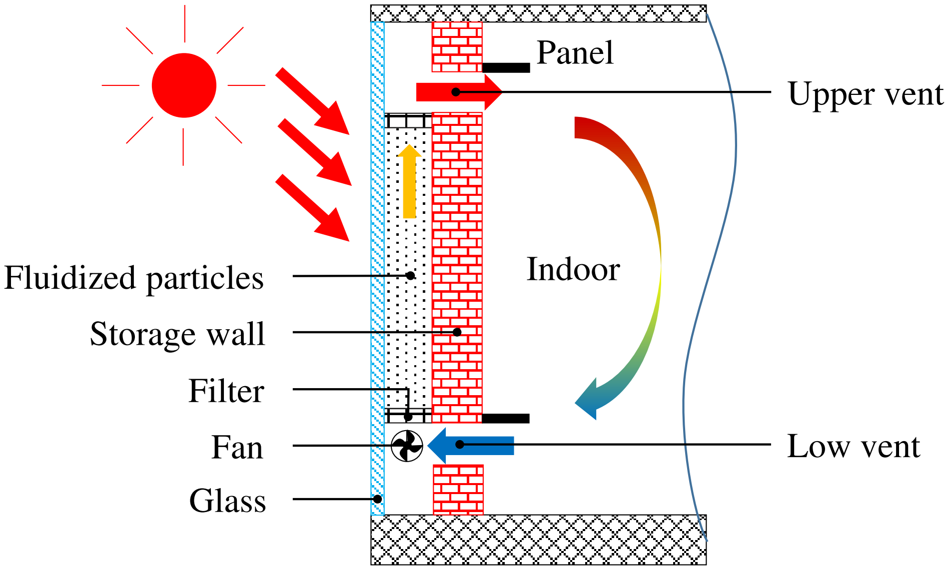
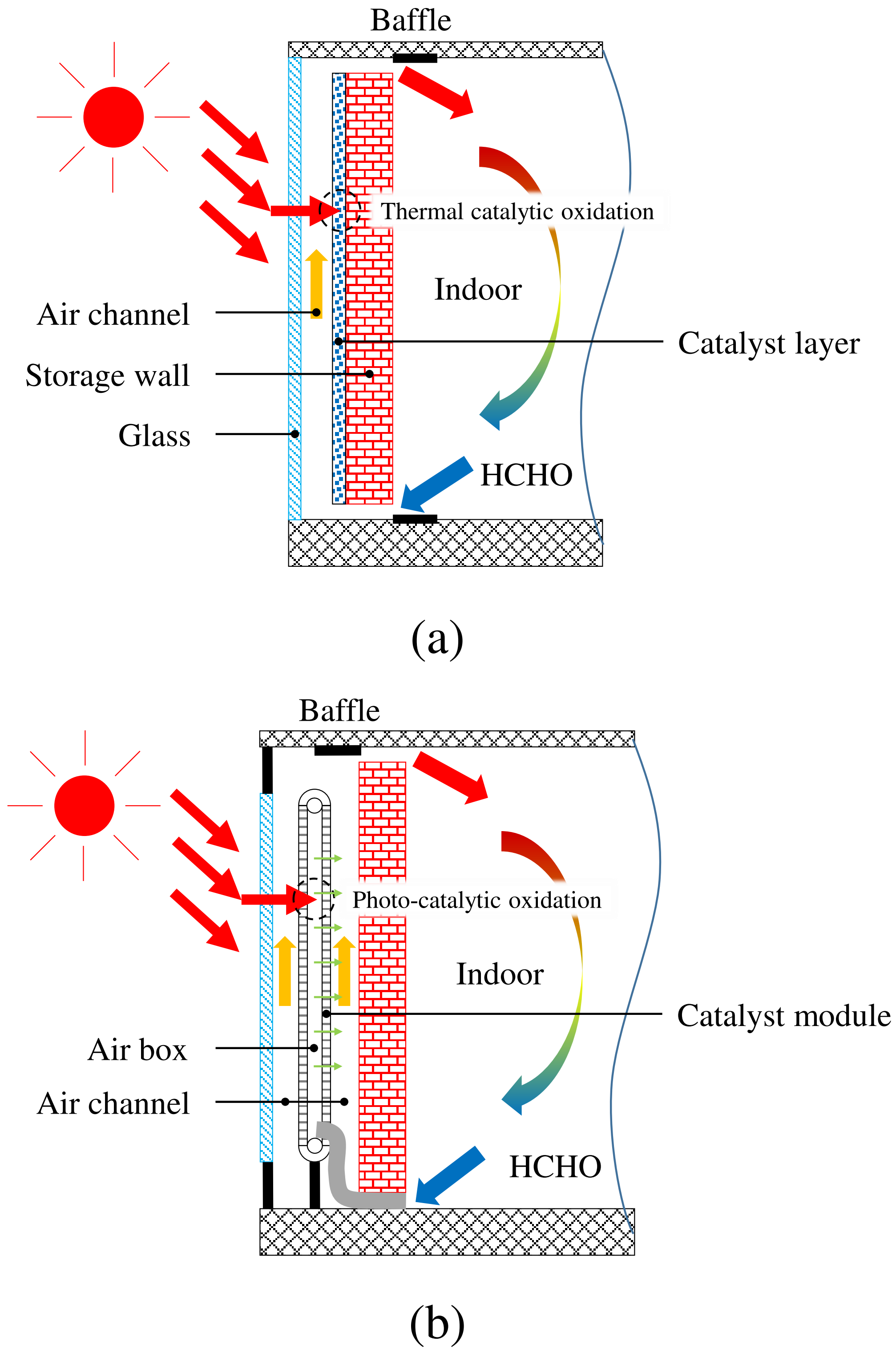


Fig. 9 A fluidized Trombe wall



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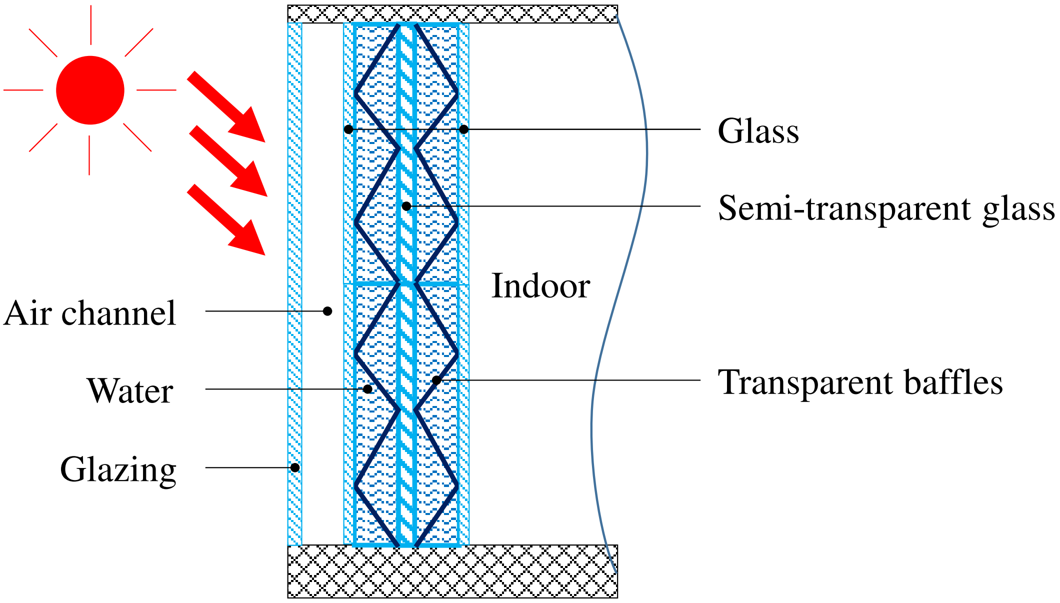
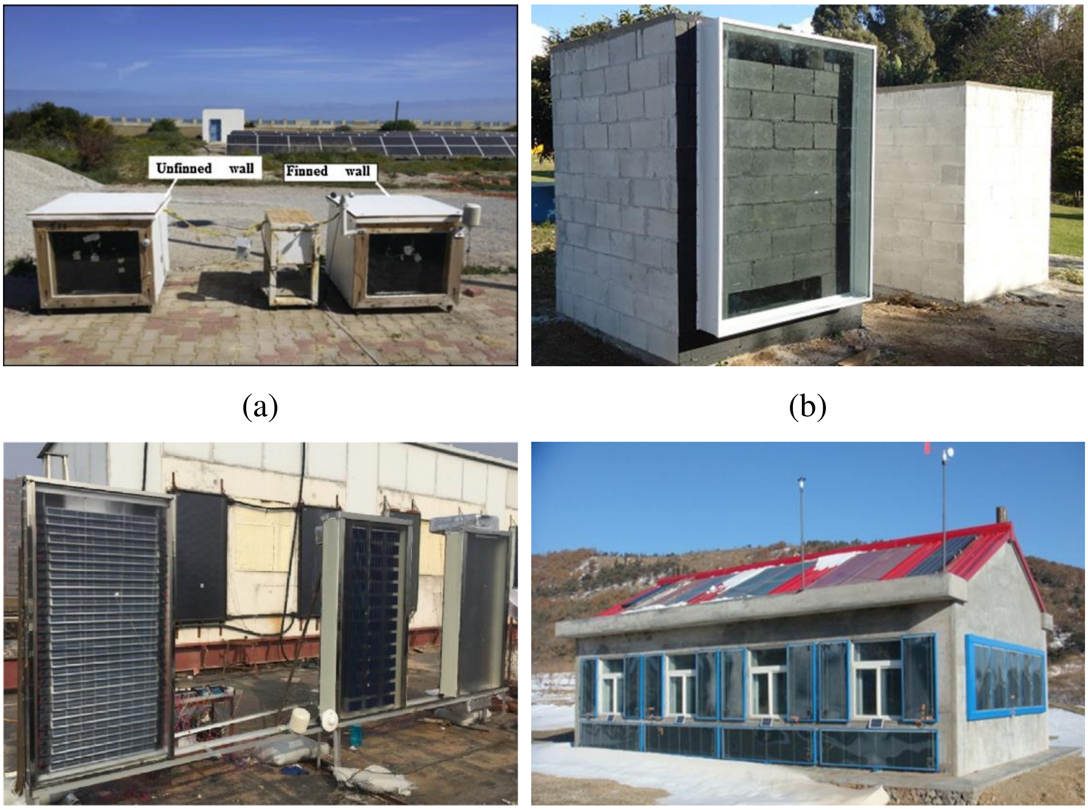


Fig. 11 A Transwall with air gap



(a) (b)

(c) (d)

Fig. 12 Different experimental methods for Trombe wall: (a) a reduced-scale thermal box [14]; (b) a full-size thermal box [113]; (c) a stand-alone Trombe wall module [83]; (d) an actual testing house [114].

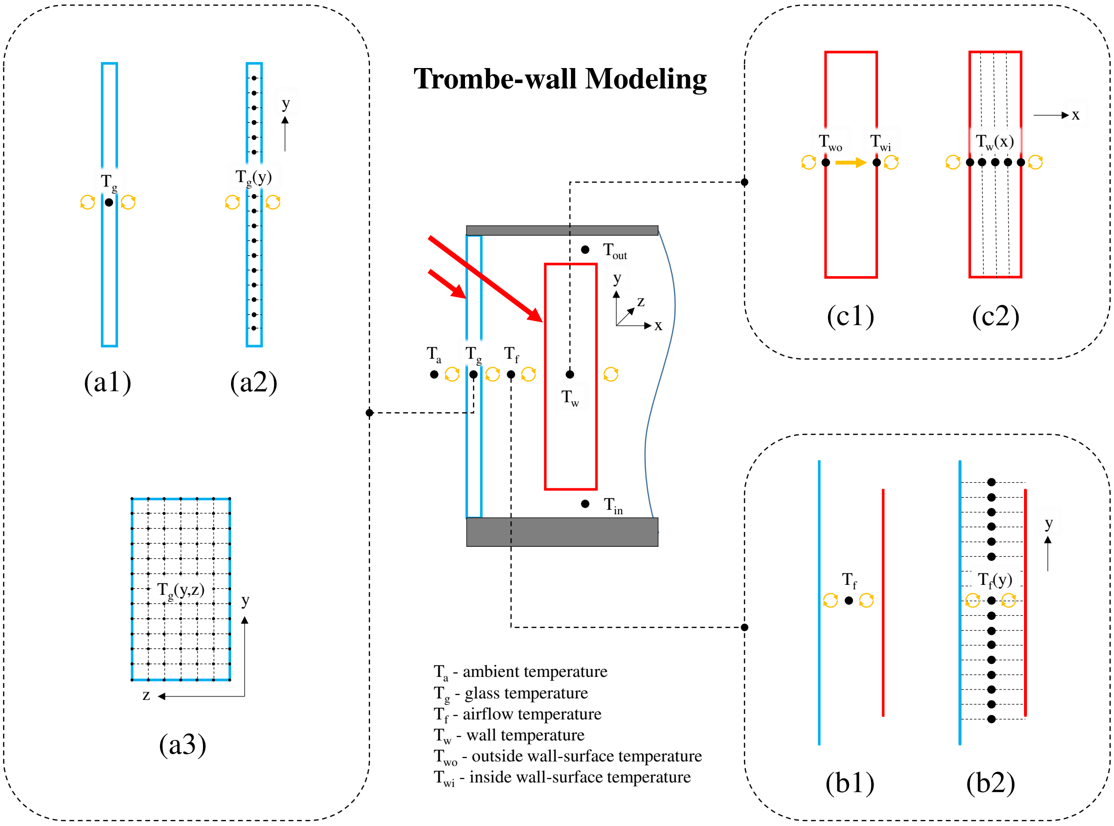


Fig. 13 Method summary for flow-simplified Trombe wall modeling

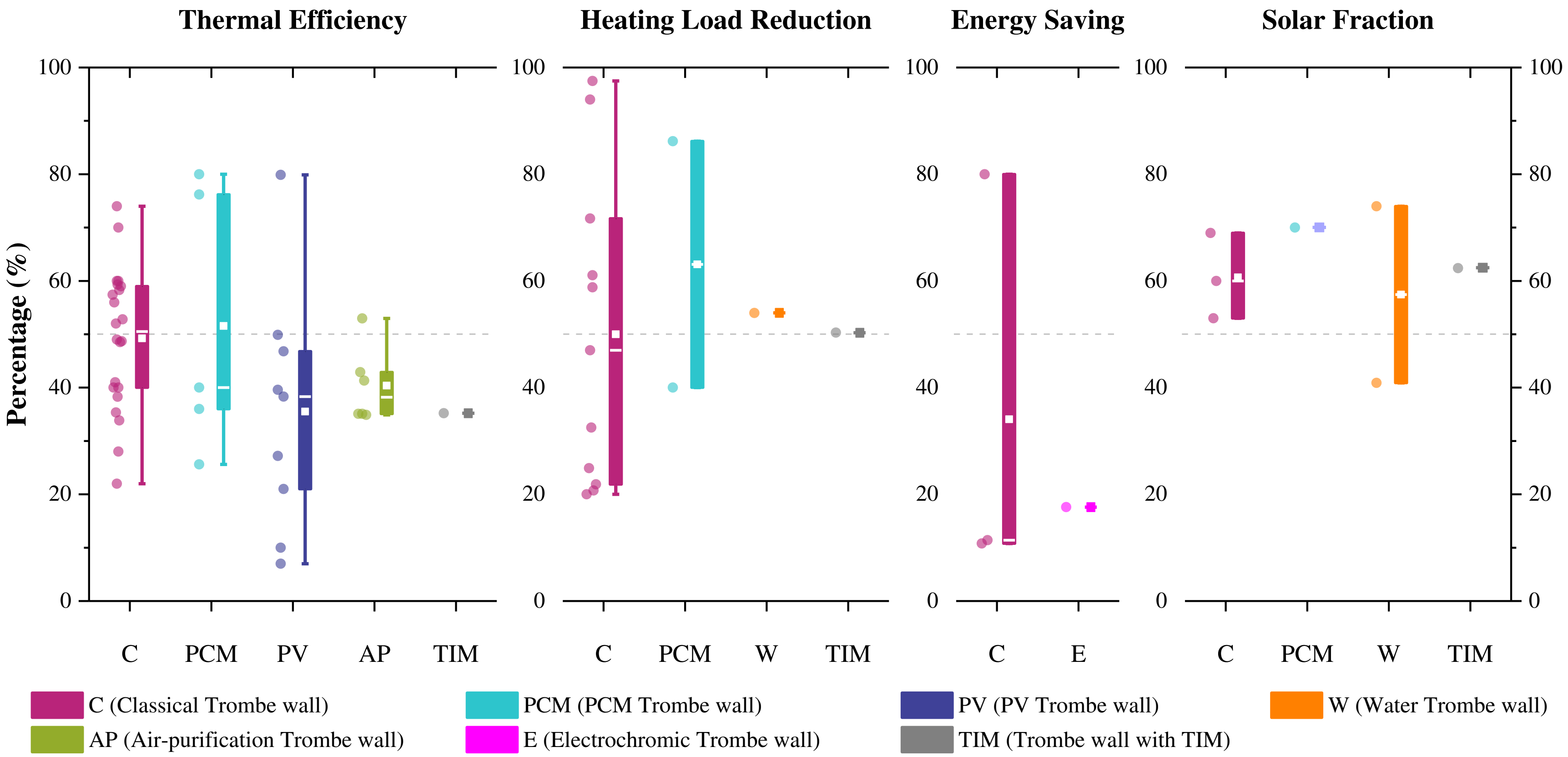


Fig. 14 Statistics for thermal efficiency [15,27,29–31,43,44,47,53,59,69,70,72,75–77,80,81,83,85,87,93,105,114,130–133,136,138,139,153,179,184,186,193,204,211–214], heating load reduction [16,53,61,107,114,117,123,148,169,175,177,206,215–217], energy saving [33,147,148,217], and solar fraction [59,153,213,216,218–220] of different types of Trombe wall.

Table 1 Comparison between each experimental method

Experimental method	Advantages	Disadvantages	Application
Reduced-scale thermal box	Space saving Money saving Flexible arrangement	Problems in similarity law	No limitation
Full-scale thermal box	More actual than reduced-scale thermal box Less requirements than actual testing house	High space costing High money costing	Experiment with certain actual meaning
Stand-alone Trombe wall module	Space saving Money saving Flexible arrangement	No adjacent room for interaction Less relation to an actual operation	Experiment for stand-alone modules Comparative experiment
Actual testing house	More factors related to an actual building More practical meaning	High space costing High money costing	Experiment with actual meaning A series of technical experiments Demonstration

Table 2 References for reduced-scale thermal box used in Trombe wall studies

Reference	Year	Trombe wall type	Size	Materials	Location
Kurtba [115]	2008	Classical Trombe wall	1.0x1.2x1.2	Standard bricks	Elazıg, Turkey
Hassanain [116]	2011	Classical Trombe wall	0.42x0.87x0.438	Wood	Ismailia, Egypt
Zalewski [74]	2012	PCM Trombe wall	0.6x1.0x0.73	Wood	Bethune, France
Abbassi [117]	2014	Classical Trombe wall	1.52x1.52x1.86	Wood	Tunisia
Abbassi [14]	2015	Classical Trombe wall	0.9x0.9x0.8	Wood	Tunisia
Dimassi [118]	2016	Classical Trombe wall	1.52x1.52x1.86	Wood	Tunisia
Shi [62]	2017	PCM Trombe wall	0.6x0.3x0.3	Wood	Laboratory, Hangzhou, China
Cekon [119]	2017	Trombe wall with TIM	-	Brick	Brno, Czech Republic
Dimassi [120]	2017	Classical Trombe wall	1.52x1.52x1.86	Polystyrene board	Borj Cedria,Tunisia
Serageldin [121]	2018	Classical Trombe wall	2.0x2.0x2.0	Wood	Alexandria, Egypt
Abdeen [122]	2019	Classical Trombe wall	2.0x2.0x2.0	Wood	Alexandria, Egypt
Ahmed [75]	2019	PV Trombe wall	1.25x1.25x2.0	Glass wool	Kirkuk, Iraq

Size = Length (m) x Width (m) x Height (m)

Table 3 References for full-scale thermal box used in Trombe wall studies

Reference	Year	Trombe wall type	Size	Materials	Location
Fernandez-Gonzalez [123]	2007	Classical Trombe wall	4.88x2.44x3.0	Wood	Muncie, Indiana
Ji [79]	2007	PV Trombe wall	2.66x3.0x3.0	-	Hefei, China
Ji [92]	2007	PV Trombe wall	2.66x3.0x3.0	-	Hefei, China
Ji [124]	2008	PV Trombe wall	3.0x3.0x2.7	-	Hefei, China
Ji [125]	2010	Classical Trombe wall	2.9x2.97x2.6	Steel panel, polystyrene	Hefei, China
Sun [93]	2011	PV Trombe wall	2.9x2.96x2.6	Steel panel, polystyrene	Hefei, China
Gracia [58]	2012	PCM Trombe wall	2.4x2.4x5.1	Alveolar bricks	Puigverd de Lleida, Spain
Krüger [113]	2013	Classical Trombe wall	1.8x1.95x2.25	Hollow concrete blocks, concrete slab	Curitiba, Brazil
Gracia [53]	2013	PCM Trombe wall	2.4x2.4x5.1	Alveolar bricks	Puigverd de Lleida, Spain
Rabani [126]	2015	Classical Trombe wall	3.0x2.0x3.0	Concrete, foam	Yazd, Iran
Rabani [36]	2015	Classical Trombe wall	3.0x2.0x3.0	Concrete, foam	Yazd, Iran
He [46]	2015	Classical Trombe wall	3.8x3.9x2.6	-	Hefei, China
Hu [43]	2015	Classical Trombe wall	3.8x3.9x2.6	-	Hefei, China
Zhou [73]	2015	PCM Trombe wall	2.6x2.1x2.0	Polystyrene composite boards	Laboratory, Beijing, China
Zhou [72]	2015	PCM Trombe wall	2.6x2.1x2.0	Polystyrene composite boards	Laboratory, Beijing, China
Berthou [105]	2015	Trombe wall with TIM	4.41m^2	Concrete, glass wool, plaster	Sophia Antipolis, France
Hu [45]	2016	Classical Trombe wall	3.8x3.9x2.6	-	Hefei, China
Sun [57]	2016	PCM Trombe wall	5.0x1.6x2.2	Concrete block	Jilin, China
Rabani [127]	2017	Classical Trombe wall	3.0x2.0x3.0	Concrete, foam	Yazd, Iran
Briga-Sá [39]	2017	Classical Trombe wall	6.0x2.4x2.3	Metallic container	Vila Real, Portugal
Briga-Sá [128]	2017	Classical Trombe wall	6.0x2.4x2.3	Metallic container	Vila Real, Portugal
Luo [54]	2017	PCM Trombe wall	-	-	Hefei, China
Xu [129]	2017	PCM Trombe wall	3.0x3.0x2.6	Steel plate, polystyrene, brick	Hefei, China
Long [48]	2018	Classical Trombe wall	2.0x2.5x2.3	Polyurethane sandwich panel	Xiangtan, China

Hernandez [130]	2018	Classical Trombe wall	7.15m^2	Hollow ceramic brick	Salta, Argentina
Dong [131]	2019	Classical Trombe wall	3.5x2.1x2.7	Aerated concrete, polystyrene board, plaster	Hefei, China
Yu [132]	2019	Classical Trombe wall	6.8x4.2x2.7	Color steel plate, expanded polystyrene,	Chengdu, China
Rabani [133]	2019	Classical Trombe wall	3.0x2.0x3.0	Concrete, foam	Yazd, Iran
Long [134]	2019	Classical Trombe wall	2.0x2.5x2.3	Polyurethane sandwich panel	Xiangtan, China
Zhou [135]	2019	Classical Trombe wall	1.5x1.8x4.0	Steel, polystyrene foam plastic	Qingdao, China
Lin [76]	2019	PV Trombe wall	3.9x3.8x2.6	Steel plate, polystyrene	Hefei, China
Lin [87]	2019	PV Trombe wall	3.9x3.8x2.6	Steel panel	Hefei, China

Size = Length (m) x Width (m) x Height (m) or Area

Table 4 References for stand-alone Trombe wall module used in Trombe wall studies

Reference	Year	Trombe wall type	Size	Location
Bilgen [136]	2001	Classical Trombe wall	0.4x0.78	Laboratory, Montreal, Canada
Ran [137]	2003	Classical Trombe wall	0.83x1.421	Quanzhou, China
Burek [138]	2007	Classical Trombe wall	0.925x1.025	Laboratory, Scotland, UK
Dragicevic [139]	2011	Classical Trombe wall	-	Novi Sad, Serbia
Hu [83]	2017	PV Trombe wall	0.802x1.574	Hefei, China
Yu [26]	2017	Air-purification Trombe wall	0.24x0.08	Laboratory, Hefei, China
Yu [27]	2017	Air-purification Trombe wall	0.5x1.0	Hefei, China
Yu [28]	2018	Air-purification Trombe wall	-	Hefei, China
Yu [29]	2018	Air-purification Trombe wall	-	Hefei , China
Yu [30]	2019	Air-purification Trombe wall	-	Hefei , China

Size = Width (m) x Height (m)

Table 5 References for actual testing house used in Trombe wall studies

Reference	Year	Trombe wall type	Experimental type	Size	Location
Raman [140]	2001	Classical Trombe wall	OE	5.0x4.0x3.0	New Delhi, India
Onbasioglu [141]	2002	Classical Trombe wall	OE	3.3x3.3x3.0	Istanbul, Turkey
Brunetti [142]	2003	Classical Trombe wall	OE	4.0x4.0x3.0	Termoli, Italy
Khedari [143]	2005	Classical Trombe wall	ME	4.0x3.0x2.0	Bangkok, Thailand
Chen [144]	2006	Classical Trombe wall	OE	3.9x3.9x2.7	Dalian, China
Chen [37]	2006	Classical Trombe wall	OE	3.9x3.9x2.7	Dalian, China
Chen [145]	2007	Classical Trombe wall	ME	3.4x3.1x2.7	Dalian, China
Mendonca [17]	2007	Classical Trombe wall	ME	3.1x6.5x3.35	Guimaraes, Portugal
Hernández [146]	2010	Classical Trombe wall	ME	750m^2	Puna, Argentine
Llovera [147]	2011	Classical Trombe wall	ME	578m^2	Andorra
Stazi [148]	2012	Classical Trombe wall	OE	-	Ancona, Italy
Kara [59]	2012	PCM Trombe wall	OE	-	Erzurum, Turkey
Koyunbaba [78]	2012	PV Trombe wall	OE	3x3.5x2.9	Izmir, Turkey
Liu [149]	2013	Classical Trombe wall	OE	3.3x3.9x2.9	Gangcha, China
Zhu [114]	2013	Classical Trombe wall	ME	75m^2	Dalian, China
Song [150]	2013	Classical Trombe wall	ME	3.7x2.9x2.8	Kunming, China
Wang [151]	2013	Water Trombe wall	OE	700m^2	Tianjin, China
Thateenaranon [152]	2014	Classical Trombe wall	ME	3.35x3.45x2.0	Bangkok, Thailand
Yu [153]	2014	Classical Trombe wall	ME	265.6m^2	Hefei, China
Wang [154]	2015	Classical Trombe wall	OE	-	Changwu, China,
Zhu [155]	2015	Classical Trombe wall	ME	-	Dalian, China
Zhang [156]	2016	Classical Trombe wall	ME	74.5m^2	Jilin, China
Thateenaranon [157]	2017	Classical Trombe wall	ME	87m^2	Bangkok, Thailand
Zhao [158]	2017	Classical Trombe wall	ME	3.0x6.0x3.0	Huzhu, China

Ma [159]	2018	Classical Trombe wall	OE	115.5m^2	Miyazaki, Japan
Souayfane [106]	2018	Trombe wall with TIM	OE	9.29m^2	Sophia Antipolis, France
Liu [160]	2018	Classical Trombe wall	ME	3.0x6.0x3.0	Xintianpu, China
Liu [161]	2018	Classical Trombe wall	ME	-	Changwu, China
Dabaieh [162]	2019	Classical Trombe wall	OE	-	Cairo, Egypt

ME: multiple experiments including Trombe wall OE: only Trombe wall experiment Size = Length (m) x Width (m) x Height (m) or Area

Table 6 Comparison between different types of modeling method

Modeling method	Main assumption	Advantages	Disadvantages	Application	Tools
Flow-simplified model	Ideal unidirectional plug flow No turbulence characteristics	Low calculation load	Less information with regard to detailed structural part	Long-term simulation	Matlab Matlab/Simulink FORTRAN TRNSYS EnergyPlus IESVE IDA ICE ESP-r
CFD model	Detailed fluidic-factors (compressibility, stress, dissipation) Description by Navier-Stokes equations	Detailed information for physical field Ability to handle different structure	Huge calculation load	Structural optimization	Fluent ANSYS CFX Solidworks Flow Simulation CFD Flex

Table 7 References for flow-simplified model used in Trombe wall studies

Reference	Year	Trombe wall type	Glass assumption			Airflow assumption		Mass-wall assumption		Tool
			U	1D	2D	U	1D	S	1D	
Kalogirou [169]	2002	Classical Trombe wall								TRNSYS
Shen [170]	2007	Composite Trombe wall								TRNSYS
Shen [171]	2007	Composite Trombe wall								TRNSYS
Ji [91]	2007	PV Trombe wall			●		●		●	FORTRAN
Ji [92]	2007	PV Trombe wall			●		●		●	
Ji [79]	2007	PV Trombe wall			●		●		●	
Nwachukwu [172]	2008	Classical Trombe wall	●			●			●	
Chel [173]	2008	Classical Trombe wall								TRNSYS
Jiang [80]	2008	PV Trombe wall			●		●		●	FORTRAN
Ruiz-Pardo [163]	2010	Classical Trombe wall	●			●		●		
Jaber [16]	2011	Classical Trombe wall								TRNSYS
Sun [93]	2011	PV Trombe wall			●		●		●	
Stazi [174]	2012	Classical Trombe wall								EnergyPlus
Stazi [148]	2012	Classical Trombe wall								EnergyPlus
Stazi [38]	2012	Classical Trombe wall								EnergyPlus
Fiorito [60]	2012	PCM Trombe wall								EnergyPlus
Soussi [175]	2013	Classical Trombe wall								TRNSYS
Atikol [176]	2013	Classical Trombe wall								TRNSYS
Wang [151]	2013	Water Trombe wall								TRNSYS
Pittaluga [33]	2013	Electrochromic Trombe wall								EnergyPlus
Abbassi [117]	2014	Classical Trombe wall								TRNSYS
Yu [153]	2014	Classical Trombe wall								TRNSYS
Bojic [177]	2014	Classical Trombe wall								EnergyPlus

Reference	Year	Trombe wall type	Glass assumption			Airflow assumption		Mass-wall assumption		Tool
			U	1D	2D	U	1D	S	1D	
Irshad [90]	2014	PV Trombe wall								TRNSYS
Aelenei [77]	2014	PV Trombe wall with PCM	●			●		●		Matlab /Simulink
Abbassi [14]	2015	Classical Trombe wall								TRNSYS
Wang [154]	2015	Classical Trombe wall								EnergyPlus
He [46]	2015	Classical Trombe wall	●				●		●	MATLAB
Sacht [178]	2015	Classical Trombe wall								EnergyPlus
Irshad [95]	2015	PV Trombe wall								TRNSYS
Duan [179]	2016	Classical Trombe wall		●			●		●	
Hu [45]	2016	Classical Trombe wall	●				●		●	
Taffesse [94]	2016	PV Trombe wall	●			●		●		MATLAB
Zhao [158]	2017	Classical Trombe wall	●				●		●	
Kolaitis [61]	2017	PCM Trombe wall								TRNSYS
Hu [82]	2017	PV Trombe wall	●				●		●	MATLAB
Yu [27]	2017	Air-purification Trombe wall		●			●			
Demou [15]	2018	Classical Trombe wall		●		●			●	MATLAB
Yu [28]	2018	Air-purification Trombe wall		●			●		●	MATLAB
Souayfane [106]	2018	Trombe wall with TIM								TRNSYS-MATLAB
Liu [160]	2018	Classical Trombe wall								IESVE
Abdeen [122]	2019	Classical Trombe wall	●			●		●		MATLAB
Martín-Consuegra [180]	2019	Classical Trombe wall								EnergyPlus
Wang [181]	2019	Classical Trombe wall								EnergyPlus
Ahmed [75]	2019	PV Trombe wall	●				●			MATLAB
Lin [76]	2019	PV Trombe wall	●				●		●	MATLAB
Lin [87]	2019	PV Trombe wall	●				●		●	MATLAB

Reference	Year	Trombe wall type	Glass assumption			Airflow assumption		Mass-wall assumption		Tool
			U	1D	2D	U	1D	S	1D	
Yu [32]	2019	Air-purification Trombe wall	●				●		●	MATLAB
Yu [30]	2019	Air-purification Trombe wall		●			●		●	MATLAB

U: uniform assumption 1D: one-dimension assumption 2D: two-dimension assumption S: steady assumption

Table 8 References for CFD model used in Trombe wall studies

Reference	Year	Trombe wall type	Dimension	Model	Mesh	Tool
Chen [50]	2004	Composite Trombe wall	2D	L	11,264	-
Chen [49]	2008	Composite Trombe wall	2D	L	9,504	-
Kurtbas [115]	2008	Classical Trombe wall	3D	L	68,013	FLEUNT
Zamora [190]	2009	Classical Trombe wall	2D	k−ω	21,150	-
Koyunbaba [78]	2012	PV Trombe wall	2D	k–ε	25,970	Ansys CFX
Hami [184]	2012	Classical Trombe wall	2D	L	-	-
Koyunbaba [81]	2013	PV Trombe wall	2D	k–ε	25,970	Ansys CFX
Liu [149]	2013	Classical Trombe wall	3D	k–ε	-	FLEUNT
Lal [191]	2014	Classical Trombe wall	2D	k–ε	29,123	FLEUNT
Hong [44]	2015	Classical Trombe wall	3D	k−ω	-	FLEUNT
Rabani [126]	2015	Classical Trombe wall	3D	-	2,700,000	FLUENT
Bajc [187]	2015	Classical Trombe wall	3D	k–ε	-	FLUENT
Hernandez-Lopez [192]	2016	Classical Trombe wall	2D	k–ε	14,641	-
He [47]	2016	Classical Trombe wall	2D	k–ε	350,000	FLUENT
Bellos [188]	2016	Classical Trombe wall	3D	-	6,000,000	Solidworks Flow Simulation
Rabani [193]	2016	Classical Trombe wall	3D	L	2,700,000	FLUENT
Mytafide [189]	2017	Classical Trombe wall	3D	-	-	CFD Flex
Long [48]	2018	Classical Trombe wall	3D	-	-	FLUENT
Serageldin [121]	2018	Classical Trombe wall	3D	k–ε	4,000,000	FLUENT
Zamora [194]	2018	Classical Trombe wall	2D	k−ω	10,000	-
Long [134]	2019	Classical Trombe wall	3D	k–ε	600,000	FLUENT
Wu [31]	2019	Air-purification Trombe wall	2D	k–ε	4,570	-
Li [69]	2019	PCM Trombe wall	2D	L	12,256	COMSOL Mutiphysics
Zhang [183]	2019	Classical Trombe wall	2D	k–ε	24,000	FLUENT

Hong [185]	2019	Classical Trombe wall	2D	k−ω	1,200,000	FLUENT
Hong [186]	2019	Classical Trombe wall	2D	k−ω	1,200,000	FLUENT
Rabani [182]	2019	Classical Trombe wall	3D	k–ε	2,500,000	FLUENT
Abdeen [122]	2019	Classical Trombe wall	3D	k–ε	1,734,360	DesignBuilder
Zhou [135]	2019	Classical Trombe wall	3D	k–ε	20,000	FLUENT
Błotny [195]	2019	Classical Trombe wall	3D	k–ε	-	FLUENT

2D: two-dimension 3D: three-dimension L: Laminar model k–ε: k–ε turbulence model k−ω: k−ω turbulence model

Table 9 Estimation methods for thermal comfort introduced in previous studies

Method	Description	References
Adaptive method	Provide the upper and lower limitation of the comfortable temperature under different thermal environment.	[38,148,151]
Predicted Mean Vote (PMV)	Provide a predicted equation and a relevant criteria for thermal sensation.	[33,46,148]
Graphic Comfort Zone Method in ANSI/ASHRAE Standard 55	Provide a standardized graphic comfort zone which is obtained based on PMV method.	[123]
Discomfort index (DI)	$DI = \frac{MSE + 5MSR}{6}$ (20) $MSE = \sum_{\tau=1}^{m} (ET - PT)^2$ (21) $MSR = \sum_{\tau=1}^{m} \left(\frac{E_\tau - E_{\tau-1}}{2} \right)$ (22) where MSE and MSR represent the steady state factor and dynamic factor, τ and m mean the current hour and total hours, ET is the effective temperature, PT is the optimum temperature and E is the absolute deviation of ET and PT.	[151]

Table 10 Evaluation indexes available in the life cycle assessment for Trombe wall [208]

Index	Description	Unit
Fossil Fuel Consumption (FFC)	Reflect the impact in an indirect way without showing the specific effect from certain aspect.	GJ
Global Warming Potential (GWP)	Indicate the impact on the global warming process with the CO_2 emissions.	CO_2 tonnes eq
Acidification Potential (AP)	Reflect the impact on the acidification of the solid or water.	mol H^+ eq
Human Health Criteria (HHC)	Indicate the harm on the human body through the inhalable harmful particle generation.	kg PM10 eq
Eutrophication Potential (EP)	Reflect the impact on the eutrophication of the river or pool that may be caused by the sewage discharge.	Kg N eq
Ozone Depletion Potential (ODP)	Indicate the effect on the ozone depletion that may be caused by the manufacture with the use of the cooling craft.	mg CFC-11 eq
Smog Potential (SP)	Reflect the impact on the harmful smog generation.	kg NO_x eq