Passive Solar Building

Zhongting Hu and Wei He

Contents

Abstract

Compared to conventional “active” environmental control system, passive solar system is a better alternative option for thermal comfort conditioning inside the buildings. The judicious use of simple passive systems can significantly reduce the building’s energy consumption for space heating, cooling, ventilation, and lighting. Hence, this chapter presents an overview of the major development of various building integrations of passive solar concepts such as Trombe wall, roof ponds, and BIPV/T. More importantly, their structures, working principles, as well as advantages and defects have been highlighted. On this basis, two types of

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theoretical methods involving heat balance model and computational fluid dynamics (CFD) are described and compared. Finally, various assessment factors for passive solar building are summarized from three aspects: energy, environment, and economy. Hopefully, this chapter can provide a good knowledge base for architects or related engineering designers in the field of passive solar design.

Keywords
Passive solar system · Building · Heating · Cooling · Assessment factors

Introduction

Today's buildings, which essentially rely on the "active" environmental control system to keep inside spaces cooler in summer and warmer in winter, often involve amount of conventional energy expense and CO_2 emission. With the growing awareness of the energy crisis, lots of researchers actively seek for sustainable and efficient methods, which can contribute to thermal comfort in a building without (or with minimum) energy expenditure. Using renewable energy to partly or completely replace fossil energy for heating and cooling is a good alternative option. Particularly, solar energy is the most abundant, inexhaustible, and clean one. In this direction, the integration of passive solar system in buildings is an optimal strategy for sustainable development, and also it has been increasingly encouraged by international regulations. As pointed out by related literatures, the passive solar techniques can reduce annual heating demand up to 25%. The term "passive solar building" is introduced to distinguish thermal systems, where the natural energy flows are utilized for the transfer of thermal energy into, out of, and through a building, as opposed to solar-generated thermal energy used primarily with the aid of mechanical power (e.g., pumps and fans). Generally speaking, the term "passive solar building" is employed to emphasize utilization energy flows both in heating and cooling. In the passive solar heating/cooling system, various envelope components of the buildings such as external walls, windows, roofs, and floors are selected to collect, store, transport, and distribute the sun's energy. Both the building construction materials (e.g., stone, bricks, concrete, and water) and the thermal process (e.g., thermal radiation, natural convection, conduction air stratification, evaporation, and thermosiphoning) are combined in various ways in passive designs. Although various designs give the passive systems considerable versatility, the decision of the most appropriate design for a given site, climate, and building type should be made by the architects and structural engineers. Indeed, mere a passing interest and superficial knowledge of solar heating and cooling is far from enough.

Passive concepts of solar energy utilization in buildings need to accommodate the following requirements:

(a) Transmission and/or absorption of the maximum possible quantity of solar radiation and reduction of heat loss to the outside environment through the use

of windows with high solar heat gain coefficient (SHGC) in winter, so as to minimize the heating energy consumption
(b) Utilization of absorbed solar energy to alleviate instantaneous heating load and store the remainder energy in the embodied thermal mass or specially built thermal storage devices
(c) Shading control devices to exclude excessive solar gains during hot summer
(d) Natural ventilation to naturally cool the buildings' inside space in summer, evaporative cooling
(e) Use of sunlight for daylight
(f) Development of building integrated photovoltaic/thermal devices for electric power production and space heating or as the shading devices to reduce the solar gains

This paper mainly explains different types of passive solar concepts utilized in buildings as well as their development and application in the processes of heating, ventilation, thermal isolation, shading, electricity generation, and lighting of buildings. The accuracy of calculation of the passive solar building performance is crucial for more precise prediction. Based on an overview of related literature sources, this paper puts forward the major numerical methods for studying the passive solar building, which can be grouped into the heat balance model and computational fluid dynamics (CFD). Additionally, it not only discusses various assessment methods to perform passive solar building but also presents related research using each method. Finally, discussion, conclusions, and fields of further research are given. This paper can be utilized as a reference for academic research and contributes to an increased understanding of passive solar building for related designers.

Types of Passive Solar Systems

Over the past few years, various types of passive solar systems for space conditioning (heating, ventilation, cooling, daylight, and electricity) have been modified or proposed to improve energy efficiency and comfort levels in buildings. Passive systems consist of key components, such as glazing, absorber, storage, and the space to be heated or cooled. The manner in which these components are arranged determines the generic passive system type. This paper discusses seven generic passive systems: direct heat gains, double-skin façade (DSF), thermal storage wall, solar chimney, sunspace, roof ponds, and building integrated photovoltaic/thermal system (BIPV/T). Although there are extensive academic researches on the above passive solar systems, this review is necessarily limited. Thus, the most pertinent content of the studies on each system is presented in this review.

Direct Heat Gains

This is a straightforward passive design which admits sunlight directly into the space for thermal heating. Also, a direct gain system plays a vital role in providing the path for visual and psychological communication with the outside environment. The position of the aperture in building envelope may be on the wall, clerestory, and roof, and it is typically based on several factors such as experience, satisfaction of user needs, noise source, and building regulations. For the application of passive solar heating, the south wall is a preferred orientation (north facing in the southern hemisphere). In general, the shapes and sizes are chosen according to the preliminary assessment of daylight and view needs.

A common example of direct gain system is a south wall with a number of windows admitting insolation into the building space and onto the floor or other walls. Beyond that, the design of the windows should consider several factors that affect performance and indoor environment, such as net heat transfer, net transmitted solar radiation, day-lighting effectiveness, and aesthetic value. For the sake of passive solar heating, windows with low U-value to reduce the heat loss and high total solar energy transmittance to increase the heat gains are preferred, such as vacuum glazing and low emissivity (low-e) coatings. Besides, a balance should be made between U-value and the solar heat gain coefficient (SHGC) because the most likely measure to reduce U-value is to lower the solar transmission [1]. For example, Elin Hammarberg and Arne Roos proposed a method called antireflection treatment with silicon dioxide (SiO_2) to improve the visible transmittance of the low-e glazing [2]. The measured percentage increase of the integrated visible transmittance was 9.8%, and a transmittance value of 0.915 was achieved. Without decreasing the visibility significantly, this method could enable the usage of antireflection treated low-e glazing in the construction of triple glazing unit windows to have desirable U-value. However, the above windows for spacing heating application are undesirable in cooling seasons when such windows are often double glazed with the exterior pane tinted. Moreover, selective absorption rejects part of the solar radiation and reduces the solar heat gain. Furthermore, D.Feuermann et al. [3] studied the reversible low solar heat gain windows. Indeed, the windows that can be reversed according to the seasons will not only reduce summer heat gains but also collect much of the beneficial solar radiation in winter.

Some methods of controlling heat gains, loss, and daylight at various times of the day and year are common, such as insulation for the windows in the night, utilization of thermal storage in the floors or walls, and shading devices (e.g., curtains, overhangs, and venetian blinds). In the selection of shading devices for windows, it is of great necessity to consider several conflicts, such as blocking the direct sunlight before it reaches the building interior to reduce the cooling loads in the cooling season, while allowing the maximum amount of solar radiation into the building interior during the heating season. Thus, adjustable devices that can be lifted or rolled either automatically or manually may be a preferable choice. Ahmed A.Y.Freewan [4] examined the effect of using shading devices on air temperature, visual environment, and users' interaction in offices located in hot climate. As shown by the results, after the use of the shading devices, the temperature in offices was reduced to acceptable level, and the visual environment was improved by controlling the illuminance level, improving uniformity, and eliminating glare. The area of the room thus heated tends to get very hot in the day, and the swing in the room temperature is usually high unless storage media is provided in the direct gain system. Additionally, Balcomb et al. [5] studied the influence of the insulation, number of glazing layers, as well as placement and type of thermal storage on the direct gain system. As revealed by the preliminary results, the percentage of solar annual heating with the same storage heat capacity for single glazed system, double glazed system, single glazed system with night insulations, and double glazed system with night insulation was about 10, 65, 80, and 90%, respectively. Moreover, a performance comparable was observed between a conventional active solar heating system and the double glazed system with night insulation [5].

Double-Skin Façade

Modern buildings, especially the office buildings equipped with the heating, ventilation and air-conditioning (HVAC) systems, often suffer from the "sick building syndrome" due to insufficient ventilation. Under such context, the concept of double-skin façade (DSF) was introduced based on the single-skin façade. If such façade system is well designed, it can not only provide good indoor air quality but also efficiently reduce the overall HVAC consumption. Moreover, the use of DSF is conductive to improving the acoustic characteristics and daylighting of building interior. Among the passive solar system, the DSFs have become a common feature of architectural competitions, especially office buildings in Europe [6]. The structure of the DSF is based on a single-skin façade (window), and the second "skin" which is usually made of glass is placed in front of the window. The air space in between (the channel) is rather important and can be mechanically or naturally ventilated to improve the thermal performance of the building [7]. Air in the channel is warmed up by the solar radiation and discharged to the outside environment from the top of the channel through stack effect. What is more, the DSF can work under different modes according to users' needs and weather conditions. In the summer, high-temperature air in the channel is exhausted to reduce cooling load. In the winter, all the openings are closed to protect heat escaping from the inside building, or the part openings are opened to collect the heat for space heating. In the mild seasons, the DSF is often used to promote natural ventilation of the occupants' space. Figure 1 shows the working modes of the DSF under different seasons.

It is a common practice to equip fixed and manually or automatically controlled shading device within the channel between two layers of the façade such as roller shades and louvered blinds [8]. The above sunshade devices can regulate the transmitted solar radiation into building interior. As a consequence, it will be able to control the daylight and the heat gains of the room. The majority of researches on the shading devices focus on the three aspects: position in the channel, blind tilt angle, and color of the materials. For example, Safer et al. [7] examined the influence of three distinct blind positions on the airflow development: (i) blind close to the external glazing, (ii) blind in the middle of the channel, and (iii) blind close to the inner glazing. The results showed that from the standpoint of the external ventilation, the blind which is close to the inner glazing seems to be the most appropriate solution. Also, Gratia and De Herde [9] as well as Jiru et al. [10] carried out similar studies and found that the positions of the blind could influence the temperature of the inner layer. With regard to

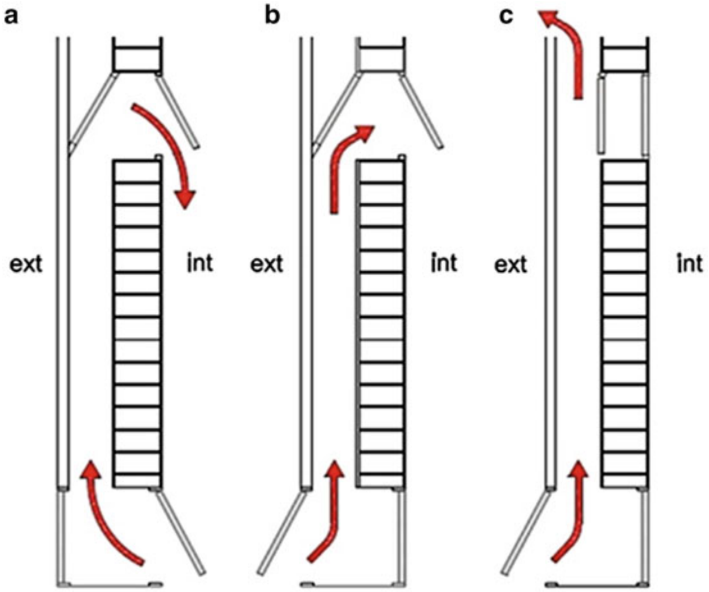


Fig. 1 Different operational modes of a ventilated DSF

the blinds placed in the middle of the cavity, the thermo circulation was well established with air flowing on both sides of the blinds. Furthermore, Iyi et al. [11] analyzed the effect of blind angles (30°, 45°, 60°, 75°) on the heat gain which is caused by directly transmitted solar radiation and convection through the facades to the internal space. It had been concluded that the presence of the solar blinds could significantly reduce the heat gain through transmitted solar radiation. With closing the solar blockages (30°), heat transfer to the building can be minimized to about 85% of the incoming solar energy. Regarding the color of the blind materials, the channel temperature with dark blind was higher than that with white blind [12]. Apart from the above research on the effect of shading devices, there are many reviews related to ventilated DSF in other aspects, such as the availability of computational models [13], the existing research methods used to study its performance [14], and the advances in its design [15, 16]. Furthermore, some studies focus on the special aspects such as daylighting [17, 18], condensation [19], smoke escape, [20] and plants within the channel [21].

Thermal Storage Wall (Trombe Wall)

In spite of the storage provided in the direct gain system, the oscillations in the room temperature are usually higher than the designed levels. A more effective method to reduce the swing in the room temperature is to place a thermal storage wall directly behind south-facing glazing (north-facing in the southern hemisphere), and the

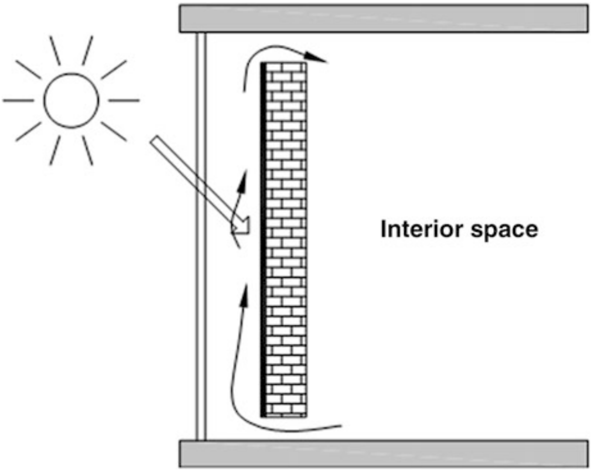


Fig. 2 Schematic of a classic Trombe wall

channel is left between the wall and glass. It was first patented by E.S. Morse in 1881 and later redesigned and re-patented in 1957 by Félix Trombe and Jacques Michel. The thermal storage wall, also known as “Trombe wall,” is a simple configuration which can accumulate the solar energy and provide heating for the interior space. As a popular indirect heat gain concept, the exterior surface of the Trombe wall is usually painted dark to maximize the absorption of solar radiation.

Classic Trombe Wall

The classic Trombe wall can not only catch solar radiation using greenhouse effect created in a glazed channel but also absorb and store heat using a massive wall. Part of the energy is transferred into the building (the room) through the wall by conduction. Meanwhile, cool air is sucked into the channel from the opening at floor level, is heated up by the wall, and flows upward due to buoyancy effect. Then, the warm air returns to the room through the opening at ceiling level. Besides, heat exchange of Trombe wall with the indoor environment is partly by transmission through the wall and partly by ventilation through the vents. Other than the use of the Trombe wall for space heating, two openings are installed at the exterior glazing for summer cooling. Namely, the upper opening at the wall and the lower opening at the glazing are closed, and the driving force generated by the buoyancy effect draws the room air from the lower vent at the wall, and the heated air is then expelled out of the upper opening at the glazing. The operating modes of the classic Trombe wall for space heating and cooling can be shown in Fig. 2.

The advantage of the classic Trombe wall is its simplicity. However, it also has a few shortcomings:

- **Low thermal resistance:** During the night or prolonged cloudy periods, some heat flux is transferred from the inside to the outside, leading to excessive heat loss from the building.

- **Excessive heat gains:** In the hot summer, the massive wall painted black may absorb unwanted soar energy and thereby increase the cooling load of the building.
- **Uncertain heat transfer in Trombe walls**: The amount of heat gains is unpredictable due to variations in solar intensity.
- **Low aesthetic value:** The black surface makes the classic Trombe walls not sufficiently beautiful.

Trombe-Michel Wall

Insulating the glazing and the storage mass are two common methods to increase the thermal resistance of the classic Trombe wall. Additionally, a low-e coating on a spandrel glass can be used to minimize the radiative losses to the exterior. A composite Trombe wall, also known as the Trombe-Michel wall, was proposed. It consists of several layers, including a transparent outer cover, an enclosed air channel, a storage wall, a ventilated air layer, and an insulation layer (see Fig. 3). It works as follows. To be specific, 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 the outside to the interior air layer by conduction through the massive wall. Then, while using the thermo-circulation phenomenon of air between the massive wall and the insulating wall, it can be transferred by convection. In addition, a small portion of the energy is transmitted by conduction from the wall into the room. In consequence, nearly all the supply is provided to the building via the ventilated air layer. Due to extremely high thermal resistance of this design (the existence of the insulation layer and the air layers), there is little thermal flux that goes from indoor to outdoor. Moreover, users can control the heating rate at all times

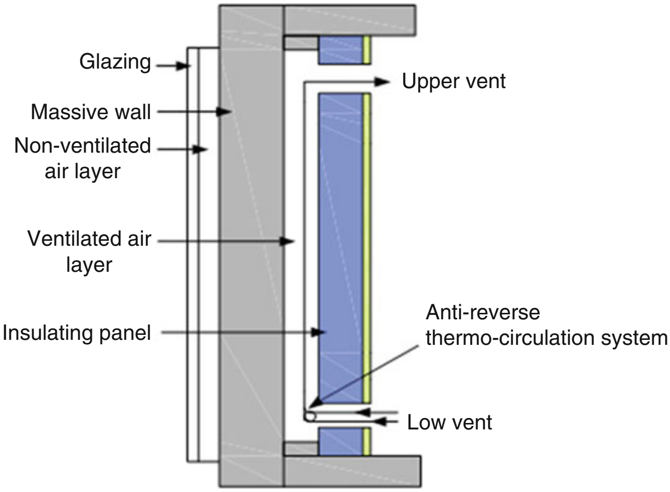


Fig. 3 A composite Trombe wall

by adjusting the air circulation. However, this type of Trombe wall cannot avoid the reverse thermo circulation of a classic Trombe wall, and a mechanism is needed to prevent it.

PV-Trombe Wall

Another invented type of Trombe wall is a PV-Trombe wall concept that attaches crystalline silicon (c-Si) solar cells on the rear side of the glazing (Fig. 4a, PVGTW). Since the unwanted thermal energy is removed by the airflow within the channel, the temperature of PV cells decreases, and the electrical efficiency increases. The PV-Trombe wall can provide space heating, generate electricity, and bring more aesthetic value. Beyond that, the opaque c-Si solar cells on the glazing hinder the penetration of the sun's rays into the air channel, and the heat gain of the massive wall facing the gazing is thereby reduced in summer. However, due to the use of the opaque c-Si solar cells, the thermal efficiency of the PV-Trombe wall is reduced significantly in the winter. To account for this, the semitransparent amorphous silicon (a-Si) solar cell is used to replace the opaque crystalline silicon (c-Si) solar cell on the glazing of the PV-Trombe wall system, and a fraction of solar radiation can be transmitted to the massive wall. Although this approach has indeed improved the thermal efficiency of PV-Trombe wall, the electrical efficiency of the system is undesirable because a-Si cells generally feature low efficiency. As illustrated in Fig. 4b, c, another two different configurations of PV-Trombe walls are developed based on the above results: one with the PV cells attached to massive wall (PVMTW) and the other with the PV cells integrated on the blind slats (PVBTW). These two configurations enable the solar radiation to totally penetrate the glass cover and enter the Trombe wall channel. Nonetheless, the former PV-Trombe wall

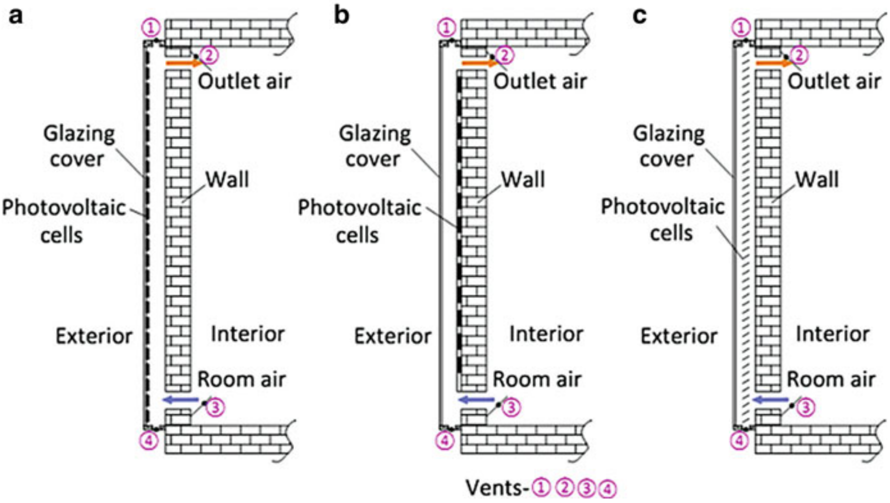


Fig. 4 Schematic of the three types of BIPV Trombe wall systems (**a**) BIPVGTW, (**b**) BIPVMTW, and (**c**) BIPVBTW [45]

(the combined PV cells and massive wall as a link wall) has undesirable electricity generation due to the shadow from frame border and the high temperature of solar cells. The later PV-Trombe wall (PV cells integrated on the blind slats) is characterized by the high thermal efficiency because of the good heat transfer between the blinds and air within the channel. On the other hand, the electric power can be obtained through the adjustable PV blinds. Thus, Trombe wall combined with PV blind is a promising alternative due to its high competitive ability in spacing heating, electric output, and the architectural acceptance of energy self-supplying buildings. The abovementioned configurations of PV-Trombe walls are shown in Fig. 4.

Water Wall

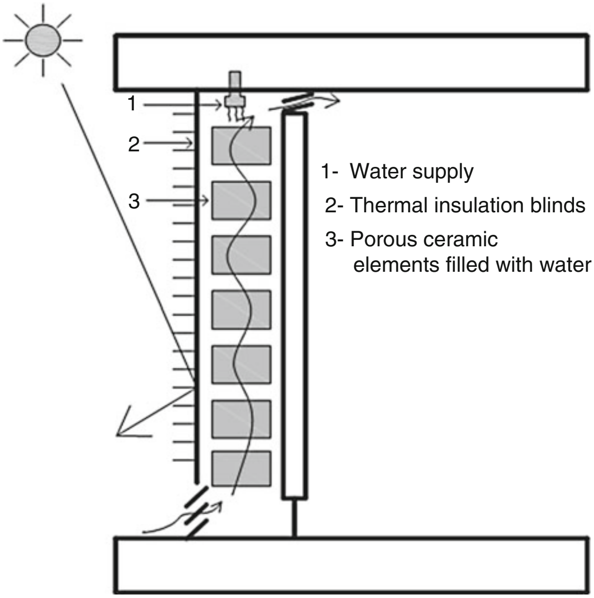
Typically speaking, the massive wall is made of the common building materials such as stone, bricks, and concrete or some materials. Another innovative design of Trombe wall is water wall which uses water to replace the bricks. In general, the exterior surface of the water container is painted black to increase the absorption of solar radiation. The solar radiation after transmission through the transparent glazing is absorbed by the black water container. Then, the water distributes the heat through convection, and therefore heat can be transferred into the living space faster than the classic Trombe wall. Due to the higher heat capacity of water, the water temperature does not rise as high as that of the masonry. Thus, less heat is reflected back through the glazing. Moreover, water wall can more effectively reduce the room temperature fluctuation and the overheating in summer. Despite these advantages, this type of Trombe wall does not earn the favor of building stakeholders due to the rusting and leakage of the water container. There is way that the water container can be used directly as the absorbed wall. By contrast, the water tubes embedded in the brick wall may be a preferable choice. Water naturally circulates in an array of vertical tubes, and the heated water can be used for space heating by different ways (e.g., floor heating, wall heating, and roof heating).

Similar to the water wall, another Trombe wall called ceramic evaporative cooling wall was designed, and clear water is used within it (Fig. 5). The porous ceramic element filled with 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 can function as a cooling chamber to cool down the outside air temperature due to the direct evaporative cooling phenomenon.

Trombe Wall with PCM

Apart from these common practical methods to store the solar gain (i.e., sensible heat storage), the absorbed solar energy can be stored as the latent heat of the phase change. Thus, another popular Trombe wall called “Trombe wall with phase change material (PCM)” is developed. Specifically, PCM is a substance with a high heat of fusion which can melt and solidify at a certain temperature. When the PCMs change from solid to liquid, large amounts of energy will be absorbed or released and vice versa. The structure of the PCM Trombe wall is identical to that of classic Trombe wall, yet the only difference is that “the PCMs are used in the massive wall.” The

Fig. 5 Ceramic evaporative cooling wall



PCM wall absorbs solar radiation during the day. Like the conventional sensible heat storage materials, its temperature will rise. However, when the PCM reaches the melting temperature, it will absorb amounts of thermal energy at an almost constant temperature. What is more, the PCM wall continues to absorb solar energy without a significant temperature rise until all solid PCMs are transferred to the liquid phase. In the night, as the temperature of the liquid PCMs falls with the reduced temperature within the channel, the PCMs will solidify and meanwhile release the stored energy into the interior space through the wall conductivity.

In conclusion, for a given amount of heat storage, the PCM units need less space than massive Trombe wall and are also much lighter in weight. Additionally, heat storage and recovery of the PCMs occur isothermally, which can help achieve thermal comfort. The main defect of the PCM Trombe wall is that the lower thermal conductivity of the PCMs results in the lower thermal efficiency. The methods, such as the use of fans or vortex generator, are therefore employed to enhance the PCM Trombe wall efficiency.

Transwall

As mentioned above, the Trombe walls can block the solar radiation from the southern side and provide the illumination for building interior. Fuchs and McClelland [46] proposed the concept of a transwall, which can not only achieve storage effect but also provide the illumination in the dwelling space (Fig. 6). The transwall consists of water enclosed between two parallel glass panes supported in a metal frame. Besides, a semitransparent absorbing plate is positioned between the parallel glass panes. Part of the incident solar radiation is absorbed within the

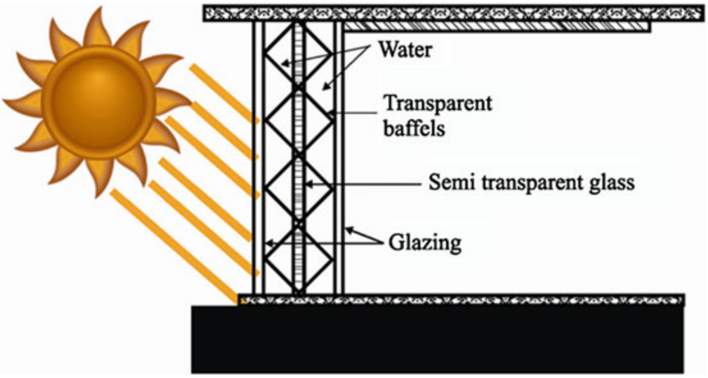


Fig. 6 A cross-sectional view of Transwall system [46]

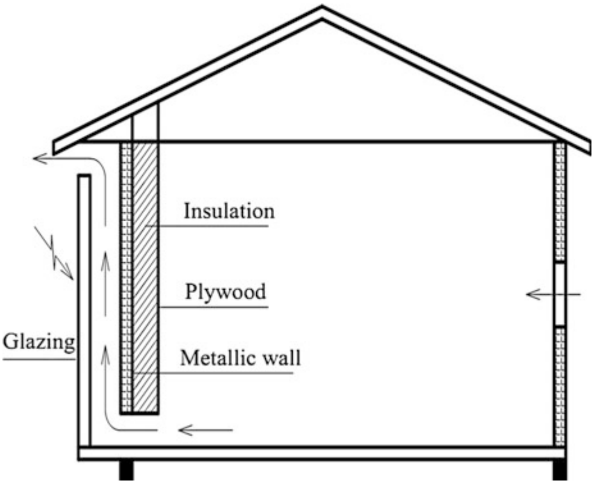
transwall, and the remaining part contributes to the illumination in the indoor space. Trombe walls are mainly used in cold and mild climates for space heating and cooling. Recently, some literatures have introduced a few novel Trombe walls that can be used for removal of formaldehyde [22] and humidification [23]. This paper will not describe them in detail.

Solar Chimney

Solar chimneys are often employed for natural cooling, and it has the same working principle as the Trombe wall. Namely, the driving force, which creates an air updraft within the air channel, is the density difference of air at inlet and outlet of the chimney. The structure of a solar chimney includes an internal wall, an air channel, and a glazing cover. Moreover, the glazing cover may be transparent or opaque. A solar chimney in building could be integrated on the wall or on the roof, as shown in Figs. 7 and 8. When the solar chimney is attached to the vertical wall, the working mode is similar to a Trombe wall. It provides warm air which is heated up by the glazing cover and absorbed into the room. For mild climate, the chimney can function as passive cooling where natural ventilation is applied. For hot climate, when the outdoor temperature is higher than the indoor temperature, it operates as thermal insulation to reduce heat gain of the room. These three operating modes can be presented in Fig. 9.

Macias et al. [24] studied a passive night cooling system that was developed and implemented for a new social housing project. This passive cooling system incorporates a solar chimney in combination with high thermal mass in the building construction. The natural ventilation is enhanced with the help of the solar chimney, and meanwhile night fresh air cools the building structure. Figure 10 shows a picture of the west façade with the solar chimney of the buildings. Punyasompun et al. [25] carried out comparative experiments on the two design configurations of the solar chimney, including the connected and non-connected solar chimney (Fig. 11). The former is a tall solar chimney with an inlet opening at each floor and an outlet

Fig. 7 Schematic of a solar chimney integrated on the vertical wall



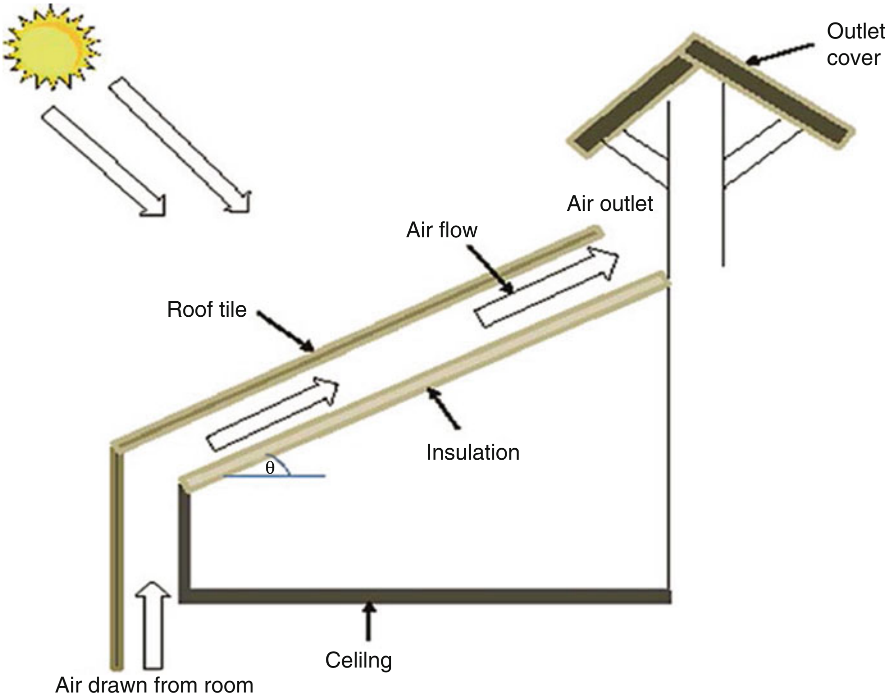


Fig. 8 Schematic of an inclined roof solar chimney

opening at the third floor (combined solar chimney). However, for the latter, the inlet and outlet openings were installed at each floor (separated solar chimney). The comparison between these two solar chimney configurations shows that, the

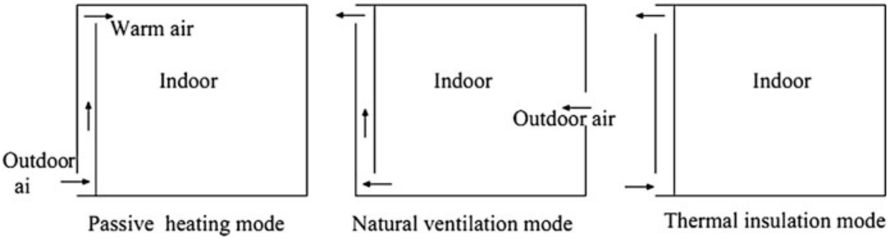


Fig. 9 Different operating modes of a solar chimney

Fig. 10 West facade with solar chimneys of the building [24]

recommended configuration is the combined solar chimney with an inlet opening at each floor and an outlet opening at the third floor. Therefore, multi-storey solar chimney is an interesting option, which could be applied for hot climate to save energy and environment.

The angle of the glazing can influence the solar radiation casted on the solar chimney and in turn affect the thermal performance of the chimney. Although the vertical solar chimney is simple, its aesthetic value is questionable compared to the solar chimney integrated in the roof structure. To that end, inclined solar chimney has been developed as an effective design strategy. Especially for the buildings with gable roofs, the solar chimneys can be well integrated as part of the roof components to minimize the fraction of the solar flux absorbed by the roof and induce natural ventilation. However, only a solar chimney system has little potential in inducing sufficient natural ventilation to

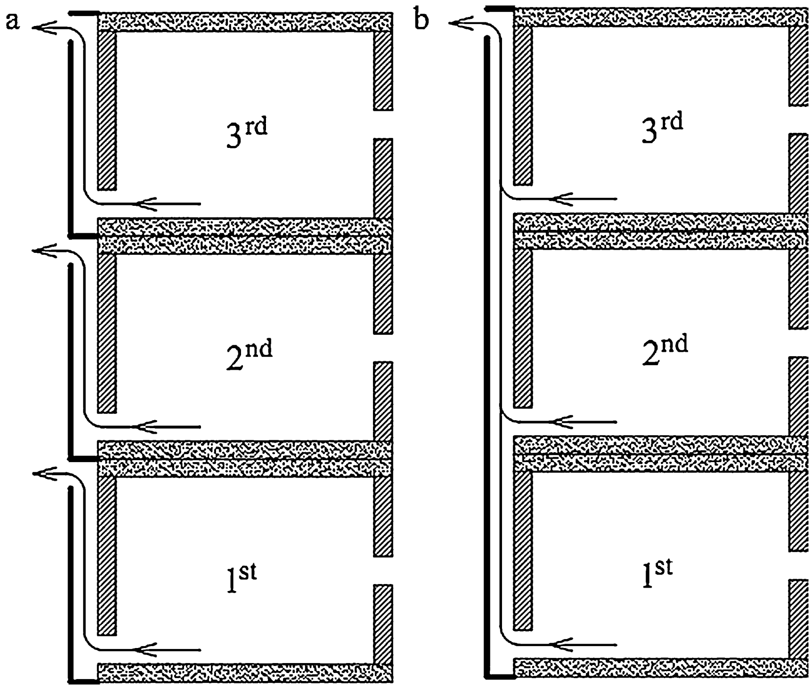


Fig. 11 Multi-solar chimney configurations (**a**) separated solar chimney. (**b**) Combined solar chimney [25]

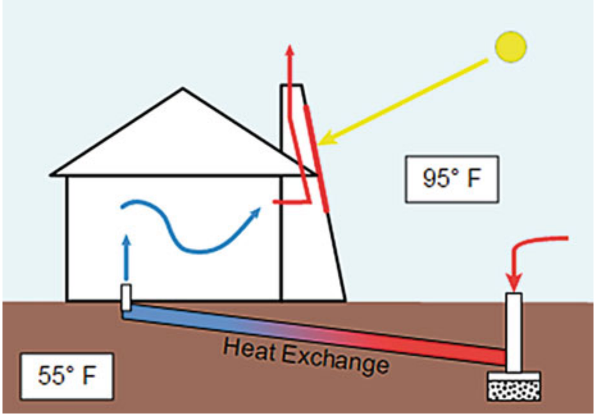
satisfy indoor thermal comfort. For a greater ventilation effect, it is essential to apply a combination of both types (wall and roof solar chimney).

There are a number of solar chimney variations. The basic design elements of a solar chimney are as follows:

- **The solar collector area:** The orientation, glazing type, insulation, and thermal properties of this element are crucial for harnessing, retaining, and utilizing solar gains.
- **The inlet and outlet air apertures:** The sizes, location, and aerodynamic aspects of these elements are also of great significance.
- **The main ventilation shaft:** The location, height, cross section, and the thermal properties of this structure are also very important.

Due to the internal gains and heat transmission through the wall and roof, daytime ventilation is usually required to improve the indoor air quality and to remove the heat. What is more, the outdoor air can be induced into buildings by solar chimneys. However, if the outdoor air temperature exceeds the thermal comfort limit, it is necessary to precool the temperature before it enters the living space to further maximize the cooling effect. Many natural means, such as evaporative cooling and

Fig. 12 Schematic diagram of integrated geothermal heat exchanger and solar chimney



ground cooling, can be used to precool the external air. Figure 12 is a passive solar system comprising of solar chimneys and a geothermal heat exchanger. When the air inside the chimney is heated, it rises and pulls the cool air out from under the ground via the buried heat exchange tube. This system realizes both cooling and ventilation during the daytime with the help of solar energy. The geothermal heat exchanger consists of horizontal long pipes that are buried under the bare surface at a specific depth. A depth of 2–3 m is generally considered since at that depth, the tube is cooler than the outside in summer.

Roof Ponds

Unlike the above described Trombe wall, roof ponds store thermal energy in the roof, rather than on the south-facing wall. When it comes to implementation of passive techniques, roof is often considered as the most important one among different elements of building envelope. This is because roof is the most exposed part of a building to the sky, and also related study proved that roof alone can be responsible for up to 50% of heat load in single-story building during the summer [26]. The conventional approaches to reduce the heat flux via roof include roof shading, false ceiling, insulation, increasing roof thickness, or spraying and flowing water over the roof. Roof ponds, which use water as thermal mass, represent a promising passive measure. It provides cooling benefits via indirect evaporative cooling and/or radiant cooling. In both processes, the roof serves as a heat exchanging element that is cooled by evaporation on its surface, nocturnal radiation to the sky, or both. The indoor space is then cooled by the ceiling coupled to the roof through radiation and convection. The driving force for the water evaporation and long-wave radiation are, respectively, the "difference between vapor pressure at water surface temperature and vapor pressure of surrounding air" as well as the "difference between water surface temperature and effective sky temperature." Since the heat exchange between indoor air and water is separated by the roof, roof ponds

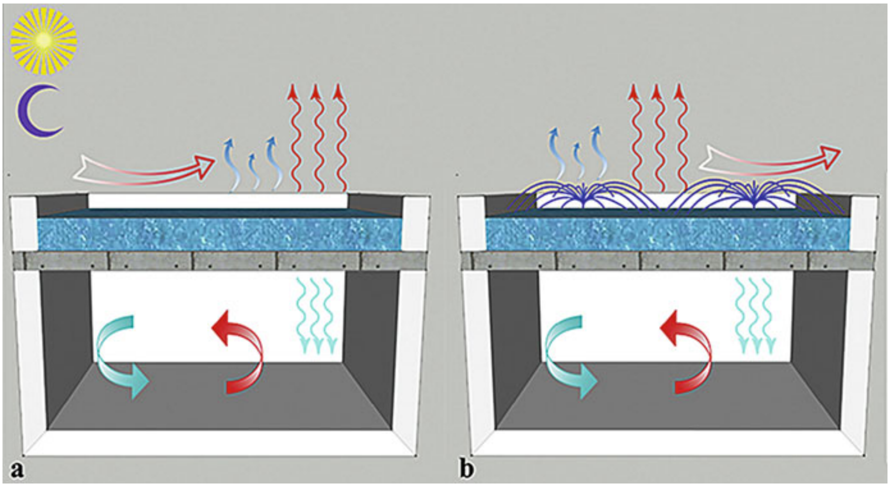


Fig. 13 (**a**) Open roof pond without sprays and (**b**) open roof pond with sprays [27]

cooling does not introduce additional moisture. During the day, the roof pond is exposed to direct solar radiation, which allows the solar energy to be absorbed and stored by water and roof. At night, the stored energy is then transferred to the ceiling by conduction and, finally, enters indoor space through radiation and convection.

Harold Hay and his colleagues invented roof pond in the late 1960s. Nowadays, different roof pond variants have been developed for heating and cooling purposes. In this section, roof ponds are categorized into six groups: open roof ponds, roof ponds with movable insulation, roof ponds with floating insulation, walkable roof ponds, shaded roof ponds, and ventilated roof ponds. The described roof ponds are mainly used for space cooling, and some of the above roof ponds can be applied for both cooling and heating.

Open Roof Ponds

As shown in Fig. 13, an open roof pond is usually supported by a concrete flat roof, and it has two types: (1) open roof pond without sprays and (2) open roof pond with sprays. Open roof pond without spraying system is the simplest roof pond structure exposed to the ambient (Fig. 13a). During daytime hours, part of solar radiation is absorbed and stored into the water before entering into the room. The relatively large heat capacity of water enables the indoor peak temperature to appear in the late afternoon hours when the ambient temperature is already cooler. In this way, it is easier to achieve thermal comfort using other passive techniques, such as natural ventilation. Additionally, in the above process, the roof pond tends to be increased until the additional heat gains are compensated by spontaneous evaporative effect of a certain amount of water, which causes the cooling effect. Part of the heat gains from solar radiation is absorbed in the flat roof. The heat absorbed by the dark surface of the roof is inversely proportional to the bottom reflectance. As illustrated in Fig. 13b, “open roof pond with spraying system” has a configuration and thermal behavior similar to that of the “open roof without sprays.” The only difference is that spraying system operates during day and night to enhance heat absorption and evaporative cooling effect. When the water temperature is 3–4 °C higher than the ambient wet bulb temperature, the spraying system is usually closed to avoid the pond warming. Although the configuration of open roof ponds is simple and preferable, the disadvantage of this system is the susceptibleness to fouling from windblown dust, leaves, bird droppings, algae, and mosquito larvae.

Roof Ponds with Movable Insulation

These roof pond variants are assumed to be covered with movable insulation with or without sprays, as indicated in Fig. 14. Besides, cover and sprays are operated independently. The supporting roof can be concrete or metal deck. In the 1960s, Hay invented the “metal roof pond with movable insulation” – “skytherm.” The metal deck can not only provide better thermal coupling with the interior space but also enhance nocturnal radiative cooling effect, while its corrugated form increases the area exposed to the sky. Another difference is that in the skytherm, the water is enclosed to bags. Cooled water bags of the skytherm transfer coolness into the building through the roof. Roof ponds with movable insulation can provide not only the space cooling but also the heating effect. For the cooling effect, the opaque insulation is in place to protect the water pool against indirect solar radiation during the day. In the night, the insulation is removed to reduce the water and roof temperature by the convection with the ambient air and the radiation to the night sky. Besides, the night cooling effect can be increased by the spraying system. The system can be used with inverted operation in winter for heating. That is to say, the insulation panels are opened during the daytime to absorb solar heat and closed at night to prevent heat loss. An air gap between the water surface and the top cover can be designed to function as an additional insulation layer.

Roof Ponds with Floating Insulation

These variants include two different configurations of roof ponds that use floating insulation to regulate amount of heat exchange with the exterior environment. The first pond variant is energy roof, which was invented by Pittinger in 1976. As shown in Fig. 15a, this system is supported by a corrugated metal deck, and the insulation panel floats on the water under a thin and transparent plastic film. For summer cooling, the water is pumped at night to transfer a thin layer of water into the upper shallow water chamber and cool the system through long-wave radiation at night. During the daytime, the floating insulation panel can reduce heat gains from solar radiation. The other type of roof pond with floating insulation is cool roof, which was patented by Richard Bourne and David Springer in 1992 (Fig. 15b). This pond is placed above a concrete roof deck covered with an impermeable and floating insulation panel. At night, the water is sprayed on the exterior surface of the floating insulation through a pump. During the daytime hours, the cooled water is flowed back into the pond to cool the roof through heat exchange with building interior.

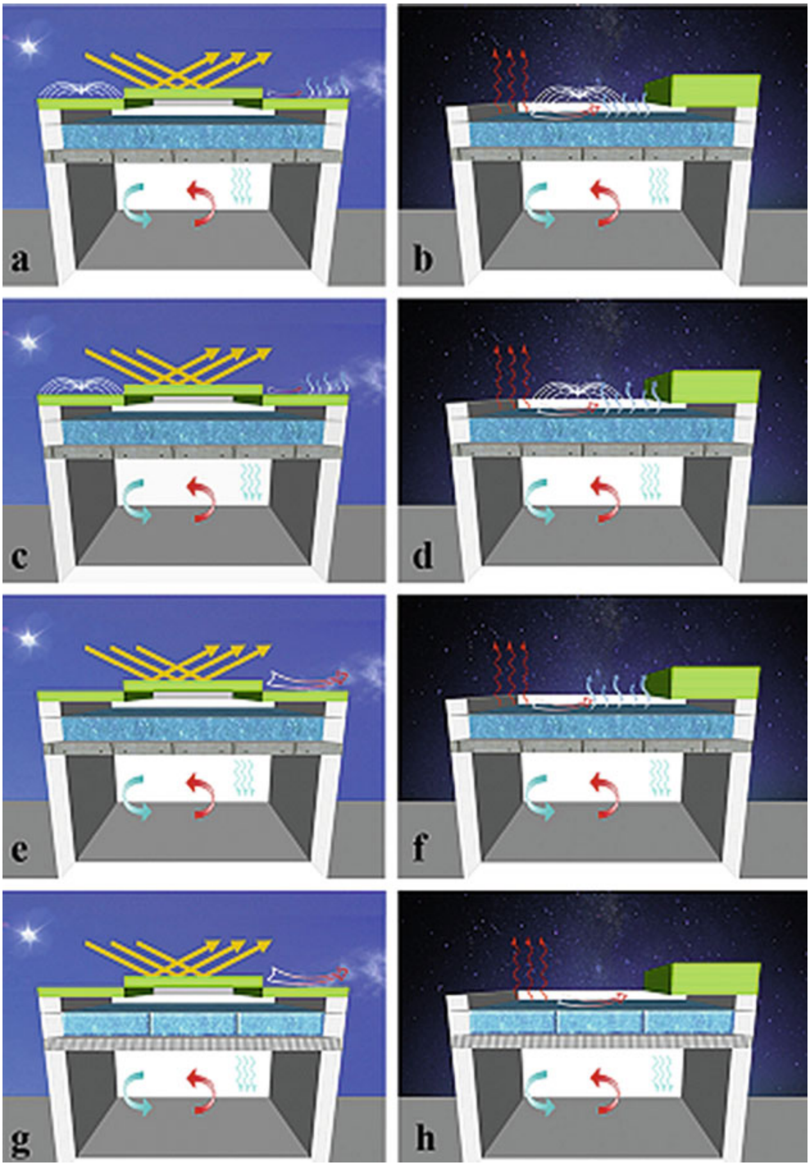


Fig. 14 (**a** and **b**) Roof pond with movable insulation and continuous water spray; (**c** and **d**) roof pond with movable insulation and nighttime water spray; (**e** and **f**) roof pond with movable insulation, without water spray; and (**g** and **h**) Skytherm [27]

Walkable Roof Ponds

These types of roof ponds allow walking over the roof surface without effects on the functionality of the roof pond system below (Fig. 16). The system is especially suitable for the buildings with reinforced concrete flat roof. The insulation panel is

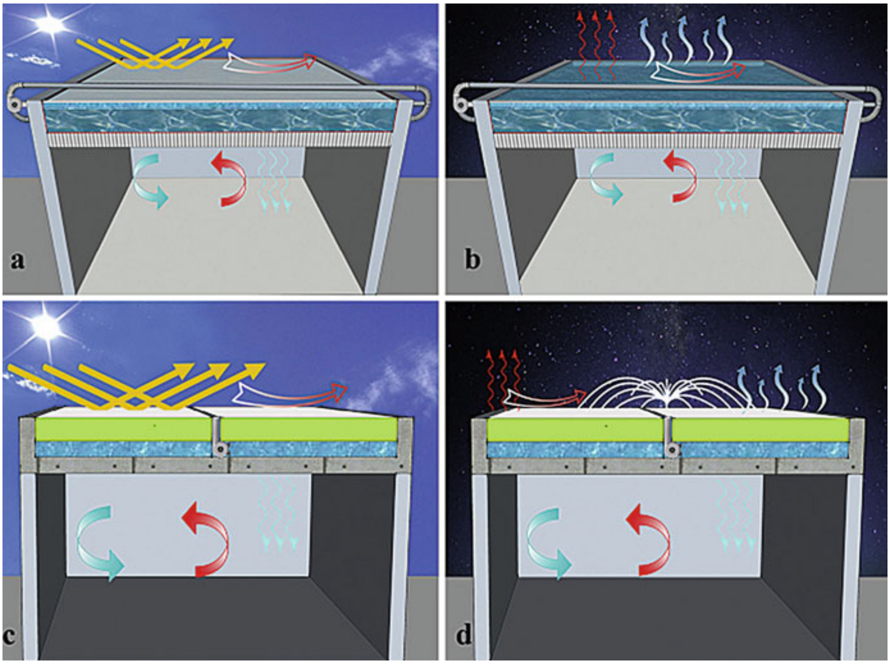


Fig. 15 (**a** and **b**) Energy roof; (**c** and **d**) cool roof [27]

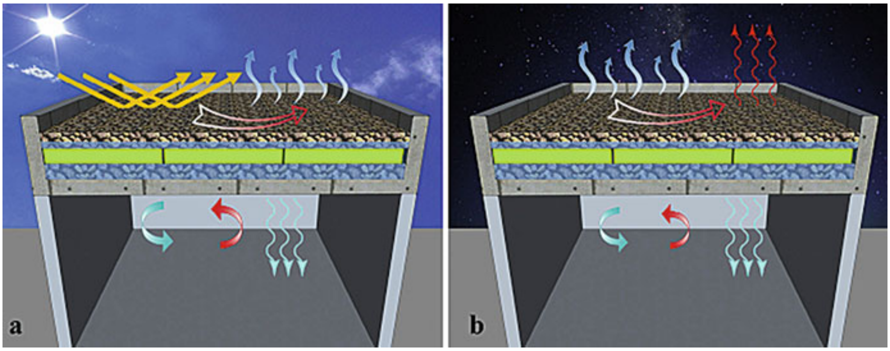


Fig. 16 (**a** and **b**) Walkable roof pond with insulation embedded within the pond [27]

embedded within the pond. In the summer, the pond is filled with water to a level about 0.03 m above the insulation. Also, the water is divided into two layers by the insulation with gaps allowing “thermosiphonic circulation.”

Shaded Roof Ponds

In this variant, the pond is covered by a structure similar to the venetian blind that can intercept direct solar radiation (Fig. 17a, b). These louvers, which are

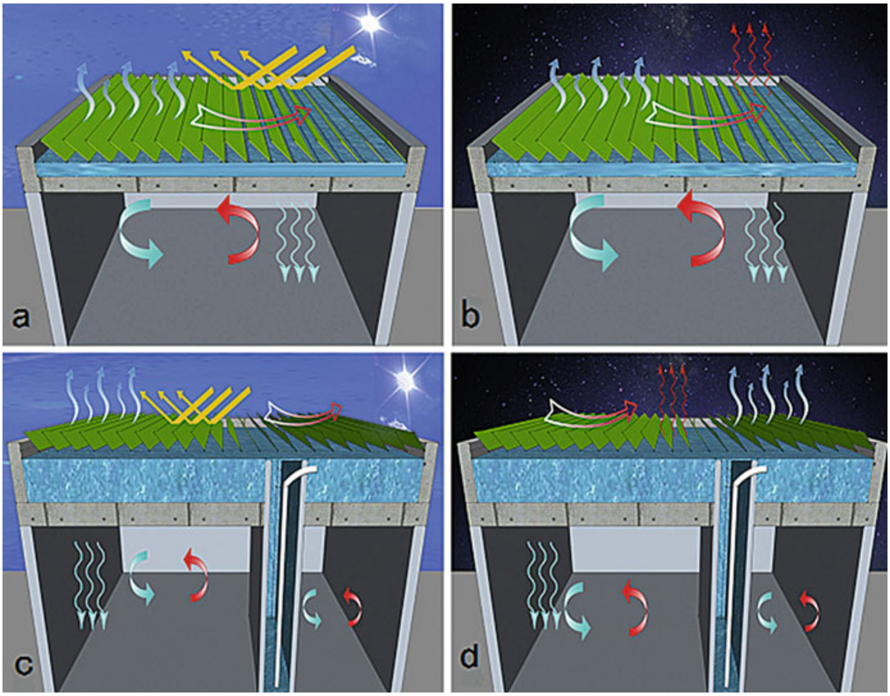


Fig. 17 (**a** and **b**) Shaded pond without water spray; (**c** and **d**) cool pool [27]

permanently integrated into the roof pond, can be fixed or operable. To be specific, the operable louvers are closed during the daytime hours to minimize solar heat gain and opened at night to provide evaporative and radiative cooling. For the fixed ones, the louver plates are designed to allow some nocturnal radiation and meanwhile block diurnal direct solar radiation. The system can be equipped with or without sprays. Additionally, the shaded pond can be coupled with vertical water tubes in the building below, and this pond variant is also called "cool pool" (Fig. 17c, d). In the cool pool, the cooled water is pumped to a storage tube in the space below and warmed by thermal exchange with indoor air. Then, it rises back to the pool again. Compared with the conventional flat shaded roof pond, the cool pool may need higher maintenance costs. The advantage of the cool pool is low water consumption.

Ventilated Roof Ponds

This variant is covered by a permanent insulation panel which has been well separated from the water level by a ventilated air layer (Fig. 18). As the system is covered by highly reflective metal sheets, the radiant cooling potential is lost, and cooling can only be achieved via convection and evaporation. In order to reduce water temperature and enhance evaporation, fans usually are employed in the inlet

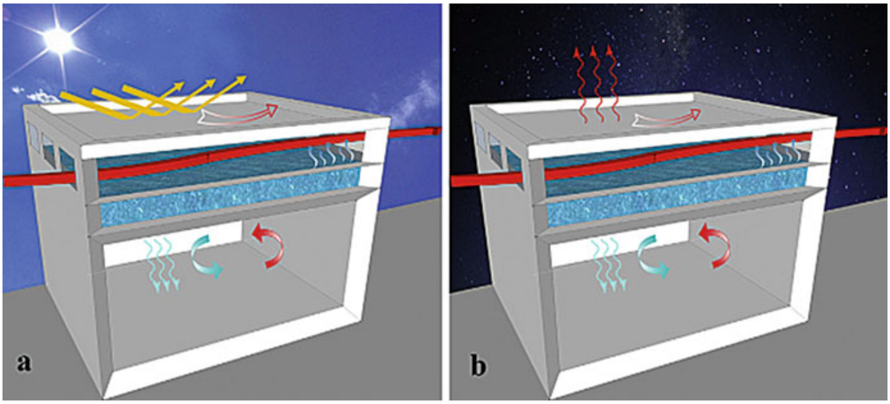


Fig. 18 Ventilated roof pond [27]

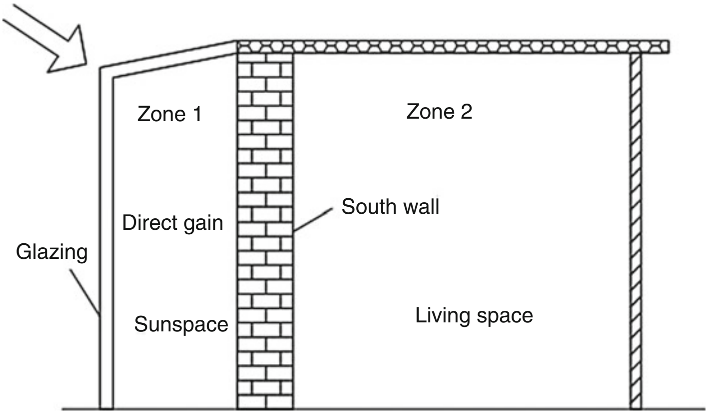


Fig. 19 Cross-sectional view of passive solar house with a sunspace

or/and outlet. Notably, although mechanical control (fans) is used to enhance the cooling effect of the roof ponds, the energy consumption amount is very small. Hence, the ventilated roof ponds can be regarded as passive techniques.

Sunspace

This concept, also known as solarium and green house, was proposed by Balcomb [5]. Sunspace is a combination of two concepts, including direct gain and thermal storage wall system. As shown in Fig. 19, the simplest configuration of the sunspace is composed of a lean-to type greenhouse enclosed by glass, a thermal storage wall on the south side (for northern hemisphere), and a living space. The greenhouse receives heat by direct gain, and the excessive heat gain from the greenhouse is allowed to enter into the living space through the thermal storage wall. When it is integrated to new or existing buildings, the attached solarium can achieve additional flat space that will be used for recreation or growth of vegetables and plants. The greenhouse is separated from the living space by the thermal wall, and the rate of heat transfer by conduction from the greenhouse to the living space is small. Therefore, such design can not only greatly reduce temperature swings in the living space but also avoid glare compared to direct heat gain concept. If more control over the temperature in the greenhouse is desired, large quantities of thermal mass should be added to the greenhouse. To trap the heat gained during the day in the sunspace, in winter night, the large glazed area is usually equipped with removable insulation which can also control the solar gain in summer.

Building Integrated Photovoltaic (BIPV) System

In general, solar energy is utilized in two different ways: one is through solar thermal route using windows, Trombe wall, roof ponds, etc., while the other is solar electricity using solar photovoltaic (PV). Solar photovoltaic technology, which uses the photovoltaic effect of semiconducting materials, is one of the simplest methods of converting solar energy into electricity. It is also a direct conversion of sunlight into electricity without using any interface. Therefore, solar PV has specific advantages as an energy source, such as no pollution, no noise, and no greenhouse gas emission. The exhibited strengths of the PV accommodate not only the increasing energy requirement of the world but also the urgent need of environmental protection. Based on the types of manufacture material, there are two basic commercial PV module technologies available in the market today: crystalline solar cell and thin-film solar cell. The crystalline solar cells have been leading the market due to its high electrical efficiency and matured technology. Since the thin film technology is more flexible than the crystalline solar cells and has low manufacturing cost, it has been served as a potential technology. However, its low efficiency restricts the wide application.

Building integrated photovoltaic (BIPV), as the photovoltaic material, can be used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades. In other words, BIPV products can transform building from energy consumer to energy producer. Besides, like a standard building envelope, BIPV serves as weather protection, thermal insulation, noise protection, etc. Similar to the BIPV, the “building applied photovoltaic” (BAPV) is sometimes used to refer to an integration which is made by installing the solar PV modules on top of the existing structures (retrofitting). The BAPV products on the facades give old buildings a whole new look, which can increase not only the appeal of the building but also its resale value. Sometimes, these two classifications cannot be defined clearly in the practical application. From the above descriptions, it can be seen that the main difference between BIPV and BAPV is the extent of tightness in the integration of PV modules and buildings. The BIPV system can decrease the material and infrastructure costs of the building. However, a significant challenge should be overcome before the installed cost of BIPV is competitive with the stand-alone PV panels. This issue can be offset by reducing the amount spent on building

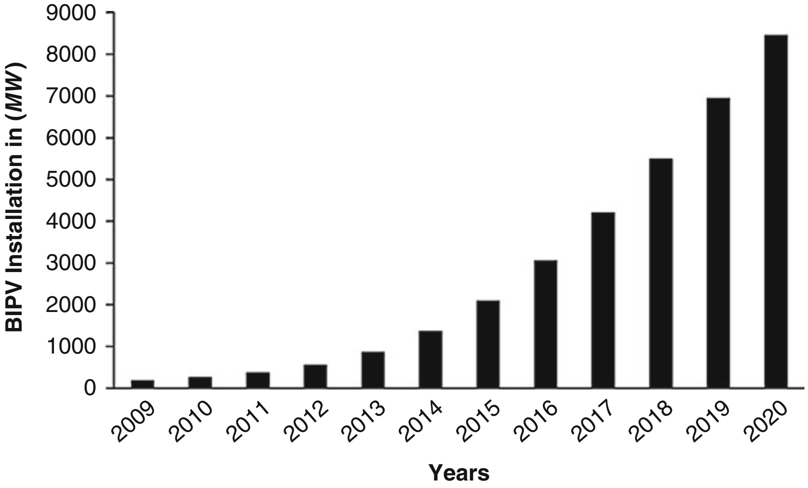


Fig. 20 BIPV market: Global installation capacity forecasted till 2020 in MW [28]

materials and labors. Unlike the BIPV system, the BAPV technology simply uses PV modules to overlap the building envelope. Additionally, their structures are simple to mount and maintain. Even without photovoltaic modules, these types of buildings are capable of functioning normally. Therefore, the choice of photovoltaic arrays depends on photovoltaic technologies, architectural forms, costs, and other building site situations.

Thanks to the reduced cost and government subsidies of PV cells, world's overall BIPV products installation is increasing every year. The future BIPV market growth has been shown in Fig. 20 [28]. BIPV installation is expected to increase with a growth rate of 30% per year, and the expected installation will be more than 8000 MW by the end of 2020. The PV panels can be integrated into different parts of building system such as roofs (including skylights), facades (walls and windows), and shading system. Roofing systems include skylights, standing seam products, tiles, and shingles. Façade systems contain glazing, spandrel panels, and curtain wall products. PV modules of different shapes can be used as the shading elements over windows or as part of an overhead glazing structure. Beyond that, their impact can be improved through using one-way trackers to tilt the PV array, which may not only maximize power but also provide a variable degree of shading. Table 1 presents the list of major projects with different BIPV categories [28]. Obviously, BIPV roofing is the leading market segment in the global market. Moreover, flat and pitched roofs are best suited for BIPV application due to the lack of ground space and large availability of unused roof space. Additionally, there is less shading effect at roof height than at the ground level. Among the BIPV roofing system, a more exquisite roofing solar product is the BIPV solar tiles and shingles. The PV module is mounted like any shingle or tile on the pitched roof, which can not only enhance the building's appearance but also create very attractive visual effects.

Table 1 List of major projects with different photovoltaic categories from 2004 to 2014 based on Ref. [28]

PV categories (year)	Project name	Project location	Capacity
Rooftop integration (2014)	Black River Park Commercial Rooftop Solar Project	Cape Town, South Africa	1.2 MWp
Rooftop integration (2014)	Solar PV Plant, Punjab	Amritsar, Punjab, India	7.52 MWp
Rooftop integration (2013)	Centro Ingrosso Sviluppo compano in Nola	Nola-Naples, Italy	20.252 MWp
Rooftop integration (2012)	Riverside Renewable Energy-Holt Logistics Refrigerated Warehouse	Gloucester City, New Jersey	9 MWp
Rooftop integration (2011)	Avidan Energy Solution	Edison, New Jersey, USA	4.26 MWp
Rooftop integration (2011)	Goodyear Dunlop Logistic Center	Philippsburg, Germany	7.4 MWp
Rooftop integration (2011)	Toys “R” Us Distribution Center	Flanders, New Jersey, USA	5.38 MWp
Rooftop integration (2010)	Shanghai No. 1/2 Metro Operation Co. Ltd	Hongqiao Railway Station, Shanghai	6.68 MWp
Rooftop integration (2010)	FedEx	Wood bridge, New Jersey, USA	2.42 MWp
Rooftop integration (2010)	GSA Bean Federal Centre	Indianapolis, Indiana, USA	2.01MWp
Industrial rooftop (2010)	VT-Sun	Chomutov, Czech Republic	2.98 MWp
Rooftop integration (2009)	Atlantic City Convention Center	Atlantic City, New Jersey, USA	2.36 MWp
Pavilion top (2009)	The Shenergy Group	Shanghai World Expo, Shanghai, China	3.12 MWp
Rooftop integration (2008)	General Motors Spanish Zaragoza Manufacturing Plant	Zaragoza, Spain	11.8 MWp
Rooftop integration (2007)	Google Head Quarters	Mountain View, California, USA	1.6 MWp
Roofs and façades	Sharp	Kameyama, Japan	5.1 MWp

(*continued*)

Table 1 (continued)

PV categories (year)	Project name	Project location	Capacity
integration (2007)			
Roofs and façades integration (2007)	Franz Fischer	Dingolfing, Bavaria, Germany	3.7 MWp
Roofs and façades integration (2007)	Michelin Solar Park, Homburg	Saarland, Germany	3.5 MWp
Rooftop integration (2006)	Hartmann AG	Muggensturm,Baden-Württemberg, Germany	3.8 MWp
Building structures with PV: canopy (2006)	Student Union Building	Malmo – Sweden	25.6 KWp
Rooftop integration (2005)	Sonnenfleck-tts-Bürstadt	Bürstadt, Hessen, Germany	5 MWp
Rooftop integration (2005)	Olympic village	Newington, Homebush Bay, Sydney	12 KWp
Adaptation of PV modules to the domed roof (2004)	Azienda Agraria Anfossi	Savona – Italy	16.20 KWp
Building structures with PV (2004)	Kowa Elementary School	Nerima, Tokyo – Japan	2.05 MWp
Rooftop integration (2004)	Molina de Segura	Molina de Segura, Murcia, Spain	5.98 MWp

(Semi)transparent BIPV products provide electric power and some of the lights for daylighting or viewing simultaneously. As a consequence, these modules can be used to replace architectural elements, especially for the high-rise public buildings which have very less area but large façade. Either crystalline silicon solar cells or thin-film solar cells can be used for the semitransparent modules. For the crystalline silicon, the required light passing through the desired structures can be altered by dimensions and adjusted by the number as well as spacing of cells. What is more, the transparency can be controlled by changing the manufacturing process in the case of thin film technology. Figure 21a, b shows the application of semitransparent PV modules in windows and skylights, respectively.

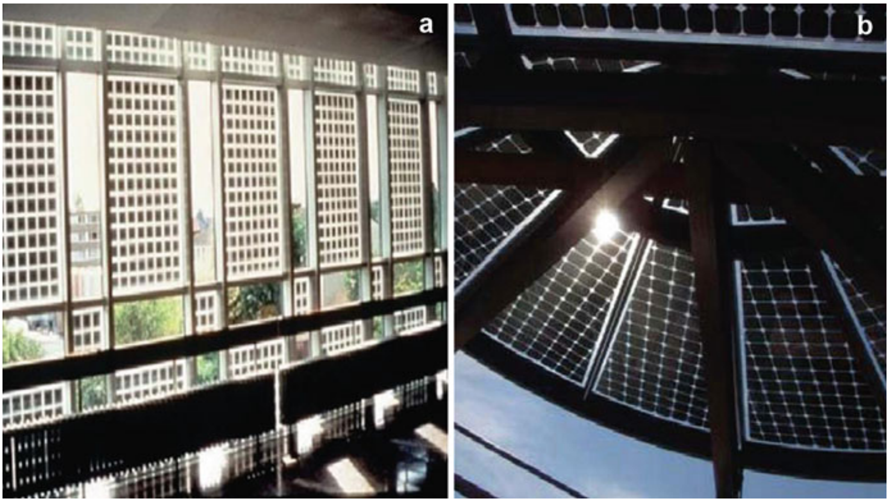


Fig. 21 Photograph of semitransparent BIPV windows (**a**) and skylights (**b**)

For an efficient BIPV system, various factors, such as the PV module temperature, shadowing, installation angle, and orientation, must be considered. Moreover, orientation of BIPV system and the installed tilt angle is critical factor for receiving the maximum solar energy. Generally speaking, the preferred orientation of BIPV system faces toward the south (in the northern hemisphere), and the fixed optimum tilt angle is considered to be approximately latitude of the location. In high-density area, the small distance between buildings will easily lead to significant shading throughout a large part of year, especially for the façade system integrated in the buildings. Additionally, shading because of trees should be taken into account. Therefore, certain distance between buildings and plantation on the north side of the building or plantation of only small trees may eliminate most of the potential problems regarding the shading. Among these factors, the PV module temperature is one of the most crucial factors that affect the efficiency of the BIPV system. The module temperature is intimately related to the environmental parameters such as solar radiation, ambient temperature, and wind speed.

Building Integrated Photovoltaic Thermal (BIPVT) System

PV cells can absorb up to 80% of incident solar radiation available in the solar spectrum, while only small part of the absorbed incident energy is converted into electricity depending on the conversion efficiency of the PV cell technology. Furthermore, the rest of energy is dissipated as heat which accumulates on the surface of the cells and causes elevated temperatures. Generally speaking, with each 10 °C increase in surface temperature of cells, the efficiency of crystalline silicon photovoltaic arrays will decrease by approximately 5%. Additionally, the cell temperature rise may cause serious degradation and shorten the lifetime of the cells. Hence, it is of great necessity to cool PV modules during the operation. A photovoltaic thermal hybrid system (PVT) is a device that can extract away the unwanted heat generated by the PV modules and bring it into use, rather than simply dissipate it to the environment. When the PVT system is integrated to a building, it is called the building integrated photovoltaic thermal (BIPVT) system. The heat recovery in the BIPVT system can supply space heating or hot water and thereby enhance solar energy utilization. In other words, both electricity and heat can be produced by one integrated system. The PV is used as (part of) the thermal absorber.

Although the concept of BIPVT has appeared for 20 years, it is still not a mature commercialized technology due to various constraints. Because BIPVT system provides greater opportunity than the BIPV for the use of solar energy technology, the research on different BIPVT systems has been conducted worldwide and achieved significant progress. Based on the working media, installation location, and shape of facing south, a BIPV/T system can be categorized as shown in Fig. 22. The BIPVT

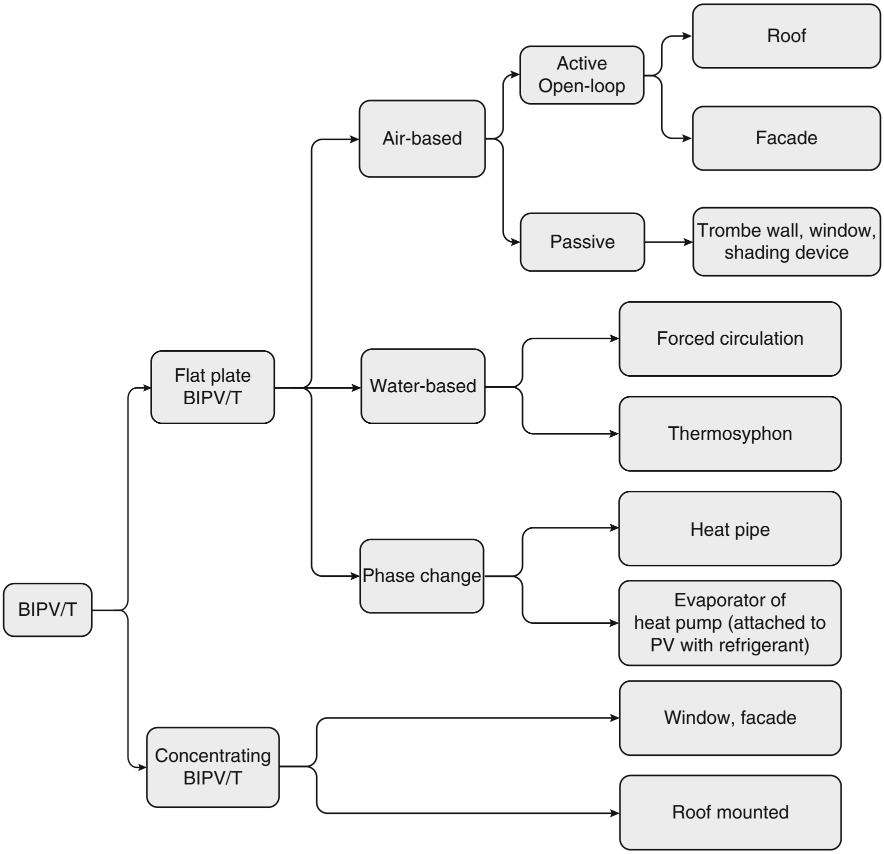
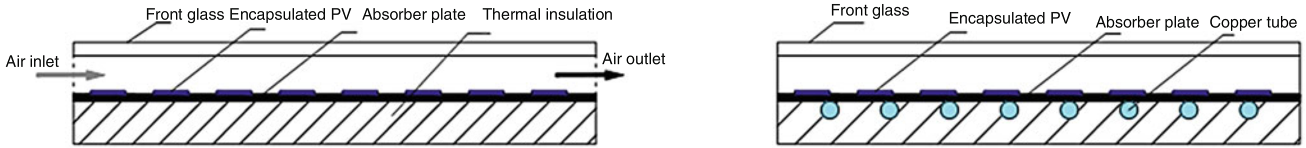


Fig. 22 Categorization of BIPV/T systems [29]

system can receive solar radiation using a flat surface or a reflective concentrating device. Among these BIPVT systems, the air /water based-flat plate BIPVT is the most commonly used and studied in the literatures. Figure 23 shows various common designs of air/water-type BIPVT system. For a passive air-based BIPVT system, the air channel behind the PV absorber is the most common configuration. Besides, the air in the channel extracts the accumulated heat from the PV absorber through convection heat transfer. The heated air is either fed into indoor space or exhausted into environment. The PV-Trombe wall system, as described in section "PV-Trombe Wall," is one of passive wall-integrated BIPVT air systems. Figure 24 shows a similar passive BIPVT air system integrated on the building façade. This is a PV double-skin facade (DSF) with top and bottom vents on the exterior surface removing waste heat and reducing the operation temperature of the solar cells by naturally ventilated air. In general, the use of forced circulation can enhance the convective and conductive heat transfer, resulting in the better performance of the BIPVT air system. However, the required fan power reduces the net electricity gain. Since this chapter mainly focuses on passive solar technology, the studies on the forced BIPVT system will not be given here in detail. For a BIPVT water system, the sheet-and-tube BIPVT configuration is the most common design. It consists of a PV module attached to an absorbing collector with serpentine of a series or parallel tubes at the rear surface of PV modules. As identified by many literatures, several environmental and design parameters should be considered for such type of collector, such as mass flow rate, PV cells packing factor, water inlet temperature, number of covers, collector length, duct depth, and shape. Apart from the sheet-and-tube BIPVT configuration, the rectangular channels and aluminum-alloy flat-box absorbers are usually used to enhance heat transfer in the BIPV/T system. Based on the sheet-and-tube BIPVT collector, Ji et al. [30] have proposed a trifunctional BIPVT collector, as illustrated in Fig. 25. The trifunctional BIPVT collector can provide not only electricity and hot air in winter but also electricity and hot water in the rest of year. Additionally, the working mode of the BIPVT collector can flexibly fulfill the requirements in different seasons, regions, and applications. Compared to the air-based system, BIPVT water system normally runs at a lower temperature, resulting in higher thermal efficiency as well as better PV performance owing to the high density and large heat capacity. Nevertheless, air cooling of PV panel is a simpler technology to regulate the temperature of PV cells owing to the low operating cost, minimal use of material, and reduced risks related to freezing or leaking. Therefore, the choice of cooling media in a BIPVT system should be made according to several factors, such as initial cost, local climate, and user's need.

There are two principal categories of a combination of PVT system and buildings: BAPVT and BIPVT. To be specific, the BAPVT system is an existing building attached to a PVT system. The simplest BAPVT system can be created by reserving a space between photovoltaic arrays and the buildings' skins. The BIPVT system is not just an addition of PVT in the building, and also good composition between materials, colors, and dimensions must be taken into account. Moreover, the real incorporated BIPVT system should achieve consistency with the building concept and framework. To achieve the best integration results, it is of great necessity to

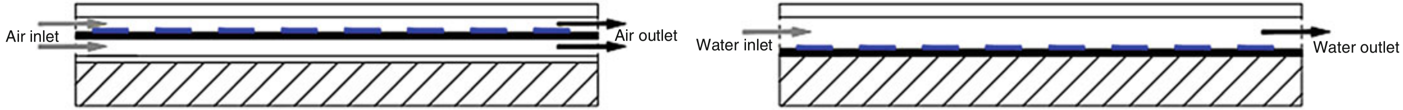


(a) Channel above PV design

(a) Sheet-and-tube design

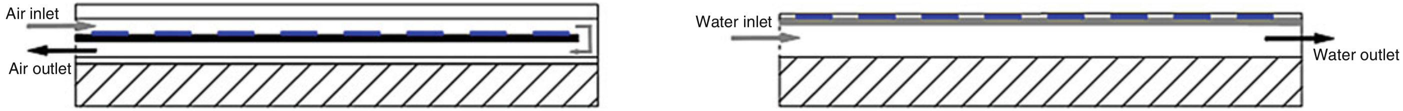
(b) Channel below PV design

(b) Box channel design



(c) PV between single pass channels

(c) Channel above PV design



(d) Double pass design

(d) Channel below PV design

Fig. 23 Cross section of some common air-type BIPVT (left) and water-type BIPVT (right)

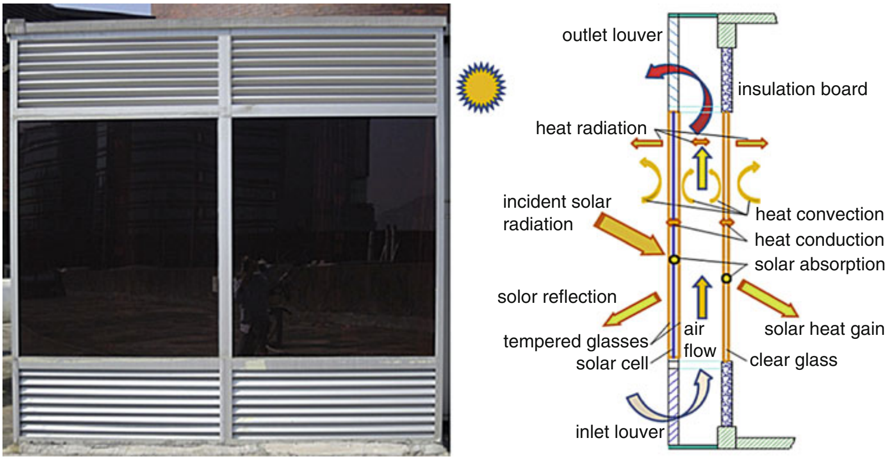


Fig. 24 Ventilated double-pane semitransparent photovoltaic window with open air cavity [31]

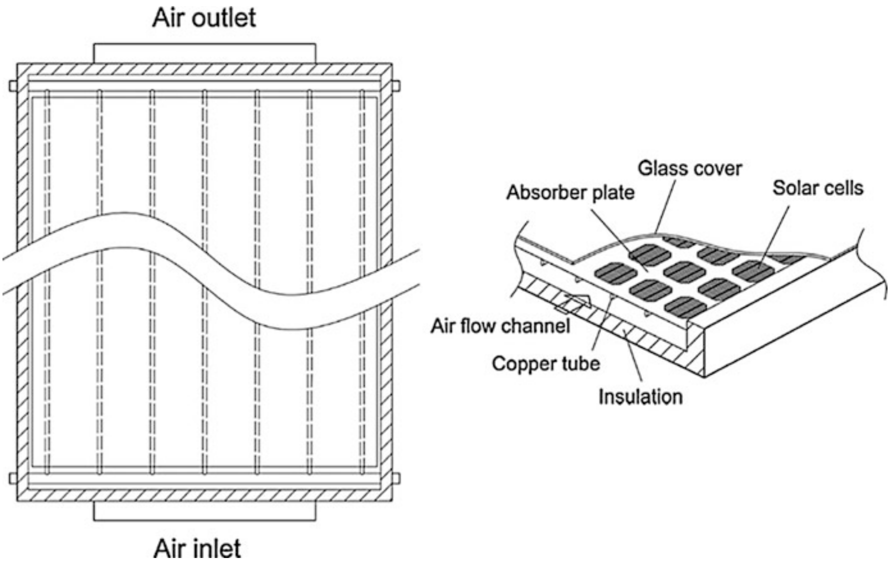


Fig. 25 Schematic of the trifunctional BIPVT collector [30]

consider the strategy design of BIPVT system in the building design stage. As illustrated in Fig. 26, the size of the PV modules was designed to match the dimensions of the curtain wall system that covers the rest of the façade area and to achieve a pleasant visual effect [29]. Additionally, the aluminum frames and the back sheets of the PV modules are black so as to allow a homogenous appearance of the BIPVT system.

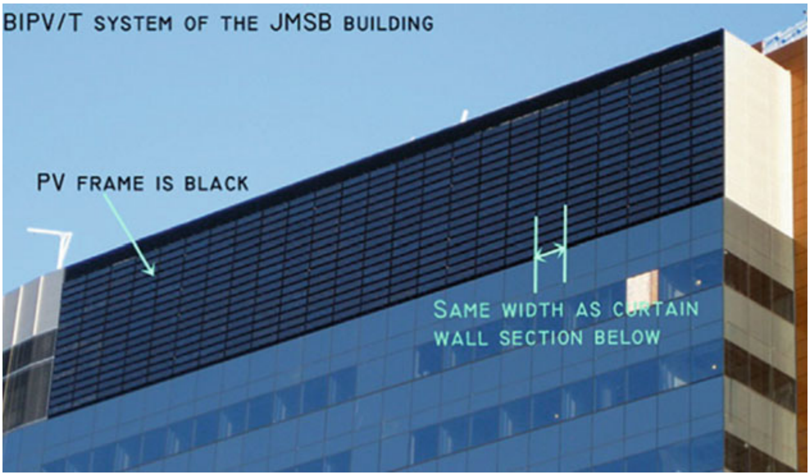


Fig. 26 The BIPV/T system of the JMSB building [29]

Theoretical Analysis of Passive Solar Building

Generally speaking, two types of research methods have been adopted in passive solar building research: experimental measurement and theoretical calculation. Compared to theoretical approach, experimental modeling has many disadvantages. Firstly, it takes longer time to test the system investigated, especially the on-site test under the unpredictable weather conditions. Secondly, it is usually difficult or too expensive to modify an established experimental prototype for different designs. Finally, repeating full-scale testing under real climate conditions is often impossible. Therefore, theoretical simulation has been widely adopted to conduct research related to passive solar building. Before practical implementation, a simulation is essential to analyze the feasibility of a passive building integrated solar system. Various theoretical approaches so far have been developed to optimize the passive solar buildings. Based on an overview of theoretical methods for passive solar building research, two most common types of research approaches are presented in this section: (1) analytical approach based on a heat balance model and (2) numerical modeling based on computational fluid dynamics (CFD).

Heat Balance Model

The heat balance model means using the energy conservation concept to establish the energy balance equations involving conductive, convective, and radiative heat transfer processes. This model includes coupled energy balance equations for each system element. Also, the passive solar system and the building interior temperatures can be observed with the calculation of energy balance equations. The heat balance model used in related researches mainly includes three categories: steady-state analysis, transient analysis, and building energy simulation programs.

The steady-state analysis is developed for use by architects and builders who wish to quickly check whether passive heating is feasible at a particular location. In this approach, one assumption is that the temperature at various positions does not change with the operating time. Bansal and Thomas [32] studied the steady-state thermal efficiency of four indirect gain passive solar heating concepts (i.e., mass wall, water wall, Trombe wall, and solarium). They inferred that a solarium was most effective at very low levels of incident radiation and low ambient temperature. Additionally, water walls and Trombe walls were much more efficient at slightly higher levels of incident radiation, while the simple mass storage wall was the least efficient. To obtain the overall solar heat gain and loss coefficients in different buildings, Bhandari and Bansal [33] carried out a similar study by integrating passive heating concepts (i.e., the direct gain, mass wall, water wall, Trombe wall, and solarium). Meanwhile, numerical calculations have been done for typical values of solar radiation and ambient temperature of typical climatic conditions in India. According to their finding, Trombe wall and water wall were more effective in the areas with high level of solar radiation, whereas solarium was more suitable for the application with low solar radiation.

Compared with the steady-state analysis, transient analysis has been increasingly applied to the passive solar building research, which mainly aims to simulate the time-dependent behavior of a passive solar building such as temperature fluctuation and thermal lag in the passive building. For example, Bansal et al. [34] evaluated the time-dependent variations of overall heat transfer coefficients of Trombe wall with or without vents, water wall, and transwall. It was concluded that the Trombe wall without vents and the water wall with heat capacity equaling to 443.2 kJ/K yielded positive heat flux entering into the room throughout 24-h periods, whereas a negative flux was found with other systems (Trombe wall with natural convection and transwall). By using the transient analysis, Tiwari and Singh [35] carried out a comparative study on a building integrated various passive heating techniques (including glass south wall, water wall, solarium, etc.) for one day and a period of a full year. As revealed by the results, the fluctuation in temperature was reduced significantly through the use of water wall in solarium system. Furthermore, the maximum of the room air temperature was also shifted toward nighttime. Additionally, from the perspective of the full-year room temperature, most of the heating techniques should be disconnected/detached during the summer period (May–October) so as to avoid overheating.

Several types of commercial building energy simulation software use the heat balance model as the core of their analysis, such as EnergyPlus and TRNSYS. With the use of these commercial programs, the simulation of a large building over an annual cycle could be completed in just a few minutes. Overall, the building energy simulation software is a powerful tool which has great potential for the design of energy-efficient buildings, especially for making critical decisions at the early stage of the design. By means of TRNSYS building energy simulation, Zogou and Stapountzis [36] investigated the energy performance of a BIPVT system incorporating PV modules to the south façades of an office building. Moreover, an air gap between the backside of the modules and the wall was employed for circulating the outdoor air to cool the modules and to preheat the outside air before its entry into HVAC system during winter. The simulation of its yearly energy performance was performed, and the investigation concluded with certain design optimization directions. Another empirical study with the EnergyPlus software was conducted on a residential building in Alcona, central Italy [37]. This study analyzed the impacts of insulation on the Trombe wall. As shown by the results, the seasonal heating energy demand for a superinsulated Trombe wall was reduced approximately 72% compared to that for a normal Trombe wall. During the hot summer, the results were opposite. The seasonal cooling energy needed was approximately 9.19 (kWh/m^2) for a normal Trombe wall and 23.31 (kWh/m^2) for a superinsulated Trombe wall.

Based on the above assumptions, it can be seen that using the heat balance model only is suitable for assessing its bulk performance and can quickly catch the main features of a system. Thus, the heat balance model is highly effective to simulate the energy savings of a large-scale system over an extended period of time (e.g., daily, monthly, or even yearly cycle). However, the detail temperature and velocity field of the working fluid of a system cannot be obtained. Furthermore, using the heat balance model cannot solve the details of the complex heat transfer processes occurring inside the passive solar elements and in the building interior. Moreover, various heat transfer coefficients “characterizing the heat transfer between surfaces and fluids” need usually to be given from previous empirical correlations. Hence, the accuracy degree of the obtained results with the heat balance model significantly depends on the selection of the correlations. It may vary significantly from one literature to another literature for the same passive solar concept and also vary from real conditions. As a consequence, the validation of the heat balance model by “a small-scale experiment” or “previously confirmed result in open literatures” is usually done simultaneously.

Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is a powerful technique to solve numerous scientific and engineering problems involving fluid flow, heat transfer, species transport, etc. Unlike the heat balance model, the velocity and temperature field of the working fluid of a specific system layout can be obtained using the CFD techniques without inputting readily available correlations of convection heat transfer coefficients. In addition, the convection transfer coefficients can be calculated according to the temperature distribution generated by a CFD simulation. What is more, the CFD model can be developed and resolved either by common written codes or by commercial software such as FLUENT, CFX, and CHAM. Many literatures of using CFD simulation to investigate the passive solar building have been reported. By using the dynamic CFD model, Khanal and Lei [38] explored the impact of flow reversal phenomenon on the buoyancy induced airflow in a solar chimney. The isotherms and contours of streamlines in the air duct for different Rayleigh gave a further insight of the flow behavior. Furthermore, Bajc et al. [39] developed a comprehensive three-dimensional CFD model of a passive house with Trombe wall. Besides, temperature field and velocity field in Trombe wall and in the adjacent room are simulated. It can enable building designers to choose the configuration of Trombe wall that is most suitable for the outer weather conditions.

Although the CFD simulation can resolve the details of convective flows of working fluid in a passive solar system as well as temperature distribution, some limitations still exist. On the one hand, the use of the CFD approach requires good knowledge of the physical processes under investigation and experience with the CFD techniques. On the other hand, a few problems may be computationally intensive due to the complex geometry and physical processes involved in the systems. Hence, it will take up to several months to simulate a complex problem using CFD "for only a few hours of the flow time."

Performance Evaluation of Passive Solar Building

Various assessment factors have been employed in the open literature to evaluate the performance of passive solar buildings. These factors can be grouped into three categories: energy, economy, and environment.

In terms of energy perspective, it refers to the reduction in building energy consumption (heating or/and cooling loads, electric power, thermal and electrical efficiency) after the use of passive solar concepts in the buildings. By using TRASYS software, Abbassi et al. [40] investigated the impact of Trombe wall area on the annual heating load. As revealed by the results, the increase in Trombe wall area gave rise to the decrease in heating load, and up to 77% of annually heating auxiliary energy of a simple classical Tunisian building can be saved with an 8 m^2 Trombe wall. Through the building energy simulation EnergyPlus, Xu et al. [41] performed a parametric study to explore the impact of PV cell coverage ratios on overall energy consumption of office buildings where the semitransparent photovoltaic façades have been implemented. As shown by the result, the use of the optimal PV cell coverage ratio can achieve overall energy consumption savings of 13% (on average) compared to the least favorable PV cell coverage ratio.

As to environmental factors, the impact of passive solar system on the living space and building exterior environment have been taken into account, including the room temperature, thermal comfort (temperature fluctuation, air change per hour, and ventilation rate), and reduced CO_2 emissions. N. Khalifa and F. Abbas [42] carried out a numerical study on a zone heated by a thermal storage wall. Moreover, three different storage materials including concrete, the hydrated salt $CaCl_2 \cdot 6H_2O$, and paraffin wax were examined. It was concluded that a 0.08-m-thick storage wall made from the hydrated salt "maintained the zone temperature close to the comfort temperature" with the least room temperature fluctuation (18–22 °C). Additionally, Jaber and Ajib [43] studied the environmental impact of Trombe wall system on residential building in Mediterranean region. Their study determined that 445 kg CO_2 was reduced annually when Trombe wall area ratio of 37% was designed.

Economic assessment is a matter of cost and benefit. The additional expense of a passive solar concept during the pre-use and operational phase is a cost, while the amount of energy savings and CO_2 reduction are benefits. By using life cycle cost (LCC) technique, Jaber and Ajib [43] investigated the economic aspect of a Trombe wall system integrated on a typical Jordanian house. Their study involved the below basic assumptions: the life span of the building and Trombe wall system used was 30 years; the inflation rate in fuel price was around 8.9%, and the interest rate was about 6.25%; present worth factor (PWF) was 44.96. The efficiency of the auxiliary heating system was 0.65, and the maintenance factor was 15% of the capital cost. As revealed by the results, LCC of house without Trombe wall system was about 49,259 Euro. Nevertheless, nearly 1169 Euro over 30 years can be saved after installment of the Trombe wall system. Furthermore, the economic optimum point occurred at Trombe wall ratio of 37% with additional investment of 1260 Euro [43]. K. Sudhakar et al. [44] presented an overview of recent advancement of BIPV technologies, and the energy payback time was employed for the life cycle sustainable assessment of BIPV module. It is concluded that m-Si BIPV modules have the highest energy payback time, whereas flexible thin-film BIPV modules have the lowest energy payback time.

Conclusions and Suggestions

Building integration of passive solar concepts is considered as a good alternative technology that can significantly relieve the building energy consumption for space heating, cooling, ventilation, and lighting. This chapter firstly reviews the development of various passive solar concepts integrated into buildings, such as direct heat gains, Trombe wall, sunspace, and BIPV/T. For the simplest direct gain window, it is more convenient and effective for space heating of a building with large glazing like office. Besides, double-skin façade (DSF) is another type of direct gain system. Compared to a single glazing, its major advantage is that the DSF can provide better ventilation for the building interior. Some methods of controlling heat gains, loss, and daylight at various times of the day and year have been commonly used in the direct gain system, such as insulation and shading devices. Compared to direct gain system, indirect gain system is more suitable for the residential buildings and also can achieve a preferable thermal comfort for the living space due to the lower room temperature fluctuation. There are various configurations of the Trombe wall, solar chimney, and roof ponds. These configurations either incorporate new elements into an original direct gain concept (Trombe wall, solar chimney, and roof pond) or employ modified direct gain concept components. For example, sunspace is a combination of the direct gain and Trombe wall. When the attached sunspace is integrated to buildings, it will achieve additional flat space that can be used for recreation or growth of vegetables and plants. Building integrated photovoltaic thermal (BIPVT) is cogeneration system that converts solar energy into both electricity and heat. Also, it is one of the most efficient ways to use solar energy. Overall, the BIPV or BIPVT systems can cut the material and infrastructure costs of the building, yet a significant challenge should be overcome before the installed cost of them is competitive with the stand-alone PV panels.

Based on an overview of theoretical methods for passive solar building research, this chapter discusses two typical research approaches: (1) analytical approach based on a heat balance model and (2) numerical modeling based on computational fluid dynamics (CFD). Their major characteristics as well as the advantages and defects are presented. Finally, various assessment factors that have been employed in the open literature are grouped into three categories: energy, economy, and environment. In terms of energy perspective, it refers to the reduction in building energy consumption after the use of the passive solar concepts such as heating/cooling load and electricity generation. The environmental factors correspond to the impact of passive solar system on the living space and building exterior environment, such as room temperature, thermal comfort, and reduced CO_2 emissions. Economical evaluation is a matter of cost and benefit. Life cycle cost (LCC) technique is usually used to assess the total cost throughout the life of a passive solar building.

For future study on the passive solar building, this paper puts forward the following recommendations. Firstly, the sociological study of the awareness of the passive solar concepts' benefits is recommended. Government may introduce subsidized passive solar building to make it more popular. Secondly, from the perspective of engineering, future studies should develop the standard guidelines on how to design and assess the performance of passive solar building for a specified country. During this process, studies on the social and cultural impediments, such as aesthetic issues, should be carried out for different nations. Thirdly, most of current studies on the passive solar building fail to consider the impact of occupants' behavioral changes. Thus, it is suggested to conduct performance analysis of passive solar building without the constraints of users' activities such as the operation of windows and lights. Finally, in most cases, energy consumption of buildings cannot be eliminated if only one passive solar technique is employed. Hence, future studies should examine how one type of passive solar concept could be combined with other passive solar strategies so as to eliminate energy loads and meanwhile provide indoor thermal comfort.

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