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The application of air layers in building envelopes: A review

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Abstract: Air layer involved envelopes (ALIEs) have gained considerable popularity in modern building design and construction, owing to their great potential in improving the building thermal performance. Basically, the air layer functions as an extra insulation layer or as a ventilation channel. This paper presents a literature review on building envelopes that contain inner air layers by tracing recent studies on existing air layer involved applications and technologies in walls, windows, roofs. The structural characteristics, the driving forces, the effects of the inner air layers, and the benefits of different types of ALIE systems are summarized and classified. And then operation modes of air layer used in building envelopes are roughly classified into three types: the enclosed type, the naturally ventilated type and the mechanically ventilated type. At the end, this paper analyzes current research gaps and provides possible future research directions on air layer technologies in building envelopes.
Keywords: air layer, building envelop, wall, window, roof, air layer involved envelop (ALIE)

1. Introduction

1.1. Energy consumption in building sector

With the rapid development of economy and urbanization, the world is now facing a great challenge of an energy shortage, environmental pollution and climate change. Globally, all the energy produced can be consumed by several main sectors, that is, the residential sector, the commercial sector, the industrial sector and the transportation sector [1]. As reported, in 2011, the primary energy consumption proportions of industrial, transportation, residential and commercial sectors were 31%, 28%, 22% and 19%, respectively [2]. On the other hand, building energy demand has been identified as the largest energy consumer and accounts for the largest percentage of the total energy consumption [3]. The building energy expenditures in different countries is illustrated in Fig. 1, the primary energy consumed by buildings accounting for 23% in Spain, 25% in Japan, 28% in China, 39% in the United Kingdom, 40% in Europe, 42% for Brazil, 47% for Switzerland, and 50% for Botswana [4]. The United Nation Environment Programme [5] also reported that 30-40% of the world's total primary energy expenditure is consumed in buildings. As the situation evolves, energy consumption in the building sector may increase to as much as the sum of the industrial sector and transportation sector [6]. In China, industry, building and transportation are the three major energy consuming sectors, in which the building sectors account for the largest proportion and enjoy the biggest potential of energy saving [7]. Moreover, with the rapid increase of building areas, the acceleration of urbanization, and the continuous improvement of residents' living standards, the building sector will continue to dominate China's energy conservation and emission reduction process.

Thus, the energy conservation of the building sector plays a key role in solving energy problems all over the world [8]. Although the high energy consumption of building sectors maybe a warning sign, it provides an opportunity for implementing sustainable energy plans in building sectors. Therefore, there is a need to optimize a building's energy efficiency [9]. Energy efficiency becomes a key point in controlling energy use, as well as maintaining comfortable environment in buildings [10].

1.2. Energy distribution in buildings

The energy consumption distributions in the building sector show large variations. Physical factors of a building, such as building orientation, geographical location, construction materials, construction categories, internal equipment and energy systems, lead to significant difference in building energy consumption [11]. The distribution of primary energy utilization in a commercial building is illustrated in Fig. 2. This figure indicates that the biggest proportion of energy consumption is the heating, ventilation and air-conditioning system (HVAC), which is the highest energy consumer in a building nowadays [12]. Then the lighting takes the second place. For this reason, the US Department of Energy highlighted the energy conservation potentiality of HVAC and lighting [13].

From surveys on office buildings in China, the energy consumption of HVAC systems accounts for a large proportion of the total primary energy use. Results showed that, in July and August, the proportion is 30–60% for 4 typical office buildings in Hong Kong, 24–54% for 105 office buildings in Beijing, the average proportion is 34.3% for 198 high-rise office buildings in Shenzhen, and 44.0% for 3 government office buildings in Wuhan [14]. So energy conservation for HVAC systems has become an important part of a national energy strategy.

The HVAC system is important in buildings as it helps to meet the requirements for thermal comfort [15]. The higher comfort level is achieved in a building, the more the energy is consumed [16]. Two measures can be taken to reduce the energy consumption in HVAC systems: one method is to manage the operation of the system properly on the premise of ensuring the reliability of critical loads [17]; the other is to improve the thermal performance of building envelopes, as the building envelopes are the interface between indoor and the outdoor environment which affect the indoor heat gain and heat loss [18]. The former belongs to the active energy efficient strategies, which involves improvements to HVAC systems, electrical lighting, and other indoor energy systems; while the latter can be categorized as passive strategies in which relevant improvements are made to building envelope elements [19]. Building energy efficiency can be increased by implementing either active or passive energy efficient strategies.

1.3. Thermal energy loss through building envelopes

Recent years have seen an increasing interest in environmental-friendly passive building energy efficiency strategies, which are expected to be a viable solution to the energy crisis and environmental pollution in building sectors. The building envelope is a critical factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions. Various components such as walls, fenestration, roof, foundation, thermal-insulation, thermal mass, external shading devices etc. make up this important part of any building. The thermal performances of these components envelope greatly affect the energy consumption in HVAC systems [20]. It has been studied that 20–50% of the cooling and heating energy consumption is caused by the envelope [14]. Actually, the building's energy demand is closely connected to the efficiency of its envelope; if the building envelope is not correctly designed, the excessive heat fluxes through the structures (vertical, horizontal, transparent, opaque) lead to a large increase in energy consumptions. Therefore it is extremely important to develop alternative construction techniques that guarantee both thermal comfort and low energy use.

Several ways can be taken to improve the performance of building envelopes, including using high-performance building materials, employing insulating materials, and improving the structure of external envelopes [18]. Many advanced and sustainable building materials have been developed for building envelope applications, such as fiber-reinforced plastic, unfired clay bricks, hollow bricks, concrete hollow blocks, aerated concrete blocks, sandwich panels, straw-clay mixtures, heat preservation and insulation glasses, hollow glasses, glass mosaic [21], etc. Many researchers studied the effects of high-performance envelopes on building energy consumption. Implementing passive energy efficient strategies (including adding EPS insulation layers in walls, employing white washing external walls, using reflective coated window glass) achieved an energy saving of 31.4% for high-rise apartments Hong Kong [22]. Another study in Hong Kong reported that an energy-effective building envelope design saves 35% of the total cooling load and 47% of the peak cooling demand respectively [23]. In Greece, implementing thermal-insulation and low infiltration strategies in roof floor and walls resulted in an energy consumption decrease by 20-40% and 20% respectively; and employing external shadings reduced the cooling load by 30%, using light-colored roof and external walls reduced the cooling load by 2-4% [24].

Using thermal-insulation materials in building envelopes not only reduces the energy consumption of HVAC system [25, 26], but also obtains a more comfortable indoor thermal environment [27]. Wilhelm et al. [28] investigated the influence of insulation materials on wall performance in Dubai. Results found that an energy-saving of 30% can be achieved with proper insulation design. Based on both experimental and numerical results, Surapog et al. [29] concluded that the thermal performance can be improved by adding insulation materials to the walls. Guo et al. [30] conducted a study on the energy-saving effect of coating exterior walls with heat-reflective insulation materials. The research results revealed an obvious energy-saving potential in Hangzhou.

A proper structural design of building envelopes can significantly lower the energy consumption caused by building envelopes. One novel design strategy is to add self-shading components, including overhangs, light shelves, louvers, etc. to glaze-based envelopes to regulate solar radiation [31]. Large glazed area in modern buildings makes the indoor environment exposed to and dependent on solar radiation, which results in large cooling demand in hot-weather conditions and can help to reduce heating demand in cold-weather conditions. Self-shading envelopes block solar radiation in summer and permits it in winter, thus, contributes greatly to reduce the cooling load in summer and heating load in winter. Laura et al [32] reported a critical analysis on the effects of different self-shading envelopes on thermal and lighting performances. Results showed that the self-shading envelope has a potential in improving indoor thermal and lighting environment. Steinar et al [33] concluded that solar shading systems are vital for office building for the purpose of reducing the cooling demand. For south-facing façades, with a proper design of shading devices, the energy demand can be reduced by 9%.

1.4. Employment of air layers in building envelopes

Another structural design strategy is to introduce air layers as an internal structure layer to building envelopes. This strategy has been extensively adopted in recent years [34]. There are many different types of air layer applications in building envelopes, including multi-layer door/windows, air flow window, interior hollow composite walls, double-skin façades, Trombe walls, solar wall/chimney, PV façades [19, 35, 36], etc. According to their operation modes, they can be classified as the enclosed type and the non-closed type. When the layer is enclosed, necessary measures are always taken to suppress the radiation, such as coating the surfaces with low emission coefficient materials or adding a radiation shield between the surfaces, thus the amount of radiation heat transfer is usually ignorable. Moreover, in the extremely narrow space in the enclosed air layer, the convective heat transfer is usually restricted. Thus, the heat transfer process in enclosed air layer could be treated as pure conduction. In this case, the thermal resistance of the air layer is big, so the internal air works as a thermal-insulation material, for its conductivity coefficient is far lower than those of other structural materials in building envelopes, thus reducing the heating loads and cooling loads; when the layer is a non-closed type, the air layer functions as a ventilation channel in which air circulates driven by buoyancy force, wind pressure, fluid machineries, or the combination of two or three of the above factors. The air movement may offer many benefits to a building, such as passive cooling, space heating, natural ventilating, and fresh air supplying. The effect of employing air layers in building envelopes has been validated by a number of publications, and a number of reviews were performed either as a summary of passive energy-saving strategies in buildings [35, 36] or focusing on a specific type of ALIEs, such as reviews on double-skin façades [37-39], passive solar heating and cooling technologies [35, 36, 40], opaque solar façade [41], transparent and translucent solar façades [42], ventilated façades [43], the application of solar chimneys [44], building integrated solar collectors [45-50], building integrated PV technologies [51-55], Trombe walls [56], etc.

However, most of previous researches articles concentrate on a specific air layer involved component by evaluating its thermal performance or its influence on indoor environment; most of the existing review focus on one specific type of the air layer involved technology in buildings, by analyzing and summarizing the research achievements, the study methods, the application situation, and its application prospect. None of the existing studies concentrates on the summarization and analysis of the air layer applied in building envelopes; little has been done to find general characteristics of these ALIEs and no study treats the air layers in these envelopes as a unified research subject; moreover, there is no systematic review on this subject. Hence, this paper aims to present a review of the literature on building envelopes containing inner air layers, which will help identify the research streams and highlight the future research directions. Observing and tracing recent studies on existing air layer applications and technologies in walls, windows, roofs and other components of building envelopes is the main objective of this article. Afterwards, the performances and benefits of these technologies are summarized and classified. The driving forces and the effects of the inner air layers in different technologies are summarized and compared. Finally, this review provides current state of research gaps and possible future research directions on air layer technologies in building envelopes.

2. Air layer utilized in external walls

There are different types of external wall systems which contain internal air layers, such as solar wall systems, double-skin façade systems, wall-based solar chimney systems, Trombe walls, naturally/mechanically ventilated façades, double-skin greenly façades, photovoltaic walls, etc. Each has a unique structure and operation modes, thus resulting in deviations in their thermal performances.
The air layer involved wall systems share the similar working mechanism of natural ventilation or mechanical ventilation technologies. When the air moves in a natural ventilation mode, the driving force which controls the airflow rate is the buoyancy effect, whereby the airflow is due to the air temperature difference (the density difference) between the inlet and outlet. The mechanical ventilated wall systems usually employ fans to promote the circulation ability of the air layer. This section summarizes some of the selected literatures of air layer involved wall systems which include the construction structure, thermal performance, energy analysis and recommendations.

2.1. Classic Trombe wall and Composite Trombe wall

The starting point of the Trombe wall is to absorb solar ray and convert its energy for heating, ventilating so as to provide thermal comfort in buildings [57]. Edward Morse, an American engineer, designed and patented the Trombe wall in 1881. But the concept was popularized by Felix Trombe and Jacque Michel in France, therefore, it is well known as the Trombe wall [56]. The Trombe wall mainly consists of a massive wall, an exterior glazing cover, and an air channel between the massive wall and the cover (see Fig. 3). The massive wall is used for absorbing and storing the solar energy that passes through the glazing cover. The massive wall must be constructed with high heat-storage capacity materials, including bricks, concrete, stone and adobe, and the external surface of the massive wall is usually colored black in order to increase the solar absorption [58, 59]. The thickness of the air channel ranges from 3 cm to 6 cm [60]. Part of the absorbed energy is transferred to the indoor space through heat convection, conduction and radiation between the massive wall and room air; the rest part is also transported to the indoor space by air circulation, in which low temperature air from the room enters the internal channel through the lower vent, gets heated by the massive wall and flows upward due to buoyancy effect, and then returns to the indoor space through the upper vent of the wall with a higher temperature [57]. The heat stored in the massive wall releases gradually through radiation and convection to increase thermal comfort.

Studies have been carried out for the purpose of improving the performance of the Trombe wall. Three aspects of improvements can be made to the Trombe wall, i.e. controlling the inlet and outlet air vents, taking thermal insulation measures, improving the air channel. The most significant measure is to install adjustable dampers on the exterior glazing and improve the vents from a fixed type to an adjustable type. Using this modification, the classical Trombe wall can be adapted to different climates, purposes and seasons, as shown in Fig.4 [61, 62].

According to Fig. 4, in the winter mode, both damper A and damper B are closed; while both the vents are left open to form an air circulation between the indoor space and air channel due to buoyancy effect. Thus room air is heated in the channel and then returns to the room through the upper vent. If there is a requirement of fresh air, damper A can be opened to allow the outdoor air to enter the channel, then, the mixture of the fresh air and room air is heated and transported to indoor space. In the nighttime of winter, all dampers and vents are closed to form an air insulation layer, as the non-ventilated mode illustrated in this figure.

Whereas in summer mode, upper vent and damper A are closed, while lower vent and damper B are open. The buoyancy forces draw indoor air from the lower vent. After being heated, the up flow of the channel is then released to the outdoor environment through damper B. Thus, the summer mode promotes space air movement and thus results in summer cooling effect for a concerned room.

The composite Trombe wall was developed for the purpose of overcoming the heat loss from the inside to the outside of a building in classic Trombe walls. It is also known as the Trombe–Michel wall, which is treated as improved type of Trombe wall [59, 63, 64]. The structure of the composite Trombe–Michel wall is similar to the classical Trombe wall except that an insulating wall is located at the back of the massive wall. Thus, a typical Trombe–Michel wall consists of several layers, including an exterior glazing cover, an enclosed air cavity, a massive wall, a ventilated air channel and an insulating wall (see Fig. 5). The absorbed heat can be transferred to the moving air layer by conduction and convection through the massive wall. Then the circulating air takes the thermal energy to the indoor space.

In nighttime and non-sunny daytime of winter, the air vents in the insulating wall should be closed to prevent heat loss from inside to outside of the room. Composite

Trombe walls improve the Trombe walls from two aspects: (1) reducing heat loss during non-sunlight time; (2) reducing excessive heat gain in hot weather [65]. The former is realized on the premise that the implementing of the insulating layer helps to increase the thermal resistance of the wall system. The latter is achieved by controlling the airflow rate of the ventilated channel, by which the heat input can be regulated. However, in this wall system, necessary measures should be taken to prevent reverse thermo-circulation when the massive wall is colder than the internal air [66]. Shen et al. compared the composite Trombe wall with the classic Trombe wall using TRNSYS software and experiential tests. The results proved that the composite Trombe wall performs better during winter, especially in cold regions [59].

Besides improving the structure, another innovative development of the Trombe wall is to fill phase change materials (PCM) into the massive wall to store and release latent heat. Studies indicated that a concrete–PCM combined Trombe wall can be used to develop low energy buildings as it has a superiority in energy storage and release [67]. Employing PCM also reduces the size and the weight of a Trombe wall, since under a certain heat storage amount, the phase change units require less space compared with the massive wall [68].

Besides the above improvements, based on the classical Trombe wall, many other configurations have been adopted to adapt this wall to different climates and seasons. For example, each of the zigzag Trombe wall, the solar water wall, the fluidised Trombe wall, and the photovoltaic Trombe wall employs a unique measure to improve the performance and applicability of a Trombe wall. And many studies have been carried out to demonstrate the efficiencies and performances of them [56].

To increase the efficiency of a Trombe wall, many researches have been processed to evaluate the influence factors, such as the Trombe wall size, massive wall material and thickness, air channel width, coating color, and glazing material and thickness. For our focus, the air channel sizes (including width and height) might affect the heat convection process greatly [56]. A study indicated that the airflow rate was greatly affected by the height; however, the channel width had little influence on the airflow rate [65]. Implementing a Trombe wall in a building reap huge fruits both on energy saving and thermal comfort enhancement. In a heating season, a Trombe wall can reduce the heating energy consumption of a building by 30% [69]; simultaneously, the moisture and humidity content of the internal room space can be decreased [70]. In a Trombe wall involved building, not only the thermal comfort of the spaces connected to the wall can be improved, but also the thermal comfort of adjacent spaces can be enhanced [66].

2.2. Ventilated or double-skin glazing façades

The concept of double-skin façades (DSF) was firstly proposed in early 1900s, but it had been progressed little until the 1990s [71]. The DSF is now becoming a popular architectural element on the premise that more and more transparent façades are employed in modern office buildings, and building energy efficiency becomes a critical point of global energy utilization.

Double-skin façade is defined as a special type of exterior building envelope, which is composed of an external façade layer, an interior façade layer and an air layer in between. The external layer, usually a hardened single layer of float glass or safety glass, provides protection against the outdoor condition and extra acoustic insulation against external noise; while the interior layer often consists of double-pane glasses [72]. The width of the air space between the two skins, named the air channel, ranges from 200mm to more than 2m [73]. Usually, an adjustable sun shading system is installed in the air channel for controlling solar radiation [74]. The DSF can work either in an air-fixed mode or an air-ventilated mode. The air-fixed mode provides extra thermal insulation for external envelopes to reduce heat transfer in winter. The air-ventilated mode deals with overheating problems in summer and helps to achieve energy savings in winter.

The driving force of the air ventilation in the channel of DSF could be natural, mechanical or a mixed of them. Both the wind pressure and the thermal buoyancy effect produced by the temperature difference between the exterior and interior façades can give rise to natural air ventilation in the channel [75, 76]. The mechanical ventilation employs some power machines to generate air flows in the cavity, while the mixed ventilation results from a combination of natural force and mechanical force. According to the different air flow paths, the ventilation working modes of a DSF can be classified into four types, as shown in Fig. 6.

In mode A, room air enters the bottom air vent on the interior façade, flows through the channel, and is then returned to the central HVAC system through specialized air ducts. For mode B, fresh air enters and flows along the channel, and finals moves to the indoor space. Outdoor fresh can be pre-heated before entering the room in winter. Type A and B are both mechanically ventilated, by which the DSF can be integrated to the building's HVAC system. Mode C acts as an external respiration double-skin façade, in which the air ventilation is usually naturally driven. It can be used for natural ventilation (to supply fresh outdoor air to the indoor space) facility when the window on the internal façade is open; on the other hand, it can be also served as an insulation external wall for an air-conditioned room when all windows on the internal façade are closed, for the external circulated air flow brings away the heat absorption on the surface of the internal façade. [77]. For mode D, the DSF serves as a solar chimney, in which the room air enters the bottom air vent, flows through the channel, and is then exhausted directly to the ambient. This mode could realize natural ventilation for a non-conditioned room by setting an air inlet on the right-side wall (to be discussed in the next section).

The DSF could be grouped to different connection types according to its air flow organization, including the Box-window type, the Shaft-box type, the Corridor type and the Multi-story type [78], as illustrated in Fig.7.

- The Box-window type is partitioned by room or by window along the structural axes horizontally and vertically. The windows in the inner layer are adjustable for organizing natural ventilation.
- The Shaft-box type can be treated as a special form of the Box-window type. A vertical shaft is formed by a number of boxes to obtain stronger stack effect. This

type requires fewer openings on the external layer.

- The inner cavity of the Corridor type is partitioned by story, and necessary horizontal divisions are made along the length. The air-inlets and outlets in the external layer are located near the floor and the ceiling. In this type, the exhaust air from one partition should be prevented from entering the above partitions.
- The Multi-story type connects the cavity by a number of stories or extended over the whole building. Big size air vents are positioned near the ground floor and the roof to achieve air ventilation in the cavity.

Significant differences exist in thermal insulation capability, sound insulation performance, fireproof performance and ventilation capacity between these types of the DSF in accordance with the different air organizations. The Box-window type and the Shaft-box type enjoy higher sound insulation performance, fireproof performance, while the Corridor type and the Multi-story type suffer from crosstalk noise effect and have a weaker fireproof performance. Both natural and mechanical ventilation could be implemented for the first three types, but only the mechanical ventilation is recommended for the Multi-story type.

Similarly to the Trombe wall, the influence factors of the DSF on its performance include the cavity depth (the air layer thickness), the cavity height, the glazing materials and the shading materials [39]. The most studied factor is the cavity depth, which may vary from 10cm to more than 2m [79]. The influence of DSF's cavity depth has been evaluated by many scholars [80]. Results show that narrower cavities results in an enhanced stack effect and a stronger air movement. Oppositely, a DSF with larger cavity depth weakens the stack effect but strengthens the heat transfer between the DSF and the indoor space. A cavity depth between 0.7 and 1.2m was recommended by Radhi et al. [80] as it achieves a balance between air extraction and heat transfer. Accordingly, in an air-conditioned building, narrower cavities is recommended since the enhanced stack effect leads to lower energy demand for space cooling. However, in a naturally ventilated building, the cavity depth still needs to be investigated based on design parameters and actual conditions in order to obtain a balance between cavity ventilation and heat transfer.

Based on the existing literatures, the DSF system has been proven to be highly useful and effective in modern office building constructions. Compared with conventional building envelopes, it introduces an air exchange chance between the outdoor air and the inner space of the DSF or between the indoor space and the DSF inner space, thus providing an additional opportunity for energy conservation and organized ventilation. Compared with single glass façade, the DSF has the disadvantage of high costs (both on construction and maintenance) and it reduces the net area of a building. But it is widely recommended by researchers from all over the world for that the DSF is cost-effective from a long-operation view since it saves as much as 50% of the building energy consumption and it is more durable when compared with single glass façade [81]. Besides, the DSF provides other benefits on reducing light pollution and noise pollution. Employing the stack effect and greenhouse effect to the inner cavity, the DSF reduces a building's cooling load in summer and the heating load in winter respectively, thus, it seizes great potential for building energy conservation. On the other hand, the thermal channel of the DSF helps to increase the internal surface temperature in winter and reduce it in summer compared to a conventional wall, so a more comfortable and eco-friendly office environment can be created for DSF mounted office buildings.

2.3. Wall-based solar chimney

The solar chimney technology, which offers an excellent natural ventilation opportunity for buildings, is now receiving increasing concern as a large amount of energy has been spent on building ventilation and air-conditioning and substantial greenhouse gas has been released due to the ventilation purpose. Recently, a number of theoretical, numerical and experimental studies have been conducted to demonstrate the ventilation performance of the solar chimney and have contributed significantly to the practical application of this technology [82].

Solar chimney utilizes solar radiation to induce a thermal buoyancy effect, thus enhancing the natural ventilation for a building. When the solar energy is absorbed, the air temperature rises and the air density drops in the air channel of the solar chimney, which makes the air to move upward and finally the heated air is discharged from the top of the chimney [83]. There are two different configurations of the solar chimneys, the vertical solar chimney and the inclined solar chimney [44]. The former employs wall solar collectors, while the latter adopts roof solar collectors. A solar chimney typically consists of an air channel, an absorbing wall and a glass cover with high solar transmissivity to maximize the solar gain so as to enhance the chimney effect. Moreover, the glass cover may be constructed integrated with photovoltaic cells or be substituted by other opaque covers in some cases [84].

The vertical solar chimney is usually attached to the external wall of a building, in which a vertical air channel is structured with a rectangular cross section [85]. The outer side of the channel is made of a glass cover, while the inner side is made by opaque and absorbing wall materials to absorb solar radiation (Fig. 8). Air enters the chimney channel from the bottom of a room requiring to be ventilated. The opaque absorbing wall captures most of the solar radiation and increases its surface temperature. Subsequently, the internal air of the channel is heated by the absorbing wall surface through natural heat convection. As a result of the air density decrease caused by the temperature increase, a natural ascending flow is generated. The heated air finally reaches the top outlet of the chimney is then discharged to the atmosphere. The absorbing wall is insulated at the backside to reduce the heat transfer from the heated surface towards the internal room space.

Employing a solar chimney helps to generate natural-driven airflow for a building, on the premise of converting solar thermal energy into the kinetic energy of the cavity air. The driving force of the air movement results from the air density difference between the inlet and outlet of the chimney. When solar chimney is attached to the external wall of a building, three different modes can be achieved by regulating the air vents, as illustrated in Fig. 9 [36, 86]. In severe cold weather, solar chimney works similarly to the Trombe wall as a passive heating facility by supplying heated outdoor air into the room space. In hot or moderate weather, solar chimney is used for natural ventilation as the outdoor air temperature is lower than the room air temperature. In hot climate, it operates in a thermal insulation mode to reduce the heat gain of an air conditioned room, as the outdoor temperature is much higher than the indoor air temperature. The vertical solar chimney is the most common layout, but it may not be so attractive from the architectural aesthetics view. Another layout of the solar chimney is to lay solar collectors along with the building roof slope [87, 88]. When a single type of solar chimney cannot satisfy the thermal comfort of a building, a combination of both the wall-based type and the roof-based type may be used, or even other active or passive heating and cooling measures might need to be applied. It is believed that an integrated design approach which combines solar chimney and other technologies can induce a higher air flow rate and can improve natural ventilation effect, thus providing a more comfortable indoor thermal environment. Other studies revealed that solar chimneys not only provide heating or cooling in sunny days, but also offer a heating or cooling capacity even during cloudy days [36].

Hirunlabh et al. [89] studied the natural ventilation effectiveness of a metallic solar chimney, which consisted of a glass cover, an air channel, an absorbing wall made by black metallic plate with a micro-fiber and plywood insulating layer. Result showed that the metallic solar chimney with a 14.5cm air channel thickness and a $2m^2$ area achieved the best ventilation performance with the highest air mass flow rate of about 0.01–0.02kg/s. The indoor air temperature was maintained close to ambient temperature, which produced a proper thermal comfort level for the occupants. Furthermore, the heat gain of the test house was significantly reduced by the air circulation in the air channel.

For multi-storey buildings, two different configurations can be applied for wall-based solar chimneys, i.e. the separated type and combined type. To evaluate the performance difference of these two configurations, Punyasompun et al. [90] carried out an experimental and numerical research on a three-storey solar chimney in Bangkok. Two small scale models of three-storey buildings were built, in which the separated and combined solar chimney were integrated into the south-faced external walls (see Fig. 10). The separated solar chimney was built with an inlet and an outlet. While for the combined solar chimney, an air inlet was placed on each floor and one air outlet was on the third floor. The comparison between the solar chimney integrated building and a normal-wall building indicated that the solar chimney could help to reduce the indoor air room temperature by about 4–5℃. And the comparison between the combined and separated solar chimney showed that the combined solar chimney has the advantage of inducing a bigger air flow rate. Thus, the combined solar chimney can be applied for hot climates to promote natural ventilation and to improve indoor thermal comfort.

The shape, the physical properties of the air channel, and the operating conditions are the key factors which greatly influence solar chimney's performance [36]. Nevertheless, solar chimneys have been verified to be capable of enhancing natural ventilation, and this approach enjoys energy conservation potential in buildings. Nowadays, solar chimneys have been applied to both residential and commercial buildings to reduce building energy consumption as well as improve the indoor air environment.

2.4. Glazed and unglazed transpired solar walls

Transpired solar collectors can be integrated to building external envelopes to obtain heating and ventilation profits in cold areas. The technology has been widely used in USA and Canada, where transpired solar collectors are served as high-efficiency fresh air preheating systems [46-49]. According to their working properties, they can be classified as unglazed transpired collectors (UTC) and glazed transpired collectors (UTC) [45]. UTC was introduced in the early 1990s for the purpose of using solar energy for ventilation and warm air heating [32]. The UTC is a wall based heating system which employs a perforated metal sheet as a solar absorber to warm the fresh air. This UTC is also named as the Unglazed Solar wall. The schematic diagram of the UTC is illustrated in Fig.11.

The absorber surface is generally constructed from perforated metal plate (steel or aluminium) and covered with a proper coating. The absorber plate is usually integrated to the external wall of a building. With the help of a ventilation fan, the outdoor air is drawn through the perforations of transpired metal plate into the internal cavity, and simultaneously the air is heated up. The warmed air is finally supplied into the indoor space. In hot weather conditions, the warmed air is directly released to the ambient through the discharge valve located at the top of the cavity to avoid over heating of the indoor air, or it can be used for other purpose such as hot water production to make full use of the UTC system [91, 92].

In a building integrated UTC system, the perforated metal plate is fixed at about 100-300mm from the external wall (also named the back sheet). The space between the absorber surface and the wall surface is sealed on the purpose of creating an air channel. The size of the perforations in the absorber plate varies between 0.5% and 2% of the total surface area [93]. An outlet vent is located at the top of the back sheet, through which the heated air is sucked into the indoor space with the promotion of an air fan. The ambient air flows pass through the perforations and absorb heat energy from the perforated metal plate and the heated wall surface. As reported, about 62% of the air's heat gain is obtained from the absorber plate, while 28% and 10% from the perforations and the back plate respectively [94]. The influence factors on the performance of the UTC includes the porosity of the metal plate, the size and shape of the perforations, the dimensions of the air cavity, the material and absorption coefficient of the collector, the suction velocity, the air velocity inside the cavity, the crosswind velocity, the ambient conditions and so on [95, 96].

Convective heat loss at the absorber surface of a UTC system is eliminated as the ambient air next to the surface is continuously sucked in two the internal cavity. Additionally, the temperature of the metal plate is kept at a low level due to the heat transfer between the sucked air and the plate, which helps to minimize the radiation heat loss. For a solar air heating system constructed by UTC, the key objective is to obtain a higher air temperature rise which contributes to increase the solar fraction [97] in the whole heating system. In this case, the UTC should be operated under a relatively low ambient temperature, thus a lower air flow rates is essential to achieve a sufficient air temperature rise for space heating. However, to eliminate the adverse effect of the crosswind, the suction velocity should be increased to a 0.03–0.05 m/s [98, 99]. Although increasing the suction velocity weakens the influence of crosswind and prevents convective heat loss, it also reduces the duration of the air stay, thus resulting in a decrease in the temperature rise as it lowers the time of heat transfer between the metal plate and the sucked air. The UTC's efficiency was tested to be above 65% when outer wind velocity is below 2 m/s, but it dropped below 25% when the crosswind velocity exceeds 7 m/s. Thus, a conflict occurs between obtaining a higher temperature rise and reducing crosswind effect. When the suction velocity is 0.05 m/s, the temperature rise is only 12-13℃ above ambient temperature [98]. Cordeau and Barrington [100] also reported that when the suction velocity was remained between 0.012 m/s and 0.016 m/s, the supply air temperature of the test room was between 10℃ and 18℃, which means that the UTC system did not work at all actually as the require indoor temperature is higher than 18℃. That is, the solar fraction of the system is zero.

To solve the above mentioned conflict, the GTC is introduced [101]. Compared with the UTC, a glazing cover is added, and relevant air vents are placed on the cover. The configuration of GTC is illustrated in Fig.12. The transpired absorber plate is constructed from metal plate with uniform-distributed holes, which is perforated and covered with selective coating, and is mounted out 100–200 mm from the back wall surface, and the distance between the absorber plate and the glazing cover is 100–200 mm. Fan draws the outdoor fresh air into the outer cavity between the glazing and the absorber plate, and then through the transpired absorber plate into the inner cavity between the transpired absorber plate and the back plate, and at last into the indoor space that need to be heated through air ducts. With the promotion of the solar energy absorbed by the metal plate, air is heated when it is drawn through the small holes on the absorber plate. At nighttime, the air inlet and the fan are closed to form an enclosed cavity in the solar wall structure. The heat loss of the external wall is absorbed by the internal air of the enclosed cavity, which offers an air insulation layer for the external envelopes. Additionally, the adverse effect of crosswinds could be eliminated as the absorber surface is isolated from the ambient by the glazing cover.

With the employment of the glazing cover, the GTC provides an opportunity to generate different air organizations in the solar air heating system. The outdoor air, the indoor air and the mixture of them can be served as the air source the solar collector when fresh air inlet and recirculated air inlet are positioned respectively on the glazing cover and the insulating wall. And the heated air temperature could be raised to above indoor air temperature when the recirculated indoor air or the mixture of the indoor and outdoor air is used for heating in a sunny winter day.

Four operation modes can be achieved in winter by the GTC solar wall system, with proper regulations of the air vents and air dampers, as shown in Fig. 13:

- Full fresh air mode: In this mode, the fresh air inlet is opened, while return air inlet is closed. The outdoor air is sent into the indoor space after being heated by the transpired absorber plate. The ventilation effect is the biggest in this mode.

This mode has the most similar operating principle compared with the UTC system.

- Mixture mode: According to different ventilation demands, the fresh air inlet is opened, and the return air inlet is also opened. The mixture of the fresh air and return air is sent into the indoor space after being heated.
- Full return air mode: When the indoor air quality satisfies daily life demands, the fresh air inlet is closed, while the return air inlet is opened. The recalculated air is sent back to the room space after being heated. In this mode, the heating effect is the biggest.
- Enclosed mode: All air inlet and outlets are closed to form an enclosed cavity in the solar wall structure. The air gap in the enclosed system is served as an air insulation layer for the external envelopes.

Compare the full fresh air mode of the GTC to the UTC, as indicated in a recent paper of Gao [101], under no-crosswind condition, the air temperature rise of GTC is lower than that of UTC by about 3.4℃, and the overall thermal efficiency is lower by about 13.0%, for the reason that the glazing cover leads to a reduction in solar radiation. But when the crosswind velocity increases, the air temperature rise of UTC decreases while the temperature rise of GTC remains almost constant. As the crosswind velocity exceeds 3.0 m/s, the exit temperature of the GTC is higher than that of UTC. Thus it is concluded that the GTC has a higher thermal efficiency than UTC under a higher crosswind velocity condition. When the room air is recirculated to the GTC system, if the outdoor air temperature is -20℃, the supply air temperature can be kept above 20℃ when solar radiation is above 150 W/m^2. Hence, the supply air temperature of a space heating room can be considerably increased due to the employment of GTC, thus the GTC is appropriate for the purpose of space heating. A case study on a five-storey hotel in Harbin reveals that the annual average solar fraction of an solar air heating system based on GTC is about 20%, which is two times higher than that of the air heating system based on flat-plate collector and nearly nine times higher than that of the system based on UTC. Thus, a large amount of energy can be saved when the GTC is applied to indoor space heating systems in cold climates.

2.5. Ventilated PV façades

Photovoltaic (PV) cells/modules are nowadays widely used in buildings for the electricity generating capacity from solar radiation [102]. A building integrated photovoltaic/thermal (BIPVT) system which combines building envelopes and photovoltaic (PV) modules, can not only generate electricity in situ, but also reduce the heating load in winter and cooling load in summer for a building's air-conditioning system [103-108]. The BIPVT technology incorporates PV modules with building envelopes such as roofs, external walls and atrium skylights [109], among which the double-skin PV façades that combine the PV modules and the DSF, are the most promising type. There are mainly two application methods to construct a DSF based BIPVT system, one is suitable for new buildings, which uses PV modules to replace the external façade of a DSF system in the external envelope directly to constitute a BIPVT system; while the other is suitable for energy-saving reconstruction work for existing buildings, in which the PV modules are added on existing external walls or glass curtain walls to form a BIPVT system. Thus, in all air layer involved external wall systems mentioned in the previous sections, including the Trombe walls, the DSF façades, the wall based solar chimneys, and the solar wall systems, opaque or semi-transparent PV modules can substitute the external façade layer to obtain electricity generation capacity.

The electrical efficiency of PV cells was tested to be in the range from 6% to 18% [110], which is affected greatly by the operating temperatures. When the operating temperature rises, the efficiency falls. Every 1 K increase in operating temperature results in a 0.25% efficiency decline for the amorphous silicon PV cells [103] and around 0.4–0.5% for the crystalline silicon PV cells [111]. Thus it is essential to remove the accumulated heat from the PV cell for the purpose of increasing the electrical efficiency. To solve this problem, ventilated PV façades combine the PV technology and external façades, in which an air layer is reserved to cool PV modules; the heated airflow could be served for other thermal applications in buildings.

Fig.14 illustrates a passive ventilated PV façade based on DSF [112, 113]. The PV modules are integrated into the DSF system by replacing the external glazing cover. With the regulation of the vents installed on the external and internal façades, the system can obtain different operation modes for summer and winter. In the winter mode of the system, cool room air is drawn into the air channel and moves upward, absorbs the heat of the PV module, becomes hot and finally travels back to the room space. Besides the benefit of electricity generation, the flow in the internal air layer helps to cool the PV module, which improves the electricity generating efficiency. In the summer mode, outdoor air is drawn into the air channel and moves upward, and finally travels back to ambient. The air flow helps to reduce the heat gain of a room and to increase to electricity generating efficiency. This system can also be used in winter conditions, in which the heated air is supplied to indoor space for space heating as an added benefit.

Fig.15 presents an active ventilated PV façade, which combines the benefits of a BIPV system and a solar thermal system [114, 115]. This system intends to achieve a most efficient operation of the PV module from both electricity generation and solar air heating. The indoor air is sucked into and flows upward along the internal air channel and simultaneously removes the heat accumulated behind the back of the module. Then the heated air is supplied to indoor space with the help of an air fan. The airflow behind the PV modules moves away the accumulated heat of the modules thus helps to increase the electricity generating efficiency.

In a BIPVT system, the external PV modules reduce the heat gain through a building's external envelope significantly by avoiding direct exposure of the external wall to solar irradiation, thus the penetration of solar radiation into the massive wall could be reduced. This effect is beneficial in summer but harmful in winter for it eases the heating capacity of the heated air for space heating. However, the BIPVT system generates electricity, and the air movement helps to increase the electricity generating efficiency, which is considered as a remedy of the thermal performance loss.

Sun et al. performed an experiment and a computer simulation for a PV Trombe wall. Results revealed that the thermal performance is reduced up to 17% due to the hindering function of PV cells on the solar radiation onto the massive wall [116]. In summer, the air movement in the channel increases the electrical efficiency of PV modules by reducing the modules' temperature and takes away accumulated heat to reduce a building's heat gain. An experimental research on a ventilated PV wall indicates that the PV module's temperature is reduced by 15℃, and thus the electricity output is increased by 8% [117].

Additionally, there will be an energy saving opportunity for the air-conditioning system as the heat gain through the ventilated PV envelope is also reduced. A number of researchers conducted studies on the impacts of BIPVT system on indoor cooling load. Brinkworth et al. [109] studied the thermal performance of wall based and roof based PV claddings. Results showed that the wall's peak outer surface temperature was reduced by 20 ℃ as compared to a normal wall due to the shading effect of PV modules and ventilation effect of the air channel. Accordingly, the cooling load is reduced significantly and the energy conversion efficiency of the PV modules is increased. Although the improvement of the ventilated air channel on the electricity conversion efficiency is limited, the influence on a building's annual heat gain through the external envelopes is huge. Yang et al. [118] simulated the performance of the PV walls in different cities in China. They concluded that compared with a conventional wall system, the cooling load is reduced by 33–50% by a PV wall. Ji et al. [119] conducted a dynamic thermal performance research on a PVT wall system in Hong Kong. It was concluded that during a summer period, the total heat gain through the envelope can be reduced by 53–59.2% when the PVT wall system is employed to replace normal external walls. Chow [120] evaluated the effect of a PVT wall on cooling load reduction in Hong Kong. The results showed that the total heat gain through a PVT wall in summer was only 50.8% of that through a normal reference wall. The In addition, the interior surface temperature of the PVT wall is lower than that of a normal wall, indicating that compared with a normal wall, a more comfortable indoor environment can be provided by the PVT wall. Many other researches have been processed to validate the superiority of the PVT wall from the aspects of the electricity generating capacity, the heat gain reduction through envelopes and the improvement of the indoor comfort level. The BIPVT system is proven to be a promising substitution of conventional external envelopes of a building.

2.6. Indirect vertical greenery walls/Double-skin green façades

Plants and greenery are essential for urban environment [121, 122]. They are served as natural resources for localized microclimatic controlling by the specialties of absorption effect, reflection ability and shading effect. Covering greenery on building surfaces is an effective way to integrate plants and buildings [123] and offers a solution for the problem that there is not sufficient public green space for city habitants [124,125]. Additionally, other benefits such as building energy savings, ambient temperature reduction and urban heat island effect mitigation attract widespread attention. There are mainly two ways to integrate greenery into building surface: the green roof and the vertical green systems. Implementing green roofs is becoming popular and many studies have been process on it [126, 127], but vertical green systems have a greater potential as the surface area of walls is usually bigger than that of the roof [128], especially for high-rise buildings.

Vertical greenery systems can be classified into two big groups, the green façades and living walls. And the green façades can be further divided into direct green façade (the traditional green façade) and indirect green façade (the double-skin green façade) [129]. The green façade is the main focus of this section since there is a structured air gap in the indirect green façades. A direct green façade is obtained by attaching creeper plants directly to the external wall, and the plants climb on their own using the building wall as the support structure [130], as illustrated in Fig. 16. The plants are usually rooted in the ground. While for the indirect green façade, the plant layer is separated from the external wall façade of a building by employing specialized vertical support structure for plants to climb. The double-skin structure increases the insulation properties of green walls by introducing an air layer between wall and green layer. Unlike the direct green façades, on which climbing plants grow merely along the wall façade without covering the window holes, the whole surface including both the wall area and the window area can be covered by plants in the indirect green façades [131].

Each kind of vertical greenery system has its own specific effect on temperature reduction. Both the plants' shading effects and cooling effects are helpful in temperature reduction, which helps to reduce the cooling energy demand of a building in summer. Vertical greenery systems have the ability to reduce temperatures not only for the inside space of the buildings, but also for the ambient temperature and surface temperatures, thus more comfortable indoor and outdoor environment can be obtained through these façades. A studied conducted by Price [132] indicated that the ambient air temperature, exterior surface temperature, interior air temperature and heat flux are all reduced by the vertical greenery system, which means a considerable energy-saving in the air-conditioning system can be achieved during summer.

For the double-skin green façades, the microclimate environment in the air cavity between a vertical green wall and external wall façades acts as a thermal buffer and reduces the heat gain through external envelopes by influencing the temperature field and velocity field of the ambient air. Thus the air gap offers an extra opportunity for building thermal insulation. A comparative experimental research was carried out in Netherlands by Perini et al [133]. The purpose of the experiments was to compare the thermal performances of the living wall and different types of green façades. Two green façades and one living wall, which were established with identical wall surface area, were tested to investigate their energy saving potential from the aspects of temperature reduction and wind velocity controlling. One green façade was a direct type and the other was an indirect type with a 20 cm air layer. The results of temperature tests showed that the living wall system had superiority in temperature reduction compared with both of the green façades, and furthermore, the indirect green façade had a better temperature reduction capacity than the direct one. Living wall reduced the ambient temperature by 5.0℃, while direct and indirect green façade by 1.2℃ and 2.7℃ respectively [133]. Different kinds of vertical greenery systems also affect the ambient wind speed differently. The direct green façade reduced the wind speed by 0.43 m/s, while the indirect green façade reduced it by 0.55 m/s in the foliage, but in the cavity the wind speed was increased by 0.29 m/s. The wind speed reduction of the living wall varied from 0.56 m/s to 0.10 m/s (0.46 m/s in average). Thus the air layer in indirect green façades enhances the thermal insulation performance when compared with direct green façades.

2.7. Double layer walls/hollow masonry walls

The double layer/hollow masonry structure has been developed to be an energy-saving type of wall on the premise that the bearing structure of a building has overcome the limitation of conventional building wall forms in which the brick wall system was the main load-bearing structure [134]. Nowadays, brick materials tend to be a type of enclosure material or decorative material, which gives rise to the implementation of the double layer/hollow wall structures. In the double layer masonry walls or hollow walls, the outer decorative layer is stretched and fixed tightly to the inner load-bearing layer [19]. The outer layer's gravity is often taken on by load-bearing connectors which link the two wall layers together. Solid bricks or blocks are the main materials for the outer layer. An air gap is reserved between the two wall layers, and insulation materials can be added to the outer surface of the inner structure layer to ensure a better insulation and soundproofed performance. Generally, for safety consideration, double layer/hollow masonry wall structures are confined to be used in low rise buildings lower than 20 meters [135].
Since an air gap is constructed between the internal and external layers of masonry walls, this type of wall is also named a cavity masonry wall. The air layer can be either closed or open [136], as illustrated in Fig.17. When it is closed, the air layer can be served as a thermal insulation layer, when radiation-prevention measures are taken, owing to the air's low heat conductivity coefficient. The double layer/hollow masonry wall works in a ventilating mode when the air cavity is open, and according to the driving force, the ventilation can be classified as forced ventilation with mechanical facilities and natural ventilation resulted from the stack effect. Most commonly, this wall system works in a ventilated mode in summer to enhance the passive cooling effect of a building. Ciampi et al. [135] numerically evaluated the thermal performance of a ventilated masonry wall. The results indicated that energy saving capacities for 6 different designs of the double-layer masonry wall increase with the increase in the air cavity width, but if the width exceeds 0.15m, there will be a diminishing return in the walls' thermal performance. They also concluded that with a well-designed ventilated masonry wall, the total cooling energy demand of a building in summer was reduced by 40%. So we can conclude that the air cavity of a double-layer masonry wall contributes a lot in reducing the energy consumption of an air-conditioning system of a building in summer.

P. Seferis et al. [137] pointed out that the performance of a ventilated masonry wall is greatly influenced by wall's own nature and the ambient conditions. The former includes the building materials used in the wall, the geometrical characteristics of the air layer and the flow regime of the air; while the latter covers the solar irradiation intensity, the localized wind direction and speed and the ambient air temperature. He conducted both an experimental and numerical research on the thermal performance and the air flow behavior of a ventilated masonry wall under summer and winter conditions. The results supported the conclusion that the circulating air works as a natural and flexible insulation layer in summer and reduces the heat gain of a building through the external envelopes. And in winter, the temperature variation of the air layer is similar to the ambient temperature, but the value is always higher, which verifies that the air layer works as an additional insulation to reduce heat loss through the external envelope.

2.8. Curtain wall constructed by non-glassy materials

In double-skin exterior walls, besides the glaze materials, various types of building materials could be applied, such as metal, stone, plastic materials, fibre-cement plates, tiles, woods, and etc. This section shows some of the curtain walls constructed by these materials.

Metallic outer skins

Metallic skin materials, including metallic corrugated plate, metallic microwell plate, metal net, metal grill, etc. enjoy the advantages of light weight of materials, the diversity of colors, ease of assembly, excellent stain resistance and long lifespan, and have attracted more and more attentions recently in building area [34]. In metallic outer skin systems, the outer-layer metallic materials are often connected to the inner wall façades, such as glass walls or traditional walls, to form a double layer outer wall system with an internal air layer. The superiority of metallic curtain walls is verified on light controlling as well as thermal and sound insulation with the help of the air circulation in the air layer.

Dry-hanging stone curtain wall

A dry-hanging stone curtain wall consists of an inner load-bearing wall, an outer stone pendant, inside metal connectors, and an inner air layer. The stone materials are riveted to inside metal frames, and the metal frames are further fixed on the load-bearing wall [138]. There is always an air layer between the stone material and the load-bearing wall, making it possible to induce air movement in the double façade wall system. Air moves between the outdoor and the internal air layer, bring away the heat gain from the outer surface of the stone materials, thus reducing the thermal load of the indoor air-conditioning. The implementation of dry-hanging stone curtain walls improves the safety and durability of the stone material and helps to keep the stones' outer surface clean, as the air layer avoids the problems of swelling, cracking, dropping and color-changing in the stone materials.

Double layer membrane structure with polytetrafluoroethylene (PTFE) or ethylene-tetra-fluoro-ethylene (EFTE) materials

Plastic membrane/cloth materials enjoy the advantages of excellent light transmittance performance, scattering property and heat absorption capacity. When utilized as building closure materials, the restrictions on shape, span and volume are eased when compared with conventional building structures, thus providing a wealth of possibilities in architectural style and image [34,138]. Membrane structure building employs a new-style space structure which combines the flexible membrane materials and variables of structural bracing systems (Fig.18). Double layer membrane structure contains an air gap in between the two membrane layers. PTFE or EFTE materials are often used as the membrane material in building envelopes. The double layer membrane structure based walls enjoy many priorities as compared with conventional wall systems. Firstly, this type of wall system has many features, such as lightweight, high strength, good weather and corrosion resistance, and outstanding heat insulation performance. Secondly, the membrane material has an excellent self-cleaning function, thus reducing the maintenance and cleaning costs. Thirdly, this wall system has a number of different structural styles, since the PTFE and EFTE membrane material can be processed into wall components with any size and shape. Additionally, the membrane material has flexibility in controlling its sunlight shading coefficient and transmission coefficient, thus, the energy consumption on lighting and air conditioning can be reduced. In these membrane material constructed building envelopes, the air layer plays an important role in thermal and sound insulating.

3. Air layer utilized in windows

Similarly to wall components, for air layer application, different utilization types can be implemented in windows. According to the window area, the utilization pattern is however restricted. The main types include multiple pane windows, airflow/ventilated windows and PV ventilated windows [139-141]. The air layer in multiple pane windows is treated as an enclosed insulation layer with respect to the air's low thermal conductivity, which reduces the heat transfer through window area, while the airflow/ventilated windows and PV ventilated windows employ ventilated air layers to produce natural or mechanical ventilation through the window area to improve the indoor thermal comfort and the indoor air quality.

3.1. Multiple pane windows

Windows are an important element of a building's external envelopes, since the glazing area provides natural daylight, natural ventilation and weather protection for a building. However, windows are questioned due to large amount of heat loss or heat gain through the window area, thus they are always treated as the weakest link of a building from the thermal insulation point of view [142]. Approximately 30% of the total heat loss through the building envelope of a typical house occurs from windows [143]. In winter, heat loss through external windows and infiltrations accounts for about 50% of the total heat loss of a residential building in Northern China.

Consequently, the glazing of a window has been increased from single to double, even triple layers to increase the thermal insulation property and sealing property of a window. Double-glazed window is becoming widespread to replace the conventional single-glazed windows due to its lower U-values, since the stationary air layer between two panes has very low heat conduction coefficient and reduces the overall heat transfer through windows. Furthermore, several methods can be taken to reduce heat loss through double-glazed windows, including optimizing the air layer thickness [144,145], filling the air cavity with aerogel [146,147] or replacing the internal air with low conductive gases such as inert gas [148,149], coating glass surface with low emissivity materials [150-152], or simultaneous combining some of these methods [153]. Filling the window cavity with low conductive gases can reduce conduction and convection heat transfer. Coating pane surfaces with low emissivity materials is beneficial to reduce radiation heat transfer. Optimization of cavity thickness of double-pane windows can significantly improve energy efficiency. Actually, in a certain range, increasing the air layer thickness is an effective way to improve the thermal insulation property of a double layer window, but if the thickness is increased beyond a critical value, a heat convection occurs in the enclosed air space and results in an increase in the overall heat transfer coefficient, which may defeat the purpose of reducing the heat loss through window area [154, 155]. Thus there is an optimal value of the air layer thickness in a double-glazed window which defines the minimum of its heat transfer coefficient. To achieve a further improvement in thermal insulation property of a window, triple-pane or quadruple pane configurations have appeared to increase the stationary air layer thickness [139,145,156,157]. Fig.19 illustrates the schematics of the double-pane, triple-pane and quadruple-pane windows.

To investigate the performance of double-pane windows, Aydın [13] numerically evaluated the conjugate heat transfer process of a double-pane window. It was concluded that optimizing internal air cavity thickness can considerably reduce energy losses through double-pane windows. Korpela et al. [158] numerically investigated the flow and heat transfer through a double-pane window and obtained a formula for optimizing window space thickness. Xamán et al. [159] conducted a numerical study on the overall convective heat transfer considering both laminar and turbulent natural convection in the air cavity. The Nusselt number correlations for both laminar and turbulent flows were presented. In order to obtain the optimal air layer thickness of a double-pane window, Aydın [160]carried out a numerical study on different climatic zones of Turkey. He determined the critical value of air layer thickness only from the aspect of energy loss. It was recommended that for different climate zones of Turkey, the optimum air layer thickness varies from 12 to 21mm. Considering both the heating and the investment costs, Arıcı and Karabay [144] determined the optimal air layer thickness of double-pane windows. In their study, the optimum air layer thickness varies between about 12 and 15mm depending on the weather condition, fuel type and base temperature. They also indicated that about 60% energy can be saved in a building with well-optimized double-pane windows.

For performance assessment of multiple pane windows, Manz and Menti [161] studied the energy performance of multiple pane windows in eight European cities.

The influence of pane numbers, air layer thickness, gas filling, and coating number and properties were analyzed. They concluded that the triple-pane windows perform best and achieve net gains at south-facing façades, while double-pane windows without any coatings lead to net losses in cold regions. Karabay and Arıcı [139] performed a thermo-economical optimization of multiple pane windows for different cities of Turkey. The results showed that the optimum number of panes varies between two and four in accordance with the climate and the fuel source. They suggested that multiple pane windows should be strongly considered especially in cold climatic regions. Söylemez [156] also conducted a thermo-economic optimization on the performance of multiple pane windows. A simple algebraic formula was obtained for estimating the optimum number of panes for windows. And the overall heat transfer coefficient values of single, double, triple and quadruple pane windows are provided. Thalfeldt et al. [162] reported that with more panes and low emissivity coatings, the energy performance can be improved. For cold climate regions, the cost optimal solution of a building is the triple-pane window with 25% window-to-wall ratio and the quintuple windows with a ratio of 60%. Arıcı and Karabay [163] investigated the fluid flow and heat transfer in double, triple and quadruple pane windows numerically. The results show that increasing number of panes can significantly reduce the heat loss through the windows. If the double-pane windows of a building are replaced by triple or quadruple pane windows, about 50% or 67% of energy can be saved respectively. They also indicated that the benefit of multiple pane windows is more profound in cold regions. Arıcı and Kan [142] carried out a numerical study to investigate the fluid flow and heat transfer characteristics in double, triple and quadruple pane windows. Results show that the most reasonable gap width is 12mm. They also presented the correlations for predicting the glazing U-value considering the pane numbers, the glass surface emissivity and the air layer thickness for both the air-filled and the argon-filled multiple pane windows.

3.2. Airflow/Ventilated windows

Increasing the glazing layer leads to an improvement in the insulation property and the sealing property of a window, thus can reduce heat loss through the window area. However, this effort may bring adverse effect to the indoor air quality since inadequate ventilation is a common problem in a tightly sealed residential building. Solving this conflict between energy conservation and indoor air quality maintenance in a residential building has become a challenge. The airflow or ventilated window was proposed for the purpose of supplying fresh air through the window frame to improve indoor air quality [164]. Airflow window works in the same way as a double-skin façade, and a dual airflow window works like a heat exchanger by transferring heat between the exhaust air and the supply fresh air [165], thus can reduce the energy wasted in heating the cold fresh air in winter and in cooling the hot fresh air in summer. Airflow windows have been verified by many scholars to be very promising to realize energy conservation as well as indoor air quality improvement in residential buildings for different climates.

As the name implies, the biggest difference between an airflow window and a conventional window is that a natural or forced airflow exists in the internal cavity between two glass layers. An airflow cavity is usually constructed with a single layer pane on one side and a double glazed insulated unit on the other side, which results in a triple paned airflow window [140]. According to different purposes, different combinations of single panes or double glazed insulated units can be adopted to form an airflow window, as shown in Fig.20. There are four operation modes of airflow windows [164,166]: the supply mode, the exhaust mode, the indoor air circulation mode, and the outdoor air circulation mode. Note that in Fig. 20, the left side is the outside of a window. In the supply mode, the outdoor fresh air is induced into the cavity and is driven to move upward by the buoyancy effect. Simultaneously it is heated by solar radiation and finally supplied to the indoor space, so this mode is often used in winter for space heating. In the exhaust mode, the indoor air is extracted through the cavity to the outside space. The mode uses indoor air to cool the window panels and to remove heat accumulated in the cavity. Thus, it is often used for passive cooling in summer. The indoor air circulation mode treats solar radiation as a heating source of the indoor air in winter, while the outdoor air circulation mode uses the solar radiation to obtain a buoyancy effect in the cavity and circulates the outdoor air to cool the window panels and to remove accumulated heat in summer. There is no air exchange between indoor and outdoor in the latter two modes. In supply mode and indoor circulation mode, as they are often in winter, the inner side layer is usually an absorptive glass layer to absorb solar energy; while in the exhaust mode and the outdoor circulation mode, which are employed as passive cooling measures in summer, the outer side is usually an absorptive glass layer. In airflow windows, venetian blinds, which can trap the solar radiation easier than the glass materials, are often added into the cavity to increase the airflow rate. All the four modes can be operated by buoyancy force from the solar radiation or by other mechanical force.

To evaluate the performance of airflow windows, many researches have been conducted. Southall [167] studied a supply air window, which consists of two glass panes that are separated by an air gap. This window provides pre-warmed air for winter ventilation using the air gap as a pathway of air supply. T.T Chow et al. [140] developed a ventilated solar-screen glazing system which incorporates a weatherproof clear glass pane and an absorptive glass pane with low shading coefficient that is mainly used for solar radiation absorption. The window is equipped with a 180° reversible mechanism, thus the switching between the summer and winter mode is allowed. The simulation results indicate that in warm climatic region, better savings can be achieved when the ventilated window is employed in summer. And the reversible mechanism is not required in this climate. They [140] also examined the thermal performance of a natural airflow window by using a dynamic model developed from the integration of energy balance and airflow networks. The findings confirmed that the natural airflow window can achieve considerable energy saving in buildings in Hong Kong and Beijing. The space cooling load can be reduced to 60% of the commonly used single absorptive glazing in Hong Kong. While in Beijing, where the reversible mechanism is necessary, the cooling load can be reduced to 75%

of the commonly used double glazing configuration in summer, and the space heat gain can be improved by 46% in winter. Jorge S. Carlos [168] presented some results of an experimental study performed on a two ventilated double window systems exposed to real outdoor weather. Results indicated that this window system is applicable to both new and old buildings by providing preheated ventilation air in winter time, by recovering part of the heat losses from indoors and by transferring solar radiation heat gains. This kind of system helps to reduce the global heating energy needs of a building, in winter, since it can lead to a significant reduction of the heat loss through ventilation. Later in 2014, he [169,170] conducted an experimental and analytical study on the solar heat gain coefficient of a ventilated double window, which was formed by two parallel windows in the same façade opening with a ventilated air-channel between them. It is concluded that the solar heat gain coefficient depends considerably on the type of glass used and its transmissivity, the air flow rate passing through the system and the percentage of glazing area. The research results of many other studies have also confirmed the advantages of using airflow windows in buildings of different climates.

Recently, a dual airflow window is developed to further improve the thermal efficiency of airflow windows, as presented in Fig. 21. The dual airflow window is often constructed with three clear glasses with no coating and two airflow paths are formed in the window. The outdoor fresh air moves into the indoor space through the outer path, and the inner path induces indoor air to the outdoor space. The mid-glazing works like a heat exchanger between the two airflows, thus the supply fresh air can be heated by both the solar radiation and the exhaust air. Unlike the single airflow window mentioned above, the dual airflow window must operate with the promotion of two air fans. Compared to a conventional window, all airflow windows can capture solar radiation to heat the air in the cavity and can direct the heated air to indoor space or outdoor space. So the solar energy is treated as an energy source of passive heating in winter or passive cooling in summer. The dual airflow window has a higher thermal efficiency than the supply and exhaust mode windows due to the heat exchanger function. And compared to the indoor air circulation mode or the outdoor air circulation mode, the dual airflow window can supply fresh air to indoor space, thus it is capable of improving the indoor air quality [164-166]. The dual airflow window can save energy consumed in space heating or cooling as well as improve the indoor air quality by supplying fresh air to indoor space.

A dual-airflow window with triple glazing can save more energy than a single-airflow window, since the former works like a cross-counter flow heat exchanger. Gosselin and Chen [165] proposed a four-step computational method which combines computational fluid dynamics (CFD) and coded radiation calculations to demonstrate the airflow and heat transfer characteristics of the dual-airflow window. And they tested a full-scale dual-airflow window system to validate the method. The comparison between simulated and measured temperatures shows a good agreement. Wei et al. [164] evaluated the energy performance of the dual-air window for different climate in China and compared it to blinds windows and low-e windows based on building a network model for calculating the complex heat transfer through the dual airflow window. It is concluded that the dual airflow windows could reduce the heating energy of a 60 m^2 apartment by 16–48% depending on the climate, compared with blinds windows. When compared with the low-e windows, the cooling energy reduction was only 11–21%. Later, in order to optimize the dual-airflow window design, they employed the orthogonal method to evaluate the influences of different design parameters. It was found that the outdoor air supply rate, window height, window orientation, shading coefficient, and window blinds position and window orientation are the most important parameters for a dual-airflow window's thermal performance. They further identified the optimal values of these parameters for design [166]. With the optimal parameters, the dual-airflow window is able to save 25% energy in warm climate regions such as Guangzhou and 34% in cold climate regions such as Harbin. Thus, they suggested that the dual airflow window is more effective in cold climate from energy saving potential point of view.

3.3. PV ventilated windows

To improve the thermal performance of a window, another alternative is to integrate photovoltaic technology into window designs by using the semi-transparent photovoltaic cell that has been developed in Switzerland [171] and Japan [172]. The see-through solar cell has the advantage that the spectrum of the transmitted natural light is almost the same as that of the direct incident light. And this new type of window offers an additional function of electricity generation. A typical PV ventilated window is made of two panes of glass, a semi-transparent photovoltaic layer and an internal air layer in between the glass layers [141]. Fig. 22 illustrates the configurations of a PV ventilated window which are designed for different climate conditions, in which the outer absorptive glazing of a ventilated window is replaced by a normal float glass pane with a see-through solar cell layer attached on the back. Two glazing assemblies are incorporated in this window system: a clear glazing as the inner pane and a PV involved glazing as the outer pane.

The working mode of the PV ventilated window system can be regulated by the controlling the air vents positioned on both the inner and the outer panes. The reversible mechanism of the air vents makes it possible to realize both passive cooling and space heating in different seasons [141]. In the cooling mode, the air exchanges between the internal air layer and the ambient, while in the heating mode, between the air layer and the indoor space. The air flow can be either buoyant-induced or mechanical-driven. In the heating mode, the system provides the advantages of electric power generation and space heating opportunity, but the heating capacity is weaker when compared with a double layer ventilated window with an absorbing glazing in the outer pane, since the PV glass pane consumes part of the solar energy for electricity generation. And in the cooling mode, with the screening effect of the PV cell together with the air exchange between the outdoor environment and the ventilation gap, the solar transmission to the indoor space and the heat transfer from the outdoor to the indoor space can be greatly reduced, resulting a reduction in the cooling load of the air-conditioning system and an improvement in local thermal comfort for the occupants. For both modes of the PV window system, the air flow in the internal layer takes away the accumulated heat of the PV cell, which ensures a high electricity production rate. From a comprehensive view, the PV ventilated window system enjoys the advantages of green electric power generation, the energy saving through the reduction in the air-conditioning load, the daylight utilization, and the indoor thermal comfort level improvement [51].

To investigate the performance of the PV ventilated window, Chow et al. [141] numerically analyzed the overall energy performance of this window system when it is employed in Hong Kong office buildings. The research results indicated that the surface transmission was found dominated by inner glass properties, but the overall heat transfer is affected by both the outer and inner glass properties. It was also found that a solar cell transmittance in the range of 0.45–0.55 could achieve the best integrated electricity saving in air-conditioning and lighting. Chow et al. also conducted a comparative study to compare the energy performances of the double-glazed, single-glazed, force-ventilated PV and naturally-ventilated PV glazed windows [173]. They concluded that for a typical summer day, the energy consumption of the air-conditioning system could be reduced by 26% and 61% respectively, by using single-glazed PV and naturally-ventilated PV windows instead of normal absorptive-glazed windows. Further [174], the natural-ventilated PV double-glazing technology was applied to a typical office building of Hong Kong, a numerically investigation showed that the air-conditioning power consumption could be reduced by 28%, when compared with that with single absorptive glazing windows. Using the simulation software EnergyPlus, Miyazaki et al. [175] investigated the performance of a PV window utilized in office buildings in Japan in terms of electricity production, daylight control, and thermal loads. The results showed that windows with the solar cell transmittance of 40% and the window to wall ratio of 50% achieved the minimum electricity consumption. With the optimum PV window configuration, the related electricity consumption of the building was reduced by 55%, as compared to a building with single-glazed window systems. He et al. [176] conducted an experimental study on the thermal performance of a double-glazed PV window and a single-glazed PV window. It was reported that, by setting up an air gap behind PV modules, the total heat gain and secondary heat gain of the double-glazed PV window were 78.3 W and 51.8 W, respectively, accounting only 53.5% and 45.8% of that of the single-glazed PV window. And due to the much lower surface temperature, the PV double-glazing window provides better thermal comfort than the single-glazed one. Yoon et al. [177] processed an experimental study an a-Si BIPV window, especially on the surface temperature. The results showed that the indoor surface temperature of the BIPV window was lower by 1℃ during the daytime in summer season due to its lower solar heat gain coefficient, and was 2℃ higher during the night time in winter season due to its better thermal insulation effect, when compared with normal windows. Thus, the using of BIPV windows in a building can achieve a high thermal comfort level.

4. Air layer utilized in roofs

When constructing an air layer in roof systems, an extra construction layer is often added to the traditional roofs. The extra layer can be a secondary roof layer, an absorber plate with glass cover, a solar air collector layer with or without glass cover, or a PV module layer. With these construction layers, the double-skin roof system, the roof-based solar chimney system, the roof integrated solar air heating system, and the roof integrated PVT system can be established respectively. The air layers in these systems can work either in an enclosed mode or in a naturally/mechanically ventilated mode. The enclosed mode provides an extra air insulation layer for the roof in winter; the naturally ventilated mode achieves a passive cooling effect in the roof system; and the mechanically ventilated mode is often employed to supply the heated air in the roof air layer to the indoor space to obtain a space heating capacity.

4.1. Double-skin roofs/Ventilated roofs

As they are directly exposed to the outdoor environment, building external envelopes play a major role in absorbing solar heat, especially for the roofs. In a traditional building, the surface temperatures of the roof can easily reach 75-80℃[178]. A numerical study showed that the heat gain through vertical façades and roof surfaces accounts for nearly 64% of the total air-conditioning system's energy consumption in a 12-storey residential building of Singapore [179]. Furthermore, the roofs absorb about three times higher solar radiation than vertical façades [180], which indicates that the solar heat gain through the roof is one of the main sources of buildings' heat gain. Thus, to reduce the cooling load of an air-conditioning system, it is essential to reduce solar heating gain through the roof of a building. Besides building roof surfaces with high solar reflectance and high thermal emittance materials, employing ventilation air layers in building roofs (named the double-skin roof) is an effective way to improve the thermal performance of building roofs in summer times [181, 182].

A double-skin roof consists of two solid roofs which are separated by an air gap in between, as shown in Fig.23. The downside roof layer is named the primary roof, while the upside one is named a secondary roof which shields the primary roof from direct solar radiation. The air layer can be either open-ended or close-ended. If the air layer is a close-ended type, it acts as an insulation layer. In the case of open-ended air layer, the air moves from the bottom to the top of the layer under the buoyancy effect or with the help of mechanical fans and takes away the heat accumulated in the air layer from solar heat gain, hence, heat gain into the indoor environment through the primary roof could be reduced, especially in summer. Internal ventilation in walls and roofs is capable of carrying heat and moisture effectively to the outdoor environment and keeping the internal part of the roof cool and dry [183]. And when the roofs and walls of a room are built with ventilated air layer, the room temperature in summer can be reduced about 5-12℃ [177].

Ventilated roofs are more useful in hot climatic conditions, particularly in wide roof area buildings. The ventilation can be either a passive type or an active type. The former uses the stack effect to drive the air flow, while the latter covers fan induced ventilation. The flow can be either laminar or turbulent depending on the cavity size. A detailed energy analysis on ventilated roof buildings indicated that, compared with non-ventilated roof buildings, an energy savings of 30% can be achieved during the summer period of Italian [184]. And during cold winter time, the air layer can be closed using suitable dampers to form an insulation air layer from an energy saving point of view. In order to improve the cooling effect of the internal ventilation in ventilated roofs, Lee et al. [182] experimentally investigated the influence of cavity ventilation, the slope of the roof, intensity of solar radiation, the size and shape of the cavity, and panel profiles on the airflow and temperature distribution in the cavity. The tests showed that when there was a ventilation in the air cavity, the middle cavity temperature dropped from 65℃ of a non-ventilated cavity to 27.5℃, showing that employing a ventilated layer in the roof, thermal accumulation in the roof can be prevented, and the cooling load can be reduced. Susanti et al. [185] evaluated the impact of natural ventilation of a roof cavity on the thermal environment and the indoor cooling load of a factory building. Comparisons between factories with a cavity roof and a single roof in the Japanese climate showed that the cavity roof was superior to the single roof in lowering the operative temperature by about 4.4℃. When the factory was air conditioned, the cooling load can be reduced approximately 50% during the summer to maintain an operative temperature of 26℃ by the natural ventilation in the cavity. Gagliano et al. [186] conducted a numerical research on the thermal performance of ventilated roofs during the summer period in Italy. The results showed that the ventilation of roofs can reduce the heat fluxes up to 50%, thus, in regions with high solar radiations, the double-skin roof might be considered an effective technique to improve the summer energy performance of a building. Oh J et al. [187] proposed a novel heat transfer model for a double-skin roof combined with an outer cool roof. The results showed that white-color cool coating on a flat double-skin roof reduces the daily heat gain by 0.21 kWh/m^2 (or 51%), and the peak indoor air temperature can be reduced by 2.4℃ on a sunny day. The double-skin roof is about 6% more effective than cool roof in reducing annual heat gain into the indoor space. Furthermore, adding an extra insulation on double-skin roof reduces the heat loss during night time, which indicates that the cool roof can serve as a supplement to the double-skin roof in reducing net annual heat gain. Adding a cool coating on the double-skin roof reduces the peak secondary roof temperature by 14.7℃, and the primary roof temperature by 4.7℃.

4.2. Roof-based solar chimney

As mentioned in the “wall-based solar chimney” section, there is also an inclined type of building integrated solar chimney, which employs roof solar collectors to absorb the solar energy to enhance the natural ventilation of a building [44]. This technology is named the roof-based solar chimney and can be integrated into the gable roofs of a building by installing roof solar collectors and glass covers on the roof. The main purpose of the roof-based solar chimney is to induce natural ventilation in the roof structure in summer. But sometimes, this configuration can also be used for space heating in winter by just adding an air fan and necessary ducts in the structure; in this case, it is named roof solar air heaters.

As illustrated in Fig.24, the roof-based solar chimney operates with the same principles of wall-based solar chimneys for ventilation purposes. It utilizes the building roof to mount solar absorber plate, and a transparent or semitransparent cover is employed to cover the absorber plate. An inclined roof-based solar chimney is mainly composed of the transparent cover, the solar absorber plate, and the air channel [188]. The cover and absorber plate are inclined and separated by the air channel. In sunny days, solar radiation penetrates the cover and heats up the absorber; the thermal energy is then transferred from the absorber plate to the internal air in the air channel and a temperature increase occurs in the air. The heated air moves upward and exits the channel at the top, while indoor cool air is drawn into the channel from the bottom inlet. Thus, the solar induced natural ventilation of the room is achieved. The performance of the roof-based solar chimney mainly relies on the chimney aspect ratio (stack height/air gap width), the ventilation height (height between inlet and outlet apertures), the aperture area, the thermal characteristics of the absorber material, and chimney tilt angle [188,189].

To investigate the performance of the roof-based solar chimney, Al-Kayiem et al. [189] simulated and tested its thermal energy and fluid flow processes. The results showed that the performance of the system is highly influenced by the solar intensity. And the system performance improves as the collector area and the chimney heights increase. But the wind speed has an adverse effect on the ventilation performance. As the wind speed increases from 1.5 to 6 m/s, the system performance reduces by 25% when the solar intensity is 900 W/m^2. Aboulnaga [190] conducted an analytical study on a 15 m^2 roof-based solar chimney which is assisted by a cooling cavity in hot arid climates. The air channel width varied from 0.08 to 0.25 m. The results showed that the maximum air velocity about 1.1 m/s. Chen et al. [191] experimentally studied on a roof-based solar chimneys with variable chimney gap-to-height ratios between 1:15 and 2:5, and different inclination angles. Results showed that the maximum air flow rate was achieved when the inclination angle was around 45°, the air gap width was 200, and the chimney height is 1.5 m. Bassiouny and Koura [192] analytically and numerically evaluated the effect of the solar chimney inclination angle on the air flow pattern and the ventilation rate. The results showed that a maximum air flow rate was achieved when the inclination angle was between 45°and 70° for the latitude of 28.48°. Mathor [193] reported that the optimum inclination angle is within 40° to 60° depending on the location latitude. When the angle is 45°, the induced air flow rate is about 10% higher than those with the angles of 30° and 60°. Hirunlabh et al. [194] investigated the performance of a roof solar chimney to maximize the induced natural ventilation. The results indicated that this system contributes to improve the indoor thermal comfort. Imran et al [195] evaluated the induced flows of roof-based solar chimneys with different inclination angles, solar heat fluxes and chimney thicknesses.

The results of showed that the optimal inclination angle was 60° for the purpose of obtaining the maximum ventilation rate. The induced air flow rate increases linearly with increases in solar radiation, and also increases with increases in the gap thickness. Deblois et al [196] examined the performance and level of energy savings of roof-based solar chimney, cross-ventilation, and standard ventilation strategies. The results indicate that the roof-based solar chimney provides free cooling and natural ventilation in all tested climates and seasons. The cross ventilation reduced the indoor cooling load by approximately 50%, and the roof-based solar chimney by up to another 80%. Zhai et al. [197] proposed a double pass roof-based solar chimney and compared its performance to traditional single pass roof-based solar chimney. The single pass chimney is formed by integrating single pass solar air collector with southern roof of the building, while the double pass one is configured by integrating a double pass solar air collector with the southern roof of the building, in which the indoor air can enter both air channels due to the chimney effect. Numerical simulations showed that the efficiency of the double pass roof-based solar chimney was higher than that of the single pass one by 10% on average, and the air flow rate could be improved by the double pass roof-based solar chimney, which indicates that the double pass roof-based solar chimney was superior to the single pass one from the points of view of both space heating and natural ventilation. Therefore, the double pass roof-based solar chimney was more potential for building energy saving and indoor thermal environment improvement.

4.3. Roof integrated solar air heaters

Solar air heaters are considered to be one of the most potential applications of solar energy utilization. They can be used for many purposes, including drying agricultural, textile or marine products and heating indoor space to maintain a comfortable environment [198]. The flat plate collector [199-201], used to be the most popular type of solar air heaters, typically consists of a glazing cover and a solar absorber plate mounted on insulated back surface. Many different configurations for solar air heaters have been reported and discussed in previous literatures, such as bare plate, back-pass, glazed, unglazed, covered, uncovered, perforated, un-perforated, single pass, double pass, triples pass[45-47, 202], and etc. Each of them has merits and demerits and can be applied to different weather conditions and various purposes. Solar air heaters can be integrated into building envelopes, e.g. the glazed and unglazed transpired solar walls in which transpired solar air heaters are integrated into external wall, and the roof integrated solar air heaters in which the flat plate collectors are integrated into building roofs to form an active space heating system. In the roof integrated solar air heaters, the building roof is served as the insulated back surface which is used to mount the solar absorber plate [48,49]. A schematic of the roof integrated solar air heater is illustrated in Fig. 25 [47].

Similarly to the roof based solar chimney, a roof integrated solar air heater mainly consists of a transparent cover, a solar absorber plate, and an air channel. The difference is that the roof integrated solar air heater adopts an air fan and some supplementary air ducts to distribute the heated air into the room space [203]. In sunny days, solar radiation penetrates the cover and heats up the absorber; the internal air also gets heated and starts to move upward; the air fan draws the heated air into the duct and supplies the heated air to the room. The inlet of the air channel can be placed either indoor or outdoor. When it is located in the outdoor, fresh air is drawn into the air channel and supplied into the room after being heated, thus a fresh air supply capacity is achieved for the system; when the indoor air is induced into the air channel, the system obtains a bigger space heating capacity.

Joudi experimentally investigated the performance of roof integrated solar air heater system for heating an innovative greenhouse in Baghdad, Iraq [204]. Tests were conducted in the winter of 2012. The results showed that the mass air flux of the roof integrated solar air heater varied from 0.006 to 0.012 kg/s·m^2. And with the mass air flux of 0.012 kg/s·m^2, the solar air heater can provide about 84% of the daily heat demand in maintaining the inside air temperature of the greenhouse at 18℃. The total energy grasped by the heater and the greenhouse can cover all the daily heating demand with an excess of approximately 46%. Saman et al. [205] analyzed the thermal performance of a roof integrated solar heating system with a phase change storage unit. The storage unit consists of several phase change material layers with a melting temperature of 29℃. Heated air generated from the roof integrated solar heater passes through the internal spaces between the phase change material layers to charge the storage unit. And the stored heat is utilized to heat the ambient air which is supposed to be sent into the indoor space. University of South Australia [206] proposed a roof integrated solar air heating/storage system, which employs existing corrugated iron roof sheets as unglazed solar collectors to absorb solar energy to heat the air in the cavity. A thermal storage unit with phase change materials is used to store heat during the daytime so that necessary heat can be provided for nighttime or non-sunshine time. When the room needs space heating during sunshine times, fresh air moves along the air channel and gets heated simultaneously, and is subsequently sent into the indoor space. When heating is not required, the heated air is sent to the thermal storage unit, melting the phase change materials for future use. Belusko et al. [203] also examined a roof integrated solar air heating system using a corrugated steel roof to function as an unglazed air collector. The results showed that the roof integrated solar air heating with glazing has a greater potential to be cost effective. Adding a glazing cover significantly improved the performance of the system to 22% above that of a heat pump.

4.4. Roof integrated PVT system

A PVT solar collector combines the PV modules and solar thermal components together to produce electricity and thermal heat simultaneously. This dual effect of the PVT collector achieves a more effective utilization of solar energy and enjoys a higher overall solar conversion rate by recovering part of the accumulated heat in the collector to apply for low-and-medium-temperature applications [47]. The BIPVT system is considered as one of the most promising PV applications, which provides electricity, space heating and day lighting simultaneously when semitransparent PV modules are employed. The BIPVT technologies can be roughly classified as the wall/façade integrated PVT technology and the roof integrated PVT technology [207]. The combination of PV modules and ventilated roofs can not only improve the solar conversion efficiency, but also reduce the cooling load through the roof.

The cross section view of a roof integrated PVT system is shown in Fig. 26. Semitransparent PV modules are installed outside the roof with an angle of 34° to the horizontal [208]. An air channel is reserved between the modules and the roof surface. And inlet and outlet vents are designed on the roof or on the module to support an air exchange between the air channel and the indoor space or between the air channel and the outdoor environment in a space heating mode or a summer cooling mode respectively. In sunny time, the PV module gets heated by solar radiation. Cool indoor air from indoor space or outdoor space enters the air channel through inlet vent, absorbs the heat of PV module. The hot air enters the room space for space heating in the heating mode or escapes to the ambient in the cooling mode. Sometimes, in winter mode, to obtain a smooth air circulation, an air fan is needed to distribute the heated air. In this system, thermal energy of the PV modules is utilized as a by-product for space heating. And the circulated air reduces the operating temperature of PV module, thus increases its electrical efficiency.

To evaluate the performance of the roof integrated PVT system, Mei et al. [207] experimentally examined the potential for high temperature operation of the system. The results showed that the temperature rise in PV modules adversely affect the electricity generation when the back ventilation is restricted. Chen et al. [208] found that the thermal energy output rated about 8.5-10 kW in a roof integrated PVT system with roof surface area of 64 m^2. And annual electricity saving of 1203 MWh was achieved by a roof integrated PVT system employing semitransparent PV modules in a building, as reported by Li et al. [209]. Song et al. [210] experimentally investigated the influence of the tiled angle on the electricity generating performances of roof mounted PV modules in Yongin, Gyeonggi, Korea, which was located in mid latitude regions. Results indicated that the PV modules installed at 30° have a better performance than vertical PV modules in terms of annual power output. Ordenes et al. [211] numerically evaluated the performance of roof integrated PVT system in low latitude regions of Brazil. It is concluded that the roof integrated PVT system produces more energy than the vertical façade based PVT system. More than 45% of energy will be produced. But for high latitude regions, the performance comparison between the inclined PVT system and vertical system is still to be investigated, since the sun path is low high latitude regions. Vats [206] studied the effect of packing factor of semitransparent photovoltaic (PV) modules in a roof integrated PVT system on the module temperature, the indoor air temperature, and the electrical efficiency. Results indicated that PV module temperature decreases as the packing factor decreases, and the electrical efficiency and indoor air temperature increase with the decrease in the packing factor. The maximum annual electrical energy output is 813 kWh in HIT PV module and annual thermal energy is 79 kWh in a-Si PV module when the packing factor is 0.62. Karava et al. [212] concluded that roof integrated

PVT system is helpful in space heating of cold climatic regions. Vats [213] conducted a comparative study on building roof integrated and façade integrated PVT systems with semitransparent or opaque PV modules with and without air duct in the cold climatic conditions of Srinagar, India. Results showed that maximum room temperature can be achieved to be 22.0℃ in the system employing semitransparent PV modules and without air duct, when the ambient temperature is 4.4℃. Thus, the roof integrated PVT system without air duct is more suitable for cold climatic conditions. S. Pantic [214] processed a theoretical and experimental study on the energy performances of three different configurations of the roof based PVT systems. Each system can significantly increase thermal efficiency and air outlet temperature. Wang et al [215] investigated the influence of four different roof integrated PVT systems r on the building's heating-and-cooling loads. The simulation results showed that PV roof with ventilated air-gap is suitable for summer application as it has a high PV conversion efficiency and results in a low cooling load in summer. In winter, non-ventilated PV roof has a higher feasibility since that it provides a low heating-load through the PV roof and a high PV electrical output.

5. Performance analysis of different types of air layer involved envelopes (ALIEs)

5.1 Summary of air layer effects and ALIE performances

Table 1 summarizes the system structures, airflow patterns, air layer effects, system benefits and functions, and the restrictions and disadvantages of different ALIEs.

All the ALIE systems are similar in structure, one is that one or two air layers is constructed in these systems to provide an extra insulation layer or to obtain an air ventilation channel; another is that a solar absorbing layer with different materials (massive wall material, metallic plate, absorptive glass, solar air collector, PV cells, etc.) is usually employed so as to convert part of absorbed solar radiation into thermal energy to heat the air layer. The operation mode of the air layer used in building envelopes can be roughly classified into three types: the enclosed type, the naturally ventilated type and the mechanically ventilated type, as presented in Fig. 27. The enclosed type often functions during winter especially during winter night time and acts as an extra insulation layer for the external envelope. Actually, almost all ALIEs used for space heating and passive cooling need to be converted into an enclosed type by closing adjustable dampers and air vents in the systems, to reduce heat transfer through the system area. Naturally ventilated air layer is often adopted in passive cooling systems and some of the space heating systems. The air layers in these systems are always heated by absorbing layers and serve as the start point of induced airflow. The internal air gets heated, moves upward along the air channel, leaves the channel at the top and enters into the ambient or the indoor space; the cool ambient air or indoor air is drawn into the channel at the bottom. The induced airflow due to the buoyancy effect actuates different air circulations to achieve a passive cooling, natural ventilation or a space heating effect. When the air exchanges between the ambient and the air channel, a passive cooling effect is produced; when air moves from indoor space to outdoor through the air channel, a natural ventilation is generated; if the air moves from outdoor to indoor or exchanges between the channel and the indoor space, a space heating capacity is obtained, and the space heating is combined with fresh air supplying or not due to different air circulations. The mechanically ventilated mode is applied in space heating systems (GTC, UTC, the roof integrated solar air heaters, the roof integrated PVT system) or the ventilated façades in which the flow resistance is larger and the buoyance effect is insufficient to support the air circulation. Air fans in these systems draw the heated air from the air channel to indoor space through related ducts.

Seen from Table 1, each of the ALIEs has its own restrictions and disadvantages. Actually, each type of the them was developed for a specific purpose in a certain climate condition, for instant, the Trombe wall, either the classic type or the composite type, the glazed and unglazed transpired solar wall, and the roof solar air heater were all developed to use solar radiation for indoor hot air supply in winter; the wall-based and roof-based solar chimney were designed for solar-driven natural ventilation for non-air-conditioned buildings in moderate or hot climates; the ventilated PV façade, the PV window and the roof integrated PVT system were designed mainly to achieve on-site electricity generation capacity in buildings, the thermal benefits in these systems are usually a by-production; the DSF, the metallic outer skin, the dry-hanging stone curtain wall, and the double-layer membrane structure were developed for high-grade office or commercial buildings for their superiority in appearance; the ventilated roof system is usually designed and constructed to obtain a passive cooling effect in the roof area, thus reducing the indoor cooling load in summer. So these envelopes are usually employed to operate under their design status in concerned climate conditions; in other seasons or other weather conditions, inevitable restrictions and disadvantages occur during the operation. Consequently, in the design stage and the construction stage of these ALIEs, necessary transformation mechanisms have to be taken into consideration, for purpose of regulating their operation modes in different seasons. For example, the Trombe walls may suffer from excessive heating problems in summer or in hot days; so they should be translated into other working modes, such as passive cooling mode or a solar chimney mode. The DSF operates in different modes to adapt to different weather conditions. The ventilated roof system has to be adjusted into an enclosed mode or a solar air heater mode in winter to prevent heat loss through the roof area. The restrictions and disadvantages of each system are illustrated in Table 1 in detail. From an overall point of view, all these envelopes have a unique disadvantage, that is, implementing each of the mentioned ALIEs in a building will certainly increase the initial cost, since various building materials and extensive construction works are needed when compared with conventional external envelopes; and for some of them, the maintenance costs also raise a lot.

According to the air layer type, the effects of ALIEs can be summarized as: reducing thermal load of a building, providing auxiliary heating, increasing electricity generating efficiency, improving indoor thermal comfort, and improving indoor air quality (see Fig.27). The enclosed air layer, the passive cooling modes of these envelopes enjoy the advantage of reducing the or cooling loads in summer, since enclosed air layers function as insulation layers and air movement in passive cooling modes take away part of the heat from outside to inside of a building. The use of both wall-based and roof-based solar chimney intends to produce the natural ventilation effect. Space heating modes of related systems help to heat the indoor air in winter, and PV module based systems provide the ability of electricity generation for a building. Implementing each of the ALIE systems to a building can change the inner surface temperature when compared with buildings with traditional envelopes, thus the indoor thermal comfort level could also be improved. Fresh air supply in space heating modes and natural ventilation mode brings outdoor air to indoor space, thus the indoor air quality also improves. Seen from Table 1, each of the mentioned envelopes can work in different modes, thus providing multiple benefits for a building.

5.2 The cooperation of AILEs and the integration of AILEs into HVAC systems

The ALIEs can work either alone or as an integrated system. From the overall view of a building, an integrated design that combines several types of ALIEs has a greater potential for energy-saving, electricity generation, ventilation inducting and other aspects. e.g. the ventilated PV façade, the PV ventilated window and the roof integrated PVT system may be combined together as a synthetical PVT system for a building. With a proper design, the air layers in different parts of the system can be integrated as an air protective layer which surrounds a building's outer surface and controls its heat and mass transfer. With the combination of the three envelope types, the electricity production can be greatly increased and the space heating and passive cooling effectiveness can also be enhanced. The wall-based solar chimney and the roof-based solar chimney can work together to achieve a higher ventilation quantity for a non-air-conditioned building. The roof integrated solar air heater and the UTC (or GTC or Trombe wall) can be designed to complement each other for the purpose of obtaining a stronger space heating capacity. The combination of UTC with ventilated PV façade is a promising concept for buildings that need simultaneously electricity and hot air heating in winter season [216]. The cooperation of double-skin glazing façade and ventilated PV façade provides a promising measure to balance the day lighting and on-site electricity generating for a high rise building. The integrated design and construction of ALIEs of a building should be treated as one of the future trend in building structure design and building energy saving, since it offers a potential in heat transfer controlling at external enclosure areas and provides an extra opportunity for space heating and passive cooling in different seasons.

Moreover, ALIEs can also be integrated into HVAC systems, for the purpose of obtaining higher energy conversion efficiencies and a higher indoor thermal comfort level. For instance, in solar chimney systems, outdoor air is induced into indoor space to form natural ventilation. But it is necessary to precool the outdoor air when the outdoor temperature exceeds the thermal comfort limit. The precooling process can be achieved by the combination of other cooling systems. Zhai [44] reported the integration of earth to air heat exchangers, evaporative cooling technique, and adsorption cooling technique with solar chimneys. Similarly, the DSF can be integrated into the air-conditioning system of a building. With a combined design, the exhaust air of the central air-conditioning system is sent into the air cavity of the DSFs, thus the heat transfer through the DSF area is partly offset by the exhaust air. This combination reuses the exhaust air to reduce the thermal load of a building, thus increasing the overall efficiency of the air-conditioning system [217]. In other integrated designs, the heated air of UTC, GTC, Trombe wall or PVT systems can be treated as the energy source of air-source heat pumps. Integration of ALIEs with HVAC systems opens up a door for integrating building envelopes with air-conditioning systems. With a proper design, the overall energy efficiency and the indoor thermal comfort will be both improved.

In the design stage of a building, an architect can determine the most appropriate type of the ALIEs according to the initial cost, the climate condition, the building type and the required function. For instance, when the required purpose of envelope is to achieve domestic heating, the Trombe wall, the composite Trombe wall, the glazed and unglazed transpired solar walls, the roof solar air heater and the roof integrated PVT system can be adopted; and the design plan can be further determined according to the investment level and the climate condition; additionally, a combination of the above envelops can help to obtain a better heating effectiveness. When the purpose is to achieve natural ventilation in non-air-conditioned buildings, the wall-based solar chimney and the roof-based solar chimney is available, and the joint utilization of these two chimneys achieve a higher airflow rate. When the intention is to improve the thermal performance of external envelopes for office or commercial buildings, the DSF, the metallic outer skin, the dry-hanging stone curtain wall, and the double-layer membrane structure can be employed. Generally, when designing an ALIE for a building, comprehensive consideration should be taken by the architect from the aspects of purpose, cost, climate, and etc. Only in this way, can the ALIE in a building strike a balance between the investment and performance.

6. Research trends and future directions

The ALIEs have been widely used to improve the passive thermal performance of a building. It has gained much popularity for its ability to reduce heat gain or loss and to convert solar radiation into thermal energy for space heating or passive cooling. The advantages of employing different types of the above-mentioned envelopes have been studied and verified experimentally or numerically by many researchers in previous literatures. A number of studies have been conducted and reported to show the performance of ALIEs over heating and cooling seasons. Additionally, some literatures summarized the existing research methods that can be used to study the performance of these envelopes. Experimental test and computer modeling and simulation employing the models of lumped model, non-dimensional analysis, airflow network model, control-volume approach, Computational Fluid Dynamics (CFD) method, and zonal approach have been reported to be capable of predicting the flow and temperature fields as well as the performance of these envelopes [37,38]. In fact, the implementation of these envelopes has become a popular worldwide practice in modern building design and construction. And the study on the performance of these envelopes has realized great achievements.

Unfortunately, almost all previous researches merely concentrate on one specific air layer involved component, experimentally or numerically investigating its thermal performance and its impact on indoor environment, or on a simplex type of the air layer involved technology in buildings, analyzing and summarizing the research achievements, the study methods, the application situation, and its application prospect. Little has been done to find general characteristics of these ALIEs and no study treats the air layers in these envelopes as a unified research subject. Few have been done to investigate the airflow and heat transfer characteristics in the slit space of these envelope systems, instead, more attentions are paid to the system performance of these envelopes.

This paper treats the ALIEs s as a unified subject and reviews the air layer applied in external walls, windows and roof. The performances and benefits of these technologies, the effects of the air layers and the operating modes of each technique are summarized and classified. And there are still obvious opportunities to catch up to further development of these ALIEs, which are outlined as below:

- Comparing the performances between different ALIEs and evaluating the applicability of these ALIEs in different climate conditions

Previous literatures often focus on evaluating the thermal performance of a specific ALIE system under a certain climate condition. However, the influence of weather condition on the performance of an ALIE has to be investigated and performance comparisons between different ALIEs have to be processed, to provide technical supports for architects when determining the most appropriate type of ALIE for a given project in a given climate.

- Developing monolithic ALIE system and integrate them to indoor energy systems

With proper designs and constructions, the air layer involved structures in different parts of a building envelope system can be integrated together to obtain maximum heating, cooling and electricity generation capacities. The air layers in roofs, walls and windows could function as a monolithic system to protect the indoor environment from the ambient. With well-designed transformation mechanisms, the monolithic system could be switched between space heating mode in winter and passive cooling mode in summer. The monolithic ALIE system can be further integrated to the air-conditioning systems and other heating or cooling systems, not only to achieve a better performance of building envelopes, but also to obtain a higher overall energy efficiency of indoor building energy systems.

- Evaluating the airflow and heat transfer characteristics in slit space of ALIEs for structure and geometrical parameter optimization

The airflow and heat transfer characteristics in the slit space of ALIEs may be affected by solar radiation intensity, the indoor and outdoor air, the indoor and outdoor air flow rate, the construction material, the geometrical sizes of the air channel, and etc. Systematic investigation of these influential factors provides a judging criterion for optimizing the geometrical parameters of the air layers in different types of ALIEs.

- Studying long term dynamic performance of ALIEs in real buildings under actual climate conditions

This long-term real-time tests of the ALIEs in real buildings should be an important direction to move on. The testing results will reflect the operational performance of the ALIEs under the real building and real climatic conditions. The long-term test results may also be used to evaluate the energy-saving potential, environmental and economic benefits of the ALIE systems under actual operating conditions, which may be an evidence to assess the adaptability of these technologies.

- Economic and environmental benefit assessment and social acceptance analysis

Economic assessment can address the initial and maintenance cost, the life cycle benefit, the energy saving potential, and the payback time related to an air layer involved envelope and its integration into a building. Environmental analysis demonstrates the life-cycle carbon emission reduction and fossil fuel energy-saving of implementing these technologies in a building. Social acceptance analysis can be conducted base on public survey results as well as the economic and environmental assessment results. The feasibility of ALIEs and their integration to buildings should be comprehensively evaluated based on the economic and environmental benefit assessment and social acceptance analysis.

7. Summary

The internal air layer has been widely employed in building external walls, roofs and windows to improve the heat transfer property of this area. In the past century, ALIE systems and technologies have gained much popularity for its ability to reduce heat gain or losses and to convert solar radiation into thermal energy for space heating or passive cooling. In design and construction process of future buildings, as building energy consumption continues to increase and energy shortage is becoming more and more serious, the implementing of ALIEs and the integration of ALIEs to other energy system in buildings will become increasingly popular.

This paper presents a literature review on building envelopes that contain inner air layers. The existing applications and technologies of air layers in walls, windows, and roofs are summarized and outlined. And the performances and benefits of these technologies are discussed and summarized. The operation modes of the air layer used in building envelopes are roughly classified into three types: the enclosed type, the naturally ventilated type and the mechanically ventilated type. The enclosed type acts as an extra insulation layer; the naturally ventilated air layer is often adopted in passive cooling systems and some of the space heating systems; and the mechanically ventilated type is applied in space heating systems or the ventilated façades in which the flow resistance is larger than the buoyance effect. Using the ALIEs, multiple benefits can be achieved, including reducing the thermal load of a building, providing auxiliary heating for the indoor air, improving onsite electricity generation efficiency, improving indoor thermal comfort and indoor air quality. The ALIEs can either work alone or work together as an integrated envelope system, or be integrated into other space heating or cooling system to obtain a higher energy conversion efficiency and a higher indoor thermal comfort level.

Tough much work has been done to investigate the performance of ALIEs, there are still many problems to be solved in applying and popularizing these technologies. This review finally provides current state of research gaps and possible future research directions on air layer technologies in building envelopes.

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List of figure captions

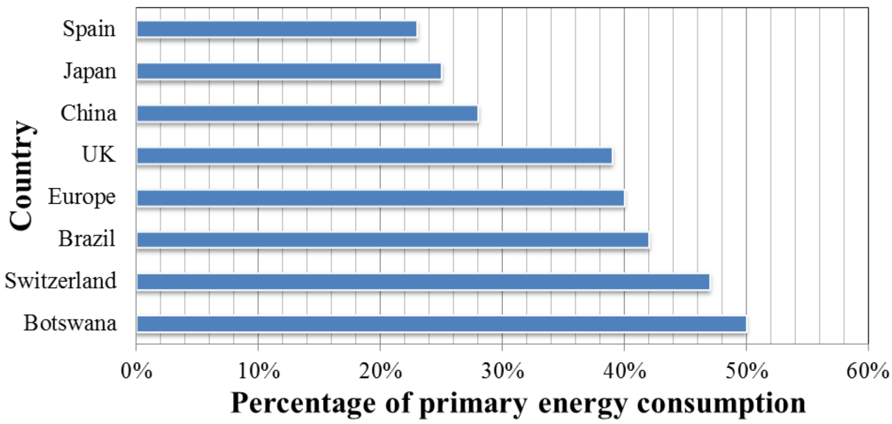

Fig.1 Building energy expenditures in different countries

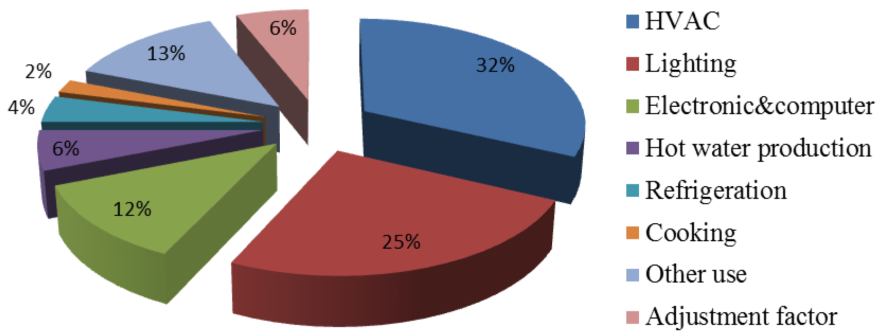

Fig.2 The distribution of the primary energy utilization in a typical commercial building

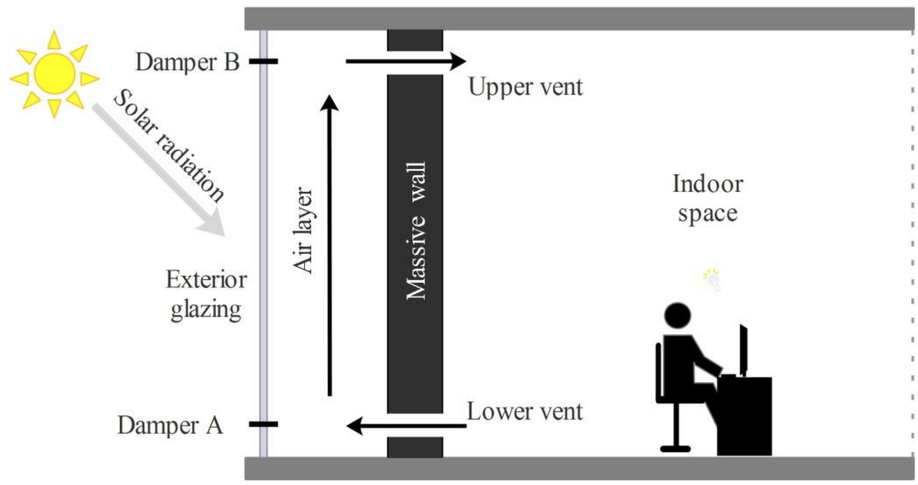

Fig.3 Schematic diagram of classical Trombe wall

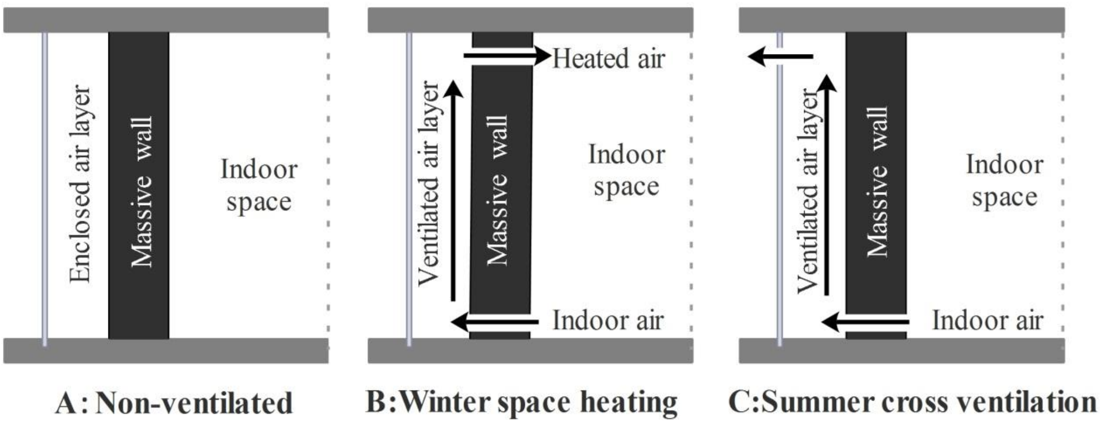

Fig.4 Different working modes of a Trombe wall: A-non ventilated mode; B-winter space heating mode; C-summer cross ventilation mode

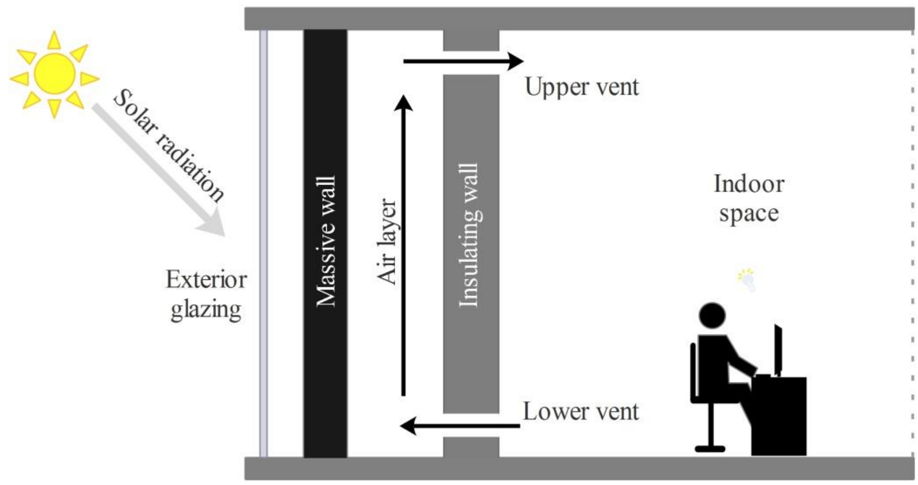

Fig.5 Schematic diagram of composite Trombe-Michel wall

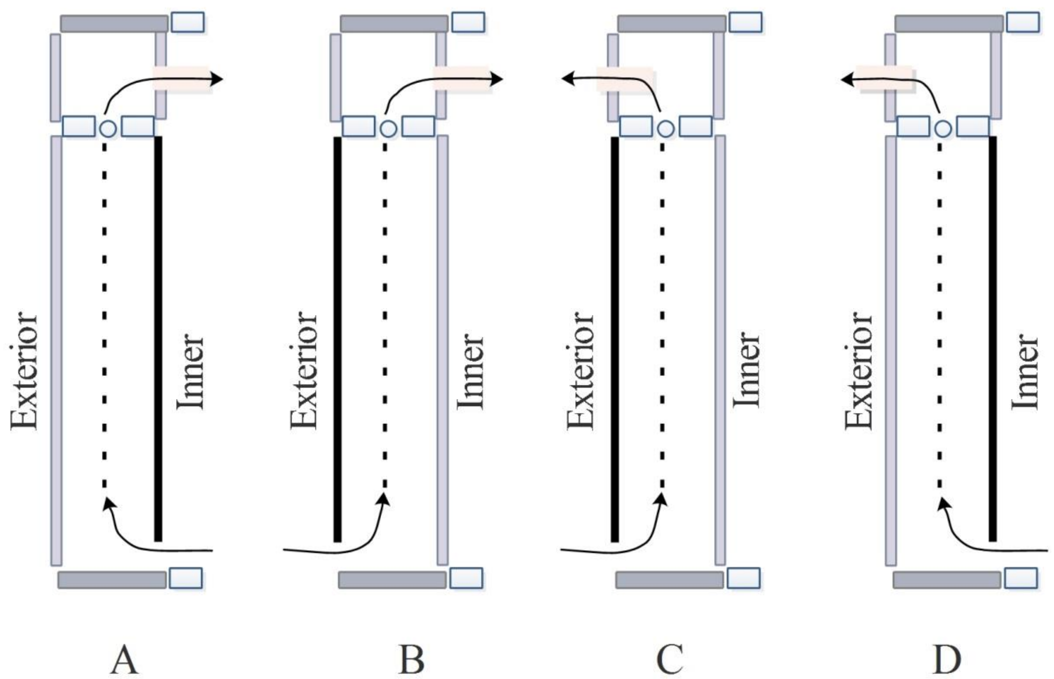

Fig.6 Schematic of the working modes of double-skin façade: A-inner circulation mode; B-supply mode; C- inner circulation mode; D-exhaust mode.

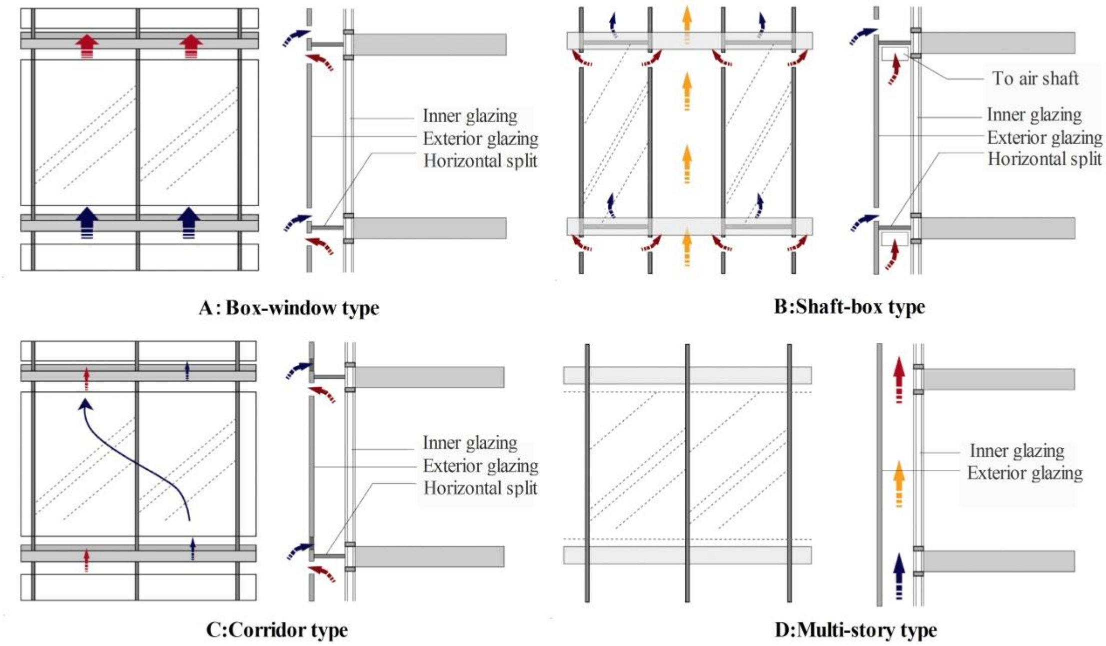

Fig.7 Different connection types of the double-skin façades: A-the box-window type; B-the shaft-box type; C- the corridor type; D-the multi-story type.

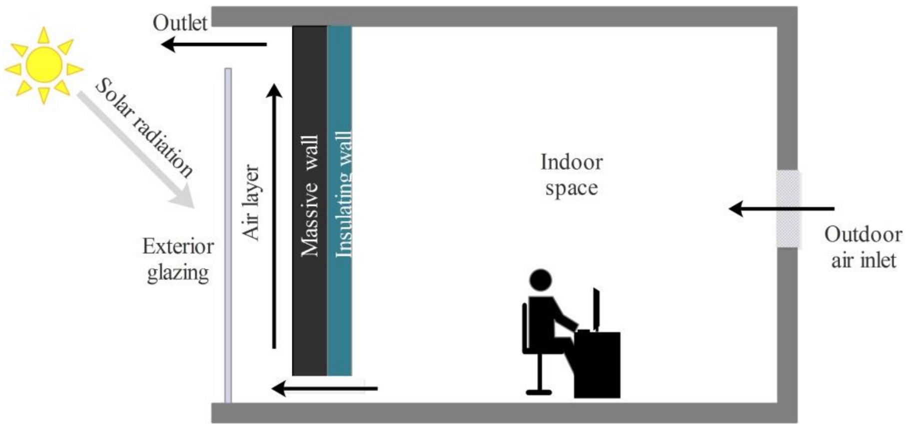

Fig.8 Schematic of a wall-based solar chimney

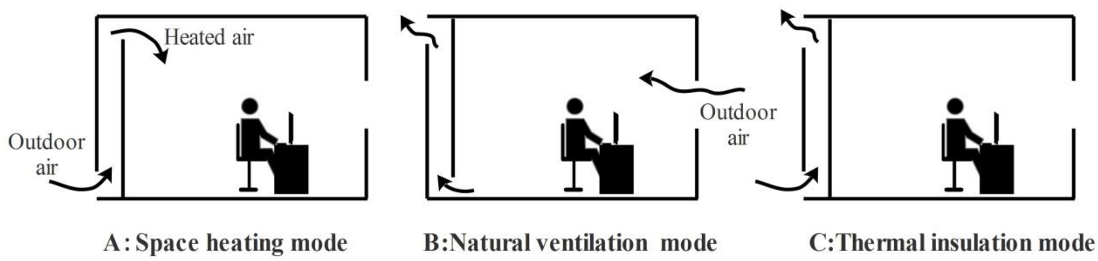

Fig.9 Different work modes of wall-based solar chimneys: A- the space heating mode; B-the natural ventilation mode; C- the thermal insulation mode.

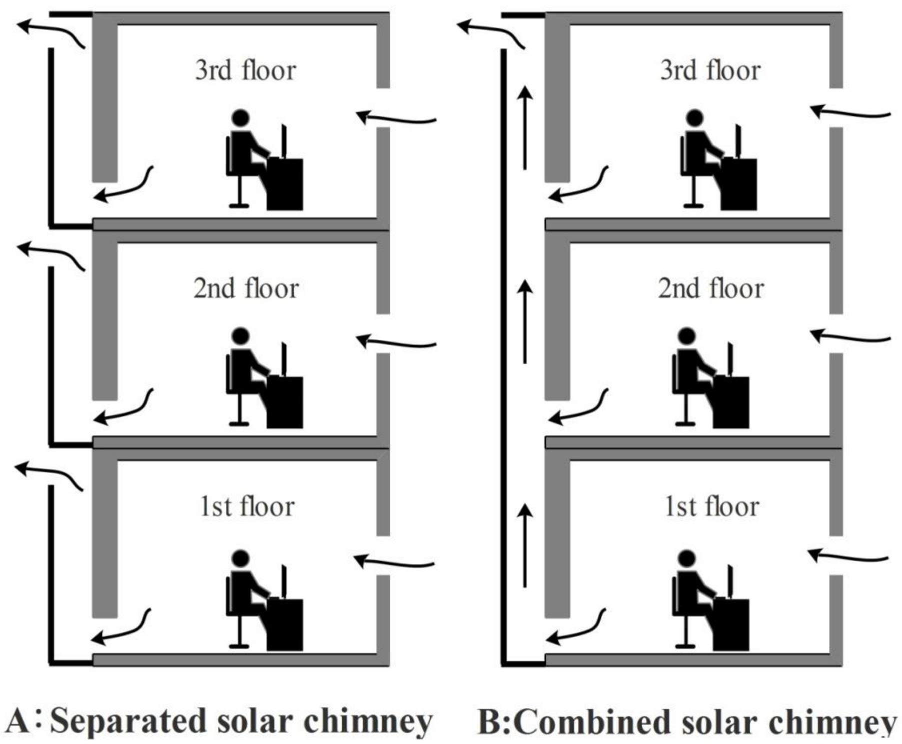

Fig.10 Configurations of wall-based solar chimneys in multilayer buildings: A-the separated solar chimney; B-the combined solar chimney.

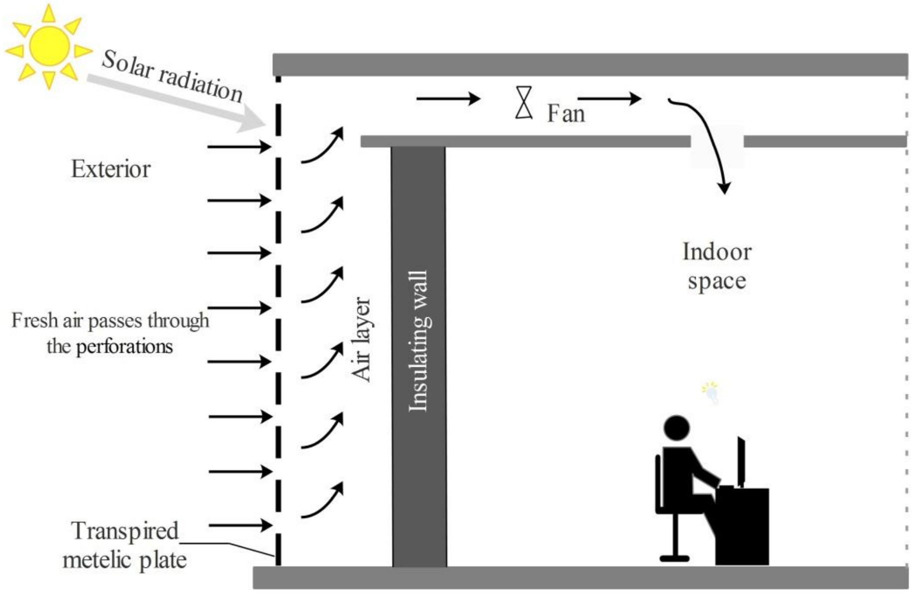

Fig.11 Schematic diagram for unglazed transpired collector

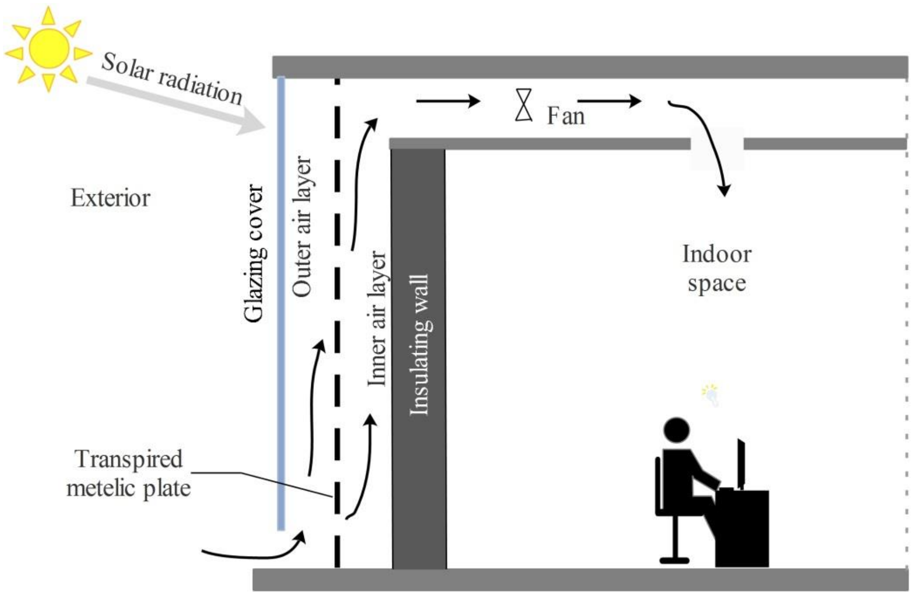

Fig.12 Schematic diagram for glazed transpired collector

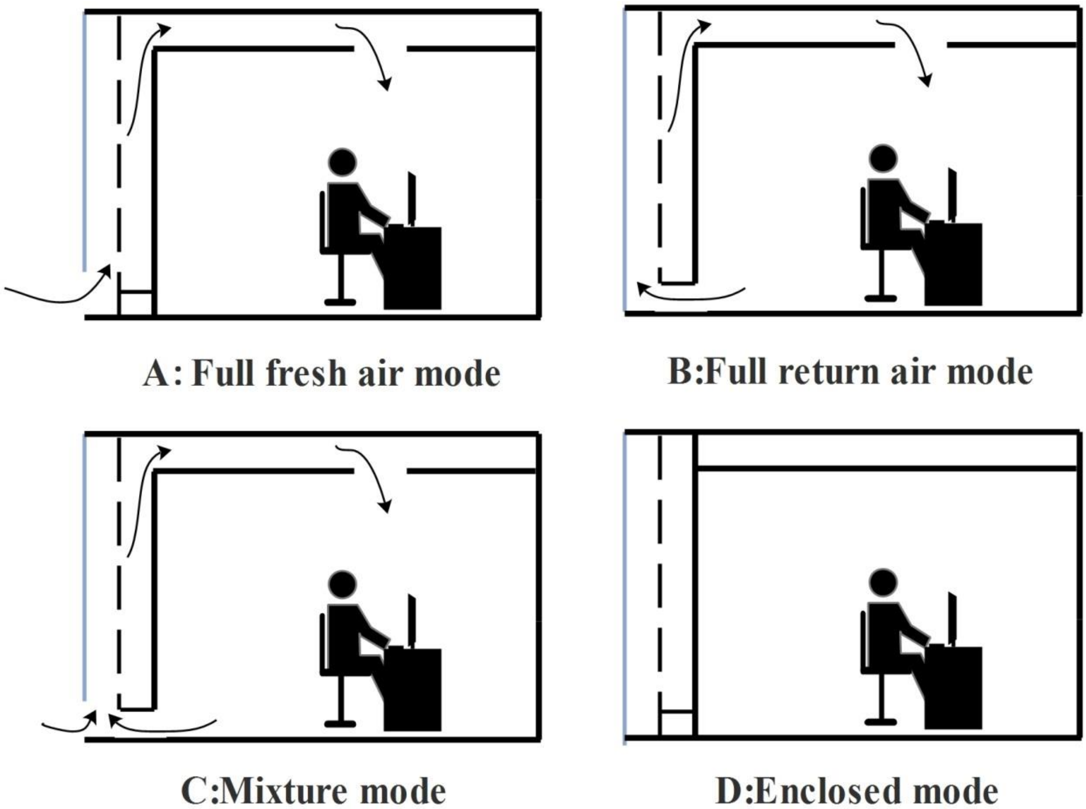

Fig.13 Different operation modes of GTC: A-the full fresh air mode; B-the full return air mode; C- the mixture mode; D-the enclosed mode.

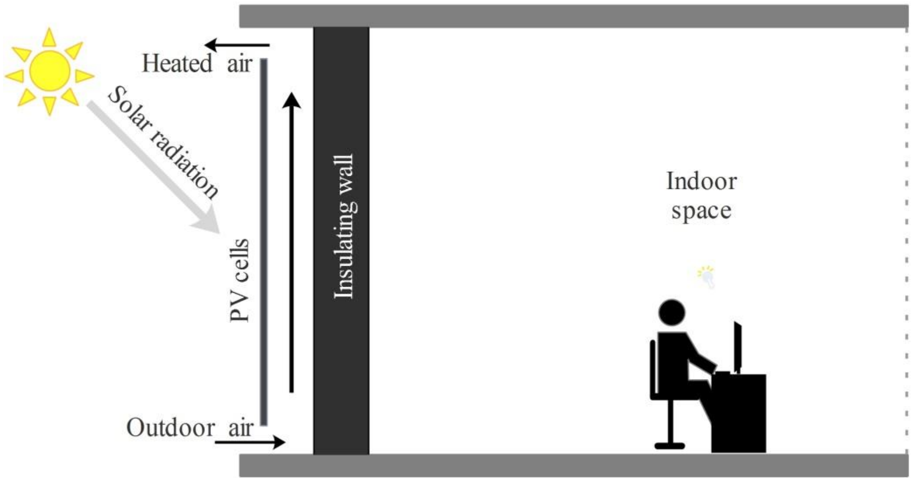

Fig.14 Schematic diagram of passive ventilated PV façade

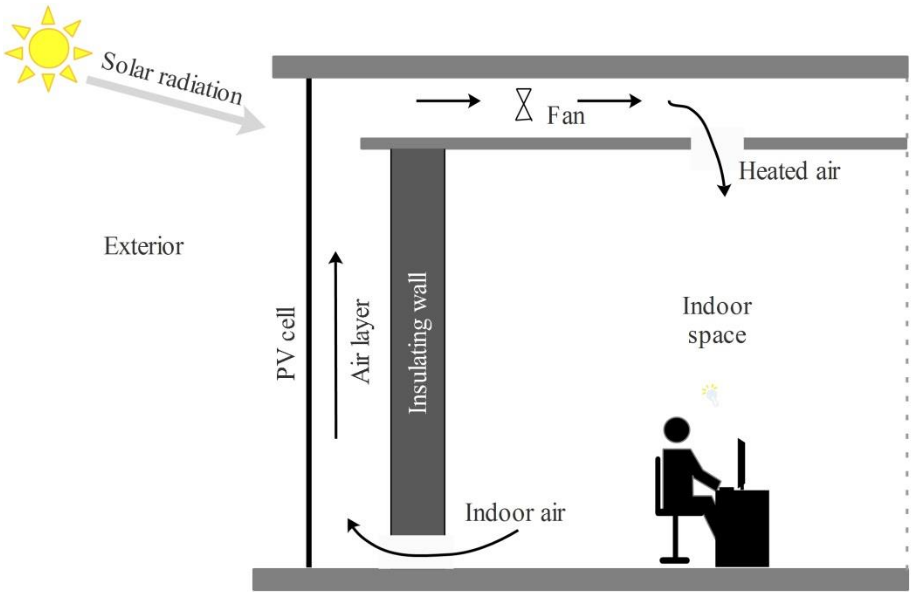

Fig.15 Schematic diagram of active ventilated PV façade

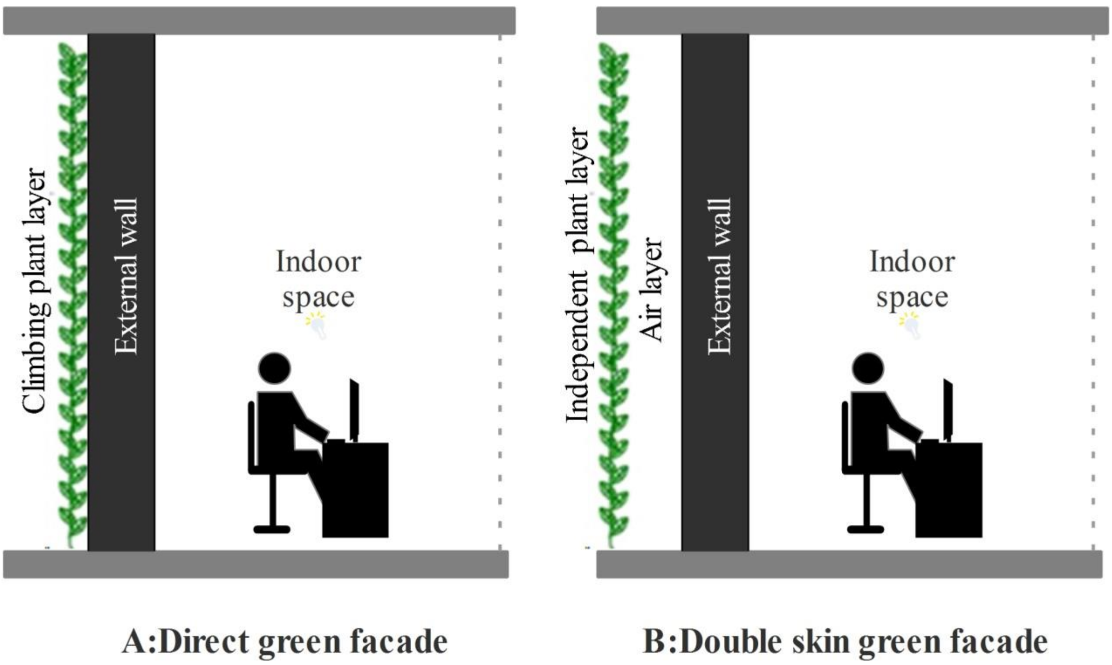

Fig.16 Direct green façade and double-skin green façade: A-the direct green façade; B-the double skin green façade (the indirect green façade).

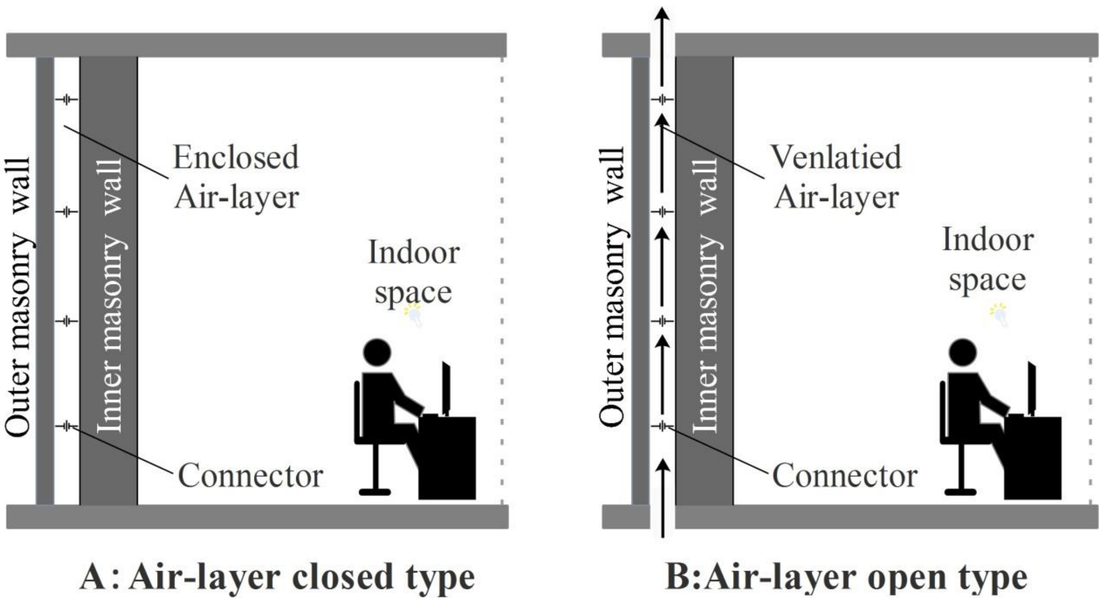

Fig.17 Schematic of hollow masonry walls: A-the air-layer closed type; B-the air-layer open type.

Fig.18 Buildings with double layer membrane structure: A-the water cube in Beijing; B-the Allianz Arena in Munich.

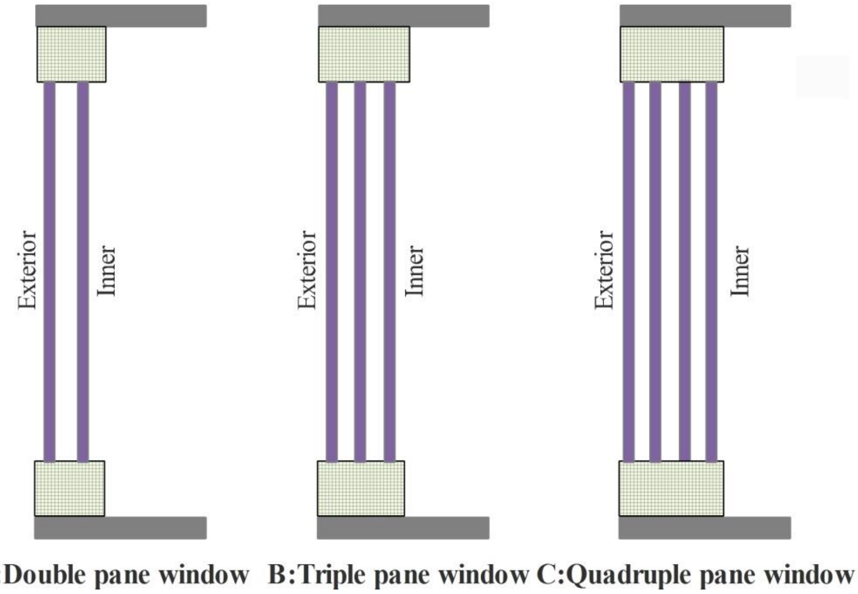

Fig.19 Schematic illustrations of double, triple and quadruple pane windows: A-the double pane window; B-the triple pane window; C- the quadruple pane window.

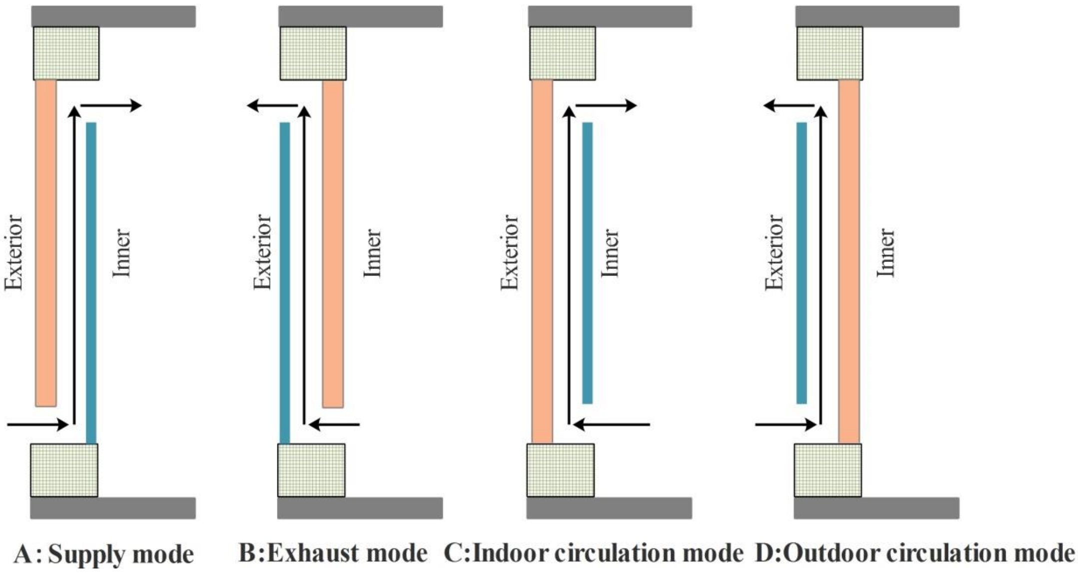

Fig.20 Different types of airflow window: A-the supply mode; B-the exhaust mode; C-the indoor circulation mode; D-the outdoor circulation mode.

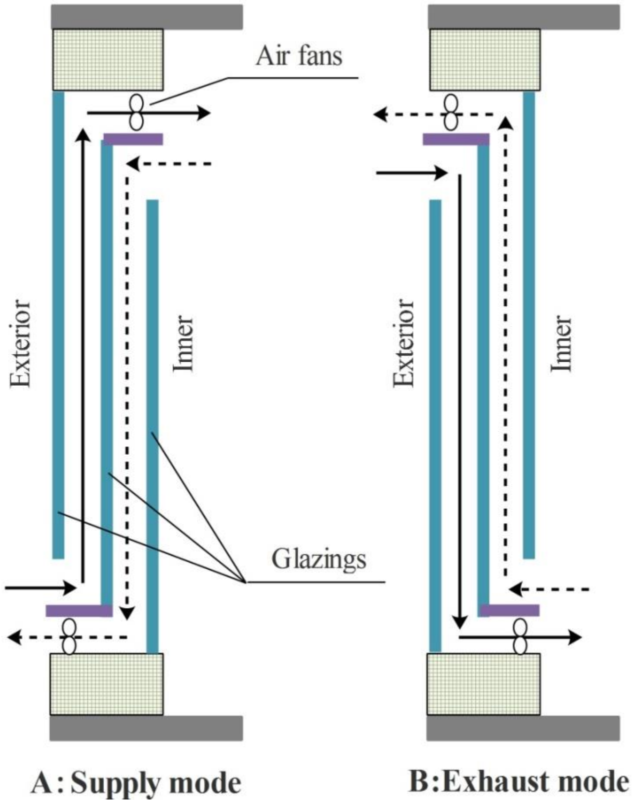

Fig.21 Two operating modes of the new dual-airflow window: A-the supply mode; B-the exhaust mode.

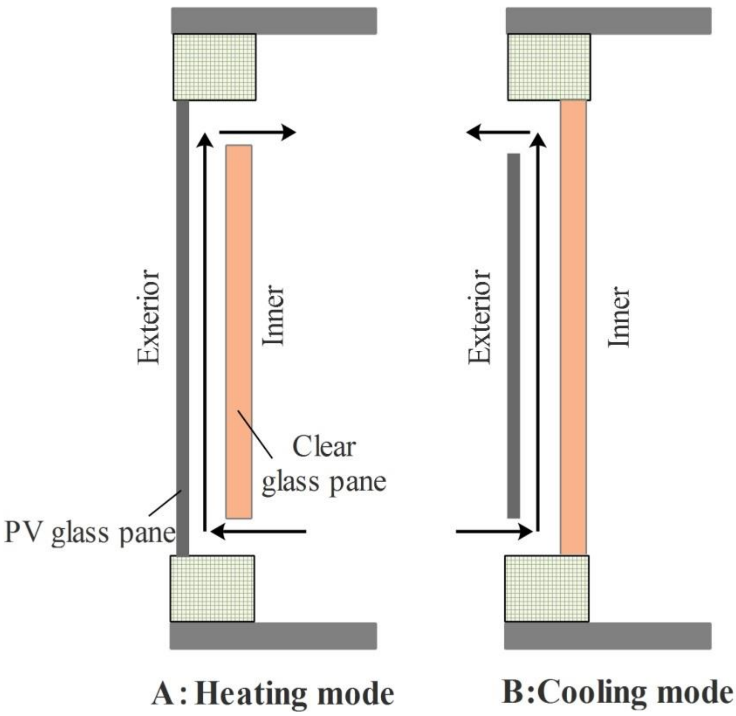

Fig.22 Different modes of PV ventilated window: A-the heating mode; B-the cooling mode.

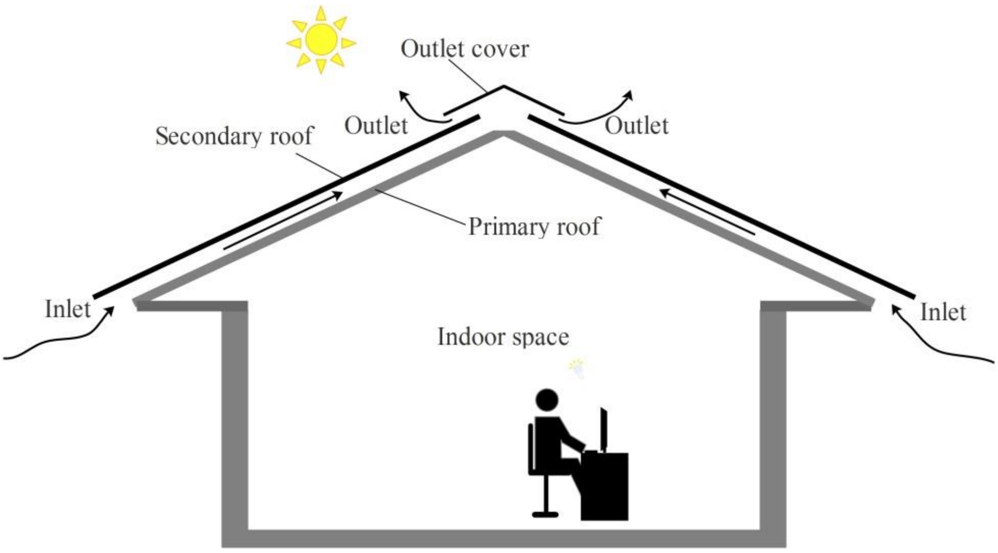

Fig.23 Schematic of double-skin roof

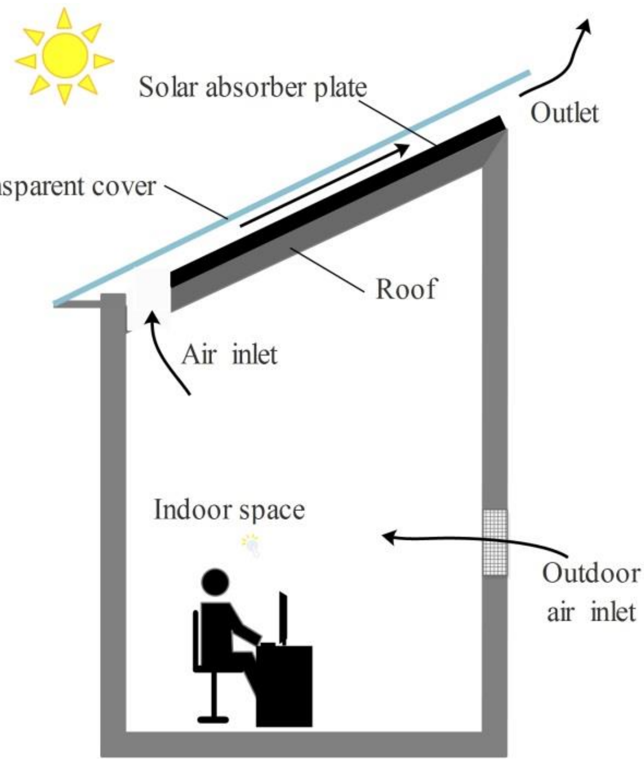

Fig.24 Schematic of roof solar chimney

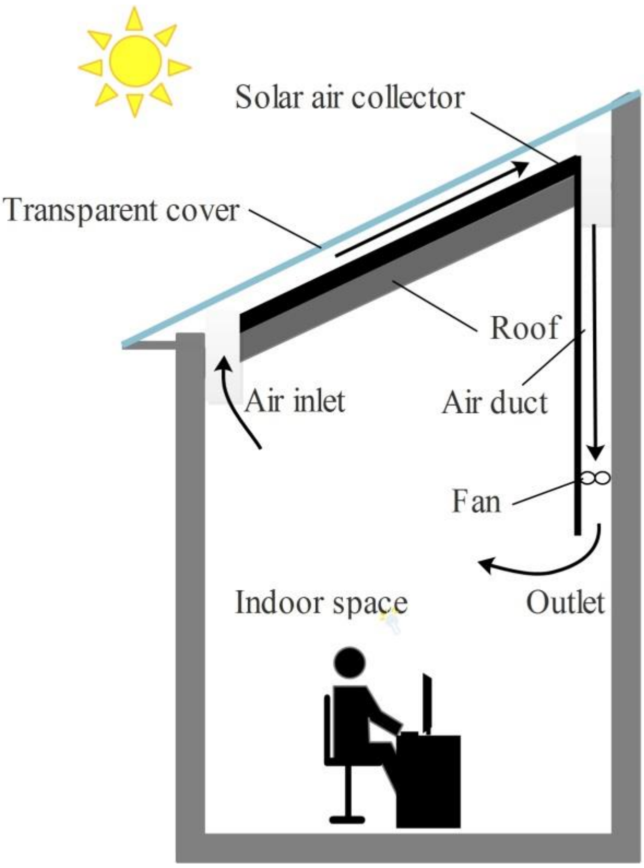

Fig.25 Schematic of roof-integrated solar air heater

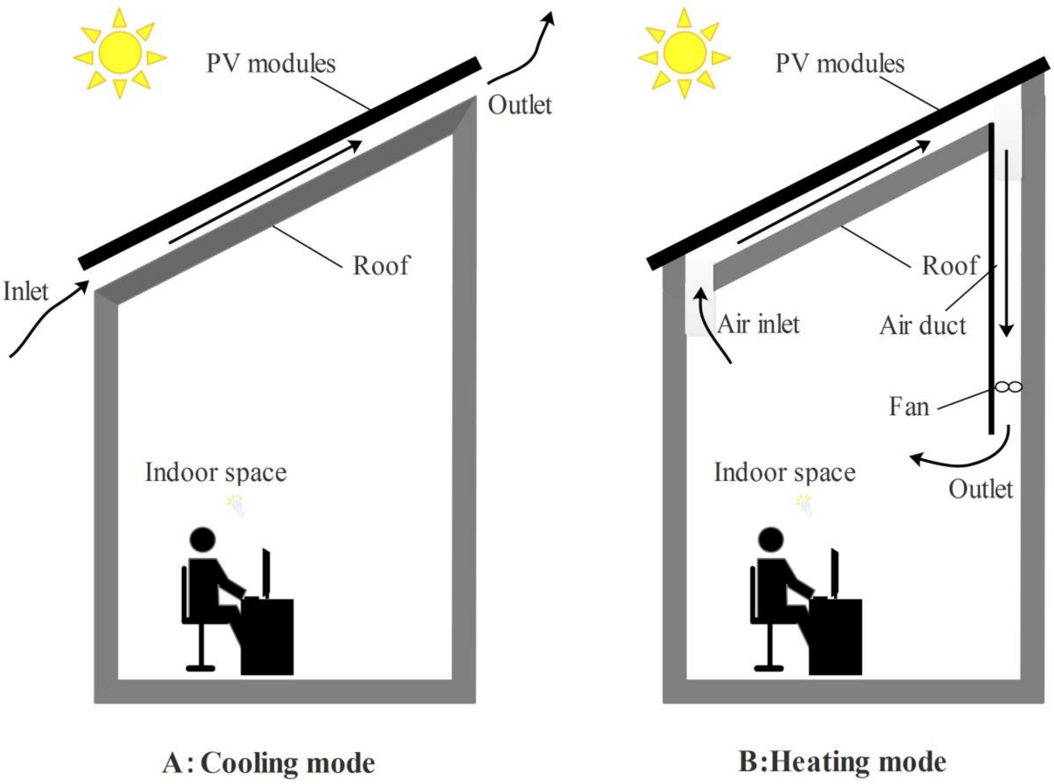

Fig.26 Schematic of roof integrated PVT system: A-the cooling mode; B-the heating mode.

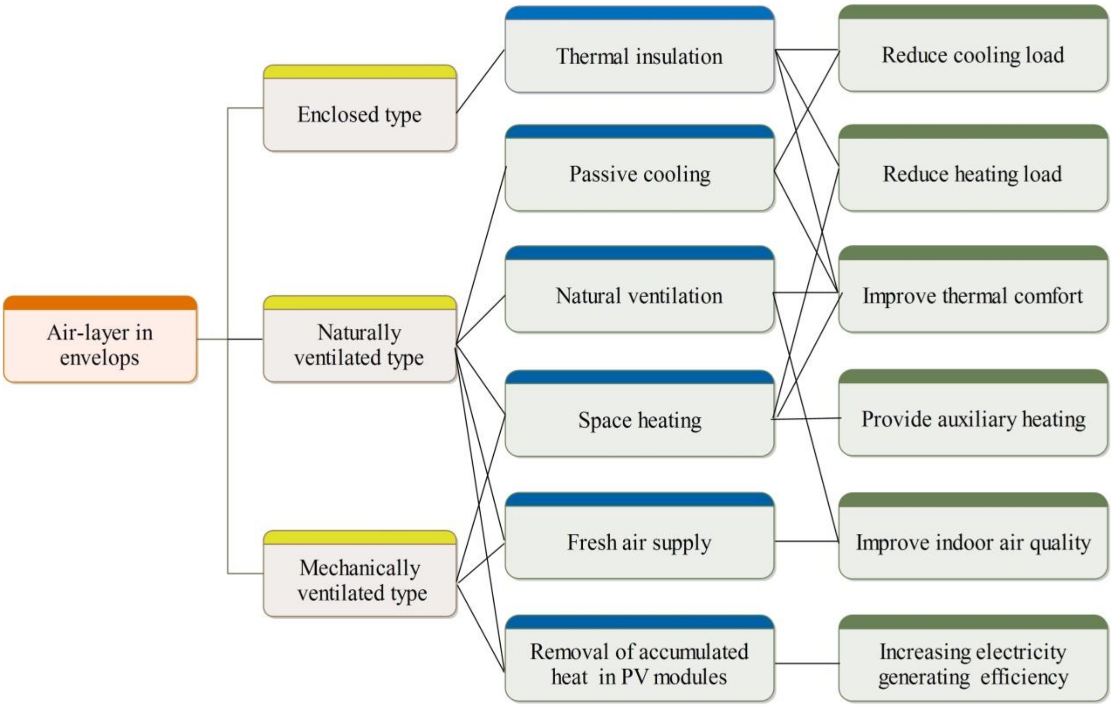

Fig.27 Summary of air-layer utilized in building envelopes

Table 1 Summary on the performances of different types of air layer involved envelopes

Envelope designs	Structure (from outside to inside)	Airflow pattern	Effect of air layer	System functions and benefits	Restrictions and Disadvantages
Classic Trombe wall	Exterior glazing, air layer, storage wall.	Enclosed air layer in winter night; Naturally ventilated in winter space heating and summer cooling mode.	Winter night: Insulation layer; Winter mode: Thermal transfer medium for space heating and fresh air channel; Summer mode: natural ventilation channel.	Winter mode: space heating and fresh air supplying: Summer mode: passive cooling of the building.	Only applicable in winter in cold climates; during summer, excessive heat gain may occur; increase initial cost of external walls. Mainly used in rural buildings.
Composite Trombe wall	Exterior glazing, closed air layer, massive wall, ventilated air layer, insulating wall.	Enclosed outer air layer; Naturally ventilated inner layer.	Outer layer: insulation layer; Inner layer: Thermal transfer medium for space heating	Mainly used as a space heating system in winter.	Only applicable in winter in cold climates; higher initial cost than classic Trombe walls; reduce usable area of the interior. Mainly used in rural buildings.
Double-skin glazing façade	External façade layer, air layer, interior façade layer.	Enclosed/ naturally ventilated/ mechanically ventilated in different working modes.	Insulation layer in air-fixed mode: Heat removal medium in external respiration mode; fresh air channel and natural ventilation channel in other modes.	Air-fixed mode provides extra thermal insulation for external envelopes; Air-ventilated mode deals with overheating problems in summer and helps to achieve fresh air supplying and energy savings in winter.	Pretty high initial cost and maintenance cost, usually used in slap-up commercial buildings; reduce usable area of the interior.
Wall-based solar chimney	Exterior glazing, ventilated air layer, absorbing wall, insulating wall.	Natural ventilated.	Absorb heat from the absorbing wall and act as the driving force of the natural ventilation, space heating or external respiration.	Mainly used as a natural ventilation system in summer; sometimes served as space heating system and passive cooling façade.	Applicable in moderate climates and hot climates; increase initial cost of external walls.
Unglazed transpired solar wall	Transpired plate, air layer, wall façade.	Mechanically ventilated.	Absorb heat from the transpired plate and act as thermal transfer medium for space heating; the air source for fresh air supplying.	Only for space heating and fresh air supplying in winter.	Applicable in moderate climate; increase initial cost of external walls; system performance is susceptible to wind velocity; fan make noise.
Glazed transpired solar wall	Exterior glazing, outer air layer, transpired plate, inner air layer, external wall façade.	Enclosed or mechanically ventilated.	Insulation layer in the off-mode; Absorb heat from the transpired plate and act as thermal transfer medium for space heating; the air source for fresh air supplying.	Only for space heating and fresh air supplying in winter in the daytime; Served as an insulation air layer at non-sunshine time.	Applicable in cold and severe cold climates; increase initial cost of external walls; fan make noise.
Ventilated PV façade	PV panel, air layer, wall façade	Naturally or mechanically ventilated.	Absorb heat from PV panel to increase the electricity efficiency; Take away the accumulated heat	Used for electricity generating all year around; Used for space heating and/or	Reduce heat gain through building boundary; increase initial cost of external walls.

			an reduce the cooling load in summer; The air source for fresh air supplying and space heating in winter.	fresh air supplying in winter; Used for passive cooling to reduce cooling load in summer.	
Double-skin green façade	Plant layer, air layer, wall façade	Natural ventilated.	Acts as a thermal buffer and reduces the heat gain through external envelope.	Used as a passive cooling system to reduce ambient air temperature, exterior surface temperature, interior air temperature and heat flux of a building.	Usually used in hot climates; extremely high initial cost of external walls; hard to maintenance.
Hollow masonry wall	Exterior masonry layer, air layer, inner masonry layer.	Enclosed, naturally ventilated, or mechanically ventilated	As an insulation layer in enclosed mode; Remove the heat from the exterior layer to reduce cooling load in summer.	Used as a low heat transfer coefficient external wall or as a passive/active cooling strategy.	Used in medium and low-rise buildings; increase initial cost of external walls.
Metallic outer skin	Metallic layer, air layer, inner wall façade.	Enclosed.	Thermal and sound insulation layer.	A novel external wall to control sunlight and to improve thermal and sound insulation property.	High initial and maintenance cost.
Dry-hanging stone curtain wall	Exterior stone material layer, air layer, wall façade.	Enclosed or mechanically ventilated.	As an insulation layer in enclosed mode; Remove the heat from the exterior stone layer to reduce cooling load in summer.	A novel external wall to improve thermal property and to extend usage life of stone materials.	High initial and maintenance cost; short service lifecycle.
Double-layer membrane structure	Exterior membrane layer, air layer, inner membrane layer.	Enclosed.	Thermal and sound insulating layer	A novel external envelope to improve the aesthetic extent of a building and with good properties in light, thermal and sound control.	Usually used in large sports stadium; high initial and maintenance cost.
Multiple pane window	Exterior glazing layer, air layer, inner glazing layer.	Enclosed.	Thermal insulation layer.	To reduce the heat transfer coefficient of the window area, thus reducing heating load or cooling load.	Usually used in an extreme climate; increase initial cost of external walls.
Airflow/Ventilated window	Exterior glazing layer, air layer, inner glazing layer.	Naturally or mechanically ventilated.	Heat removal medium in external respiration mode; fresh air channel and natural ventilation channel; air source for space heating mode.	Use for fresh air supplying and space heating in winter; Used for passive cooling and natural ventilation in summer.	Applicable in moderate climate; high initial cost; noise caused by fan.
Dual airflow window	Exterior glazing layer, air layer, middle glazing	Mechanically ventilated.	Air source for fresh air supplying;	Used to further improve the thermal efficiency of airflow	Applicable in moderate and cold climates; high initial cost; fan

	layer, air layer, inner glazing layer.		The thermal heat exchanges between the two airflows.	windows since it functions like a heat exchanger.	make noise.
PV ventilated window	PV panel, air layer, inner glazing layer	Naturally ventilated.	Absorb heat from PV panel to increase the electricity efficiency; Take away the accumulated heat an reduce the cooling load in summer; The air source for fresh air supplying and space heating in winter.	Used for electricity generating all year around; Used for space heating and/or fresh air supplying in winter; Used for passive cooling to reduce cooling load in summer.	Reduce heat gain and sunlight; increase initial cost of external walls.
Double-skin roof	Exterior roof layer, air layer, inner roof layer	Enclosed or naturally ventilated.	Enclosed as an insulation layer in winter; Take away the heat from exterior layer to reduce cooling load in summer.	Used as a high performance roof system to reduce the heat transfer through roof area.	Used in hot climate; high initial cost.
Roof-based solar chimney	Exterior glazing, ventilated air layer, absorbing wall, insulating wall.	Natural ventilated.	Absorb heat from the absorbing wall and act as the driving force of the natural ventilation.	Used as a natural ventilation system in summer	Applicable in moderate climates and hot climates; increase initial cost of external walls.
Roof integrated solar air heaters	Exterior glazing, ventilated air layer, solar air collector layer, insulating wall.	Mechanically ventilated.	Absorb heat from the solar air collectors and act as air source of space heating.	Used to improve the roof performance and as a space heating method.	Applicable in cold and server cold climates; increase initial cost of roof; noisy.
Roof integrated PV/T system	PV panel, air layer, roof layer	Naturally or mechanically ventilated.	Absorb heat from PV panel to increase the electricity efficiency; Take away the accumulated heat an reduce the cooling load in summer; The air source for fresh air supplying and space heating in winter.	Used for electricity generating all year around; Used for space heating and/or fresh air supplying in winter; Used for passive cooling to reduce cooling load in summer.	Applicable in cold and server cold climates; increase initial cost of roof; noisy.