Passive Systems for Buildings Using Buoyancy-Driven Airflows

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Abstract: The need for countries to become less dependent on fossil fuels has been determinant in recent years due to increasing energy and comfort concerns in modern building design. Therefore, the maximization of the use of renewable energies, like the sun, and the use of natural energy flows become strategies to explore. There are already passive building systems that show interesting performances. Different studies have proved that the above-mentioned systems can lead to important energy savings. However, these systems have their limitations and new innovative building solutions are needed, mainly in the field of passive solar energy collection and natural ventilation strategies. Furthermore, building envelopes face nowadays a new paradigm in which buildings need to be more reactive and adaptive to external climate changes and indoor thermal comfort demands. Hence, this paper makes a review of the most recent patents on building solar air systems that make use of solar energy to induce the buoyancy effect for heating, cooling and ventilating. The patents presented demonstrate the increasing tendency in the development of building passive solutions that can satisfy, in just one system, more than one role: heating, cooling and ventilation.

Keywords: Building envelope, buoyancy effect, natural ventilation, passive solar cooling, passive solar heating, solar air system.

1. INTRODUCTION

The solar thermal passive systems, including air systems, are getting a major importance for energy saving measures in the built environment. Hastings [1] mention that the air is a reliable and economical heat carrier for heating, cooling and ventilating a building space. However, the majority of studies and the built examples of solar air systems in buildings make use of fan-forced mechanisms for air circulation. Natural air driven systems proved to be more complex in what concerns predicting and guaranteeing the expected behavior in real climate conditions. Therefore, the challenge for researchers to integrate these systems in buildings is huge. Hence, adapting to the modern building functions some principles of vernacular architecture may be an interesting strategy. The use of renewable energies is seen nowadays as one of the steps for minimizing the conventional energy consumption with primary fossil fuel energy [2]. Many studies [3, 4] have proved that providing passive components to buildings could represent important savings in their energy consumption.

Buildings' envelopes are also facing new developments towards a new approach that consists in being more adapted to the outdoor climate and to the occupants' needs. The conventional role of the building envelope, as a protective skin, is being replaced by a more active one, namely as an energy collector and as an energy transport system [5]. Recent studies about indoor comfort reveal that building occupants feel more comfortable and respond with more tolerance to climate variability with indoor natural-ventilated environments [6]. The investment in new envelope concepts offers the opportunity to use the natural energy flows provided by external climate which starts with a better use of the solar gains and also of the buoyancy driven natural ventilation, among others [5]. In sum, a closer relationship with the outdoor climate is essential and the buildings should include envelope solutions that can modulate the signals coming from outside [6, 7] in order to obtain benefits in the interior spaces. In such context, passive air systems can have an important role in this new generation of building envelopes, in an integrated way, along with other passive or active systems.

2. COMMON SOLAR AIR SYSTEMS

Solar chimneys (see Fig. (**1**)) are building passive systems that make use of the buoyancy effect operating in a natural ventilation mode. Its purpose is to generate airflow through a building, converting thermal energy into kinetic energy of air movement [3]. The driving force that produces the natural convection in a solar chimney is the density difference of the air at inlet and outlet of the chimney caused by internal and external air temperature differences. When a

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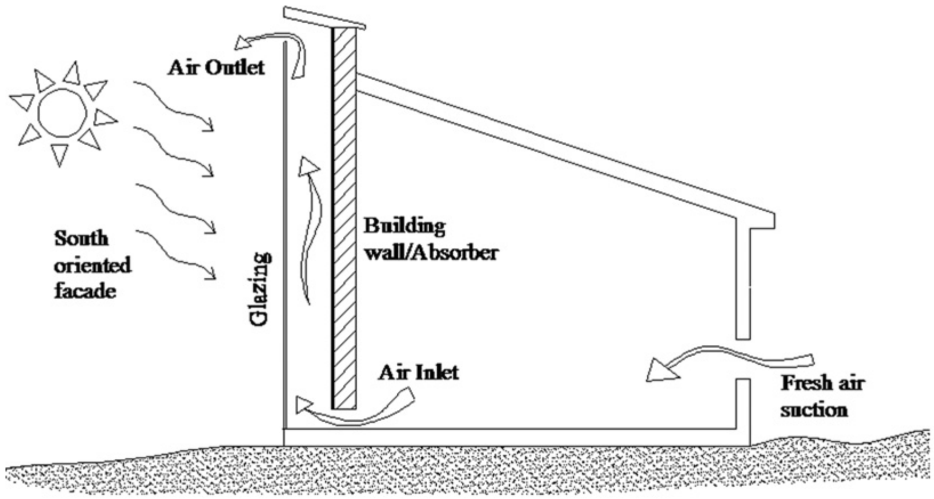

Fig. (1). Solar chimney for buildings in ventilation or cooling mode.

glazed vertical side-wall and an absorber wall are used, this difference is enhanced by the effect of solar radiation through the glazing that heats the air inside the air channel, inducing even more the buoyancy-driven airflow. For this reason, these devices are usually placed on the south or south–west facades of buildings [8].

Usually the solar chimneys operate with a natural ventilating or air cooling purpose (see Fig. (**1**)). In the ventilation mode, the fresh outdoor air is admitted through the vents or open windows in the building envelope, replacing the hot air present in the solar chimney, which tends to rise up inside the air channel to the top exhaust vents (air outlet). Studies related with this subject have shown that these systems are able to ventilate the inner spaces even on cloudy days [3] but, in real conditions, wind forces can enhance or oppose the solar chimney buoyancy effect flow if some design conditions are not seized.

Solar chimneys can have large sizes but they can also be designed place in walls or in roofs. Recent studies explore the use of small size solar chimneys while maintaining, where possible, the same ventilation performance [9, 10]. One of the limitations of these systems is that air needs a larger volume to transport a small amount of heat [11].

A building solar air system is a system that collects solar energy and converts it into heat, this heat being then transported by the air to be stored or for direct use [11]. The major component of any solar system is obviously the solar collector [3]. Apart from the solar chimney there are other systems that make use of solar induced natural convection. Windows are the most commonly used building solar collectors and some of them work as part of a building integrated passive solar air system [12, 13]. Beyond the solar chimney, the most studied and implemented systems in buildings are the Trombe Wall and the Double Skin Facade [3, 14].

The Trombe wall is similar to the solar chimney concept. The classical Trombe Wall comprises an absorber wall, blackened in one side and covered by a glazed vertical wall on the outside, but separated from the wall by an air channel. The absorber wall absorbs and stores the thermal energy caused by the solar radiation through the glazing. The stored energy is then conducted to the indoor environment. In the second generation of Trombe walls, apart from the wall absorber and the glazing, there is air circulation in the channel due to buoyancy effect, functioning in the air heating or cooling modes. Improvements have been made through the years on the Trombe wall design, mainly in the vents/dampers control, thermal insulation and air channel design. Adjustable openings/vents for winter and summer conditions have allowed obtaining good improvements in its thermal behavior [3]. Some identified disadvantages of this system have motivated some developments [8].

The Double Skin Facade (DSF) is now often used. It is a facade system that combines an inner wall, glazed or not, with an outer glazed skin separated by an air channel. The buoyancy effect is also the driving force that promotes the upflow of air. There are several classifications for these systems. They mainly differ on the ventilation mode and on the partitioning of the air channel. The control of air inlet and outlet openings in the outer and inner walls regulates the possible ventilation modes. DSF can act as a buffer zone between outdoor and indoor spaces, as an intake air facade, as an exhaust air facade for natural ventilated purpose (similar to a solar chimney) and as outdoor or indoor air curtain [15]. Related with the physical separation inside the air channel, there are several classifications on the literature they are: the corridor facade; box-window facade; shaft-box facade and second skin facade [16, 17], to name a few.

There are also some applications of solar air collectors in building roofs [3]. Roof devices have the advantage of providing higher surface collector areas. However, they are not as efficient as the vertical one because they have a lower difference of level along the airflow path which reduces the buoyancy effect. Therefore, the air flow rates can also decrease [3, 4].

According to the latest insights, the best results for a thermally suitable environment for human comfort are normally achieved with the use of a combination of more than one passive strategy, especially for some outdoor climatic conditions [3]. Thereby, some developments on solar collectors for buildings are based on the combination of different thermal storage systems. The solar energy collection, distribution and storage, together with ventilation concepts, seem to be essential for an integrated passive solar approach for buildings [11].

3. NEW SOLAR AIR SYSTEMS

The first patented solar air heater was designed and built in the USA in 1881. Since then many other step by step developments have been made. The promise of this technology gained the attention of governments, increasingly motivated by environmental and energy concerns [1]. Within the range of possible solar air systems, there are facade or roof integrated panels (flat plate collectors), windows, transparent second facades (DSF) and glazed indoor spaces (atriums, sun spaces or attics).

Ventilated building facades are being introduced, for instance, into commercial buildings and schools but these systems are not commonly used in houses or apartment buildings due to their cost or because they may be less appropriate for residential design. Hence, windows with ventilation ability may be of great interest for residential buildings [18, 19].

Chen and Paige [18] developed a ventilated window that makes use of buoyancy forces to improve air quality while Trumbull [19] invented a solar heating window. The slanted-box like object (see Fig. (**2**)) presented by Trumbull [19] is insulated at the top (26), bottom (22) and lateral walls (not visible in the figure) and can be installed through a wall of a building or to a sliding window (12). The sunlight passes through the glazing (30), with a tilt angle of 60º, heats the metallic collector (40) and this leads to a thermo-siphoning effect. Indoor air enters in the pre-heated chamber (51), through a lower vent (60). Since the temperature in the channel, formed by the glazing and metallic collector, is higher than that of the pre-heated chamber, the air flows upwards in the mentioned channel. Therefore, hot air is delivered to the indoor space through the top vent (62). The lower and top vents can be closed during the night or in the presence of specific conditions where sunlight can be prevented, in one of the versions of this invention, the collector can be rotated in order to be suitable for extreme latitudes. Geographically, this system can be applied in any window between 150º Southeast and 240º Southwest and at latitudes from the 20*th* parallel all the way north [19]. After six hours of operation, the air temperature difference between the top and lower vents reached as much as 23 ºC, in an experiment, at Royal Oak, Michigan, USA. The correspondent air flow rate is not presented by the inventor.

While the previous inventions are adequate for windows, Christensen [20] developed a solar air collector flat panel for ventilation and space heating to be mounted in the opaque building envelope. In this solar collector (see Fig. (**3**)) the conventional insulation material on the back face of the system is replaced by a permeable back panel (5) and a permeable heat absorber means (4), through which the heated convection airflow passes, as seen in Fig. (**3**). This heat convection airflow through the interior of the solar panel prevents the convection heat loss in the opposite direction. The back panel (5), made of perforated aluminium, also reduces the

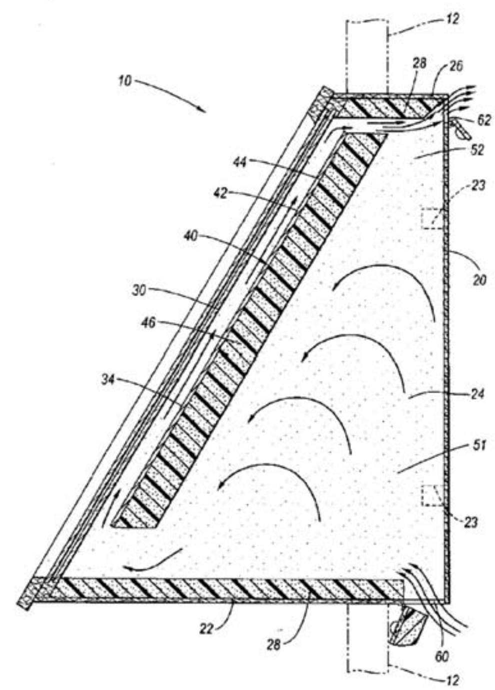

Fig. (2). Solar heating window & through-wall device (for the complete description of the numbers see [19]).

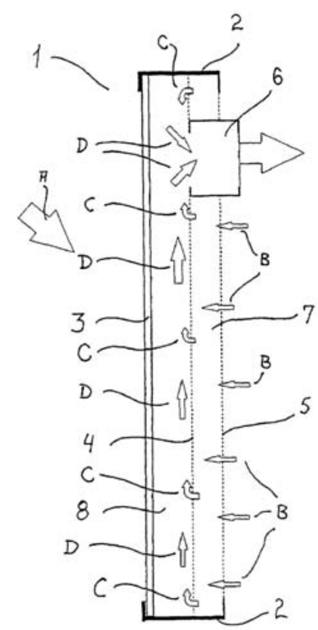

Fig. (3). Longitudinal section of a solar collector panel (for the complete description of the numbers see [20]).

radiation heat loss from the heat absorber means (4), since the side of the back panel (5) facing the heat absorber means (4) is white or of a light color. The heat absorber means (4) may be also made of perforated aluminium, painted black on both sides so that the absorption coefficient is high. Additionally, the solar collector panel (1) consists in an aluminium frame (2) that holds a transparent front panel (3), the heat absorber means (4) and back panel (5). The outlet duct (6) is located at the upper part of the solar collector panel (1) [20].

The solar radiation (A) is transmitted through the transparent front panel (3) and reaches the heat absorber means (4) which absorbs around 80% of the radiation and consequently makes its temperature rise up to e.g. 40º- 90º C. On the other hand, the white surface of the back panel (5) reflects about 70 to 75% of this radiation back to the heat absorber. The absorbed heat radiation is used to heat the air, as it is explained below.

The fresh air coming from the surroundings (B) is drawn through the perforated back panel (5). After passing the perforated cold back panel (4), the air crosses the channel (7) and reaches the heat absorber (4), the heat absorber means being at high temperature (40º- 90º C as mentioned above). The airflow passes then the permeable absorber means (4) where it is heated. Then, due to the buoyancy effect, the hot air moves upward (D) in the channel (8) (with approximately 5 cm width) towards the outlet duct in the top (6) and may be used either for ventilation or space heating [20].

In another version of this invention, the panels can be extended to larger areas, assembling several solar air collector panels coupled together in series, having a common outlet duct (6) [20]. Hence, the air coming from the surroundings (B) is distributed to a larger area and the air velocity inside the panel is, therefore, lower. This property is important because the panel stays less susceptible to big particles carried with the airflow, resulting in a reduced necessity of air filtering and cleaning of the solar panel [20].

Double skin facades are used for reducing energy consumption in winter but they have proved that they can be ineffective, if not deleterious, in summer [21]. The double skin facade has mainly two purposes: to reduce the heat loss but also recover the heat generated in the air channel. This air heating is mainly due to solar radiation over the outer skin but also by the recovery of the inner skin thermal loss. Many curtain walls or double skins used in buildings lead to overheating in summer. Therefore, great care should be taken regarding this problem. In order to reduce energy consumption in summer, solar shading is strongly needed.

The moveable-sunshade system from Lilli and Lilli [21] functions as a double skin facade (during cold season) and, in another mode of operation, shades the facade during the summer season, see Fig. (**4**). The cost of the moveable-sunshade system is higher than that containing a single mode of operation. However, according to the energy saving that is achieved throughout the year, the cost of installation of the moveable-sunshade system is amortized in a few years [21].

The above-mentioned moveable-sunshade system is an integrated system which comprises a plurality of sunshade slats (1) and of panes (5), see Fig. (**5**), both movable, each one forming a single body with the other. The slats and

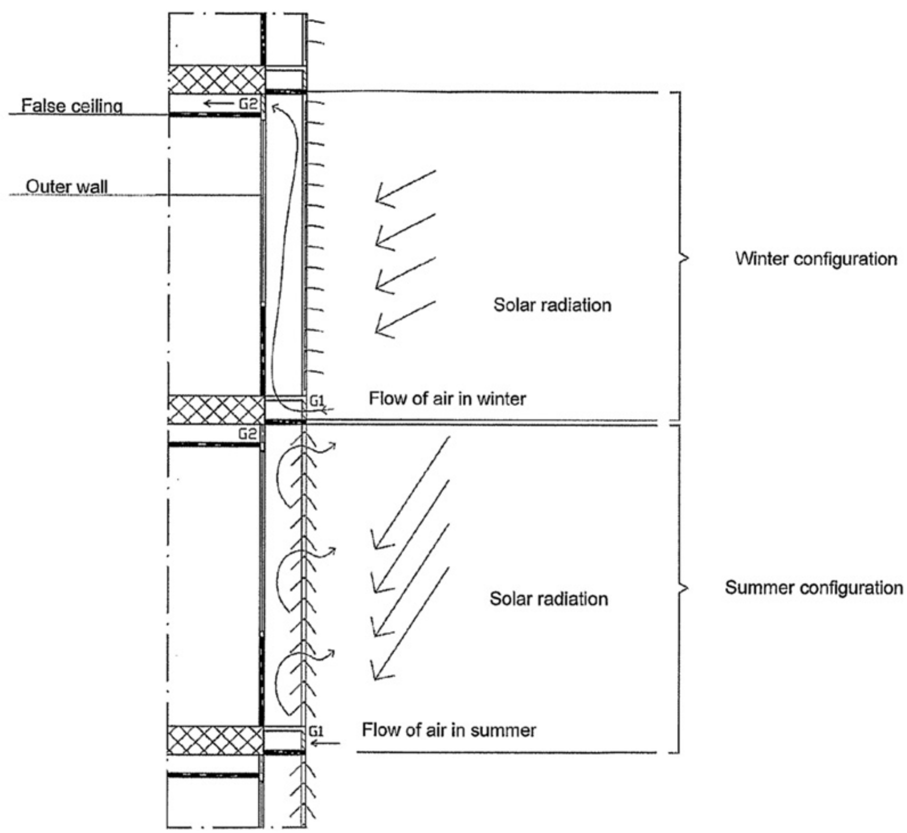

Fig. (4). Vertical cross-sectional view of the double skin facade with a moveable-sunshade system for winter and summer (for the complete description of the numbers see [21]).

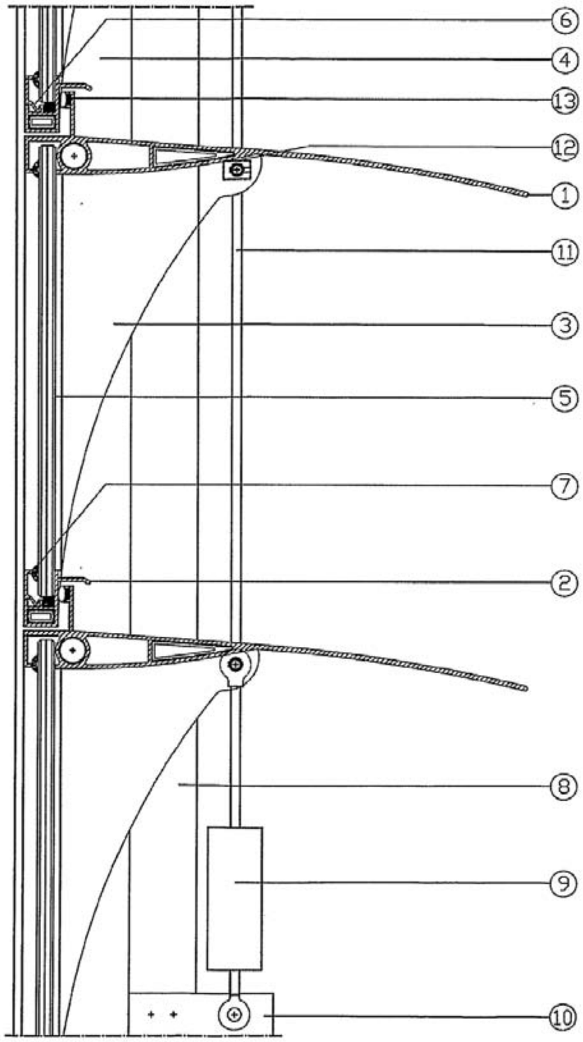

Fig. (5). Detail of the double skin facade with a moveable-sunshade system for winter configuration (for the complete description of the numbers see [21]).

panes are connected in series by means of a crank mechanism that enables the simultaneous orientation. The top sunshade slat (1) and the pane (5) are equipped with two ending fixing elements or gusset plates (3) and a bottom sectional strip (2). The gussets are inserted in a side frame (4) that is fixed upright (8).

In the winter period the system is designed to be set in an inactive position, i.e., with the sunshade slats (1) in a substantially horizontal position, Fig. (**5**), and the panes (5) in the vertical position: the configuration of a double skin facade. The sun rays during this period have low inclination and are intercepted only in a minimal extent by the sunshades slats (1) and heat the air gap between panes (5) and outer facade. The flow of air at input from the grating G1 is recovered *via* the top grating G2, see Fig. (**4**), and sent to the central-heating system of the building [21].

In the summer period the system is in the active position, see Fig. (**6**), with the sunshade slats (1) rotated by an amount

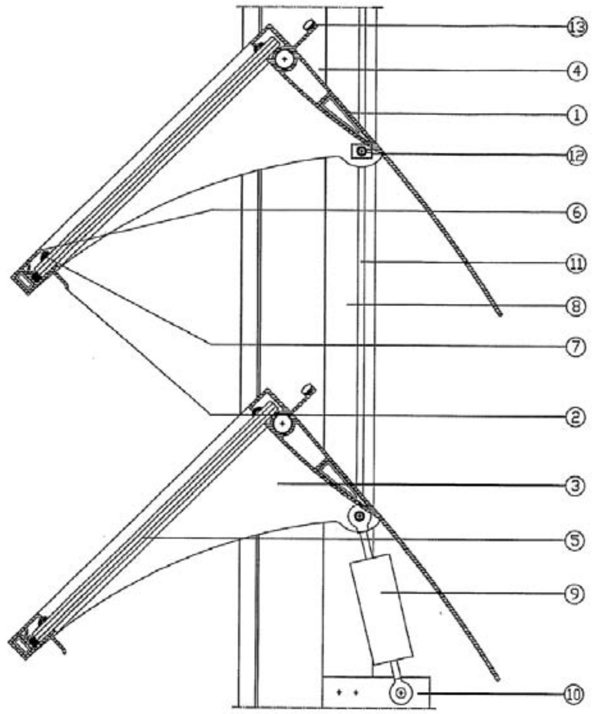

Fig. (6). Detail of the double skin facade with a moveable-sunshade system for summer configuration (for the complete description of the numbers see [21]).

necessary for intercepting the sun rays and for keeping the outer wall of the building in shade. The rotation occurs by acting the means of movement (9) and (11), actuated by a provided motor or by manual control. Therefore, the achieved sun interception leads to a reduced heating of the air gap between the pane (5) and the outer facade of the building. Another advantage of the addition of the pane (5) is the circulation of the external air, as depicted on Fig. (**4**). The grating G2 remains closed (Fig. (**4**)) and the flow of air at input from grating G1 is evacuated through the pane (5) [21].

In sum, the moveable-sunshade system results in considerable energy savings during all seasons of the year.

Facade systems can work also as indoor ventilating devices Fig. (**7**). Cho and Cho [22] developed an air circulation system of a building using a curtain wall as a ventilator. It consists in a ventilation system for high-rise buildings with the purpose of blocking radiation heat from the sun from being transferred to the internal space, to act as an exhausting space and as a ventilated facade also. It comprises an external curtain wall (200), located at a certain distance from the outer wall (22), as it can be seen in Fig. (**7**).

External air enters through a ventilation opening (210), disposed in the lower portion of the external curtain wall (200). The above-mentioned ventilation opening (210) can be opened and closed. An air stream exhaust port (220) is provided in a space between the rooftop of the building and the upper end portion of the external curtain wall, extended horizontally to cover part of the rooftop. The air stream ex-

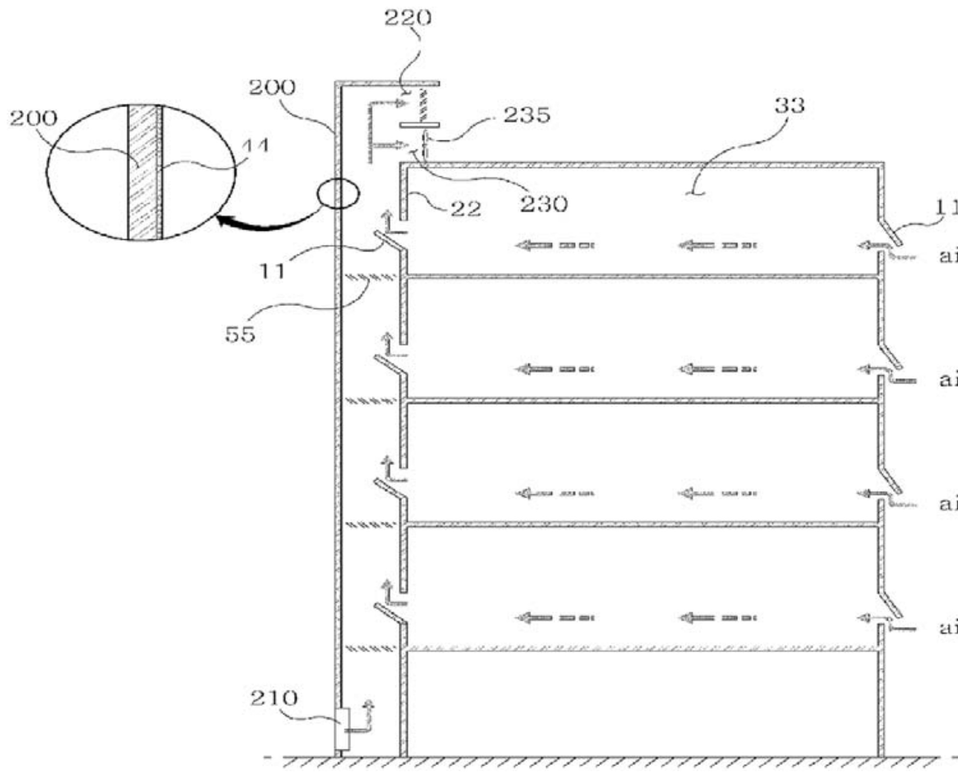

Fig. (7). Sectional view showing a ventilation system for high-rise building (for the complete description of the numbers see [22]).

haust port (220) has a pivot slit capable of being closed and opened. A forcible exhaust port (230) is also installed in parallel to the air stream exhaust port (220) and forms a separate exhausting space. The air stream exhaust port (220) is responsible for the natural ventilation and the forcible exhaust port (230) which performs forcible ventilation using an air blower (235). Not all the side walls are surrounded by the external curtain wall. One or two sides must be left without curtain. The orientation of the side/sides without curtain wall is usually the northern sides [22].

This invention has different versions. In a first version, the external air is introduced into the internal space (33) through a window (11) positioned at each store and in a building side that was left without curtain wall. The air circulates inside the space (33) and the exhaust air is discharged through a space between the curtain wall (200) and the outer wall (22), *via* window (11). This window is formed by a pivot in a way that the upper side can be opened outwards, for more air discharge efficiency. The exhausted air is discharged through the space between the external curtain and the outer wall and rises up to be discharged outside through the air stream exhaust port or the forcible exhaust port to the outside. The external curtain wall includes a glass and a solar heat shielding film (44) which is attached to the inner face of the glass. The temperature in the inner side of the curtain wall increases by solar radiation and induces the heating of the air inside the space between the curtain wall and the outer wall, promoting a more active rise up of air by the buoyancy effect. Cho and Cho [22] mention that the shielding film prevents radiation heat of the sun from reaching the internal space and simultaneously it induces the upstream air in the space between outer wall and the curtain wall, preventing from being transferred to the internal space [22].

In a second version of the invention, Cho and Cho [22] developed the same system but with an additional shielding glass (100) installed inside the space between the external curtain wall and the outer wall, as seen in Fig. (**8**).

In the zones where the shielding glass is installed, the shielding film is attached to the surface of the shielding glass (outer or inner) with the same purpose as referred to before. However, in the present embodiment of the invention, the upflow of air is induced by both sides of the shielding glass, (see Fig. (**8**)).

In another version of the invention, window (11) is closed (Fig. (**7**) or Fig. (**8**)). When the windows (11) of the building are closed the external air is not supplied into the internal space (33) and the internal air is not discharged. In this version, the external air suction (210) is opened and introduces external air in the space between the curtain wall (200) and the outer wall (22). The air moves upward and is discharged through the air stream exhaust (220) or the forcible exhaust port (230), creating a ventilated facade.

Additionally, this system may also include fire safety concern, by the application of a fire-retardant damper (see number (55) in Fig. (**7**)) at each floor level. The fire-retardant damper can be opened or closed. Due to the presence of the fire-retardant damper (see Fig. (**7**) or Fig. (**8**)), another operating mode can be obtained. During the winter time, the external air suction port (210) can be closed and the fire-retardant damper may be blocked. This avoids the upflow of air, creating a buffer zone, in the space between the

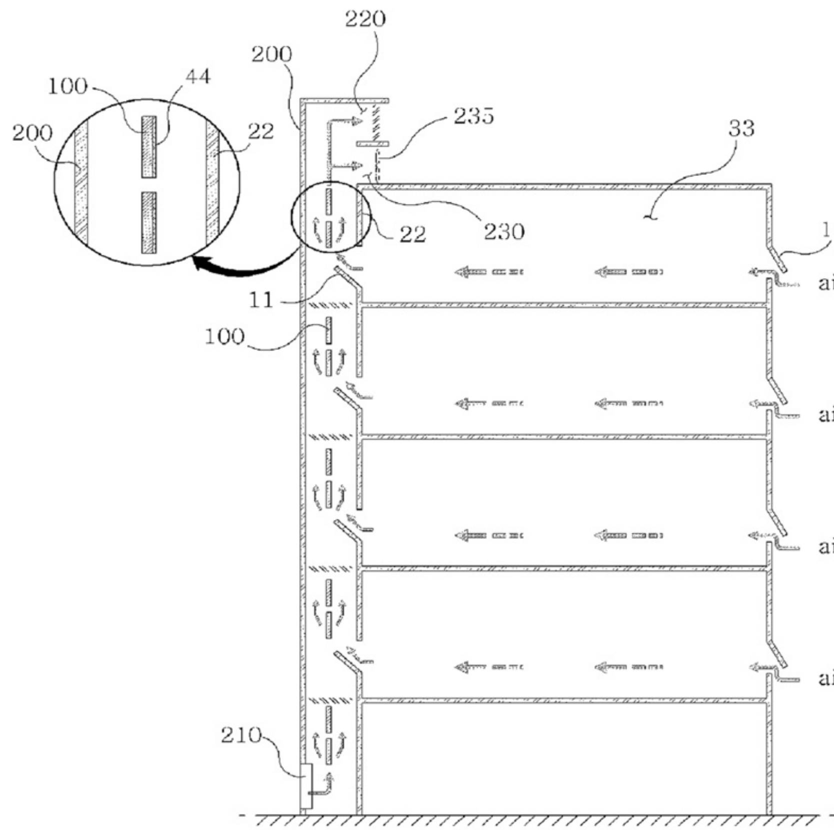

Fig. (8). Sectional view showing a ventilation system where a shielding glass is installed (for the complete description of the numbers see [22]).

external curtain wall (200) and outer wall (22). The air present between the external curtain wall and outer wall is heated, and remains there, thereby maximizing the insulation effect and enabling the reduction of the indoors heating cost [22].

In sum, it is very important to underline that this invention [22] serves more than one role, responding to different outdoor and indoor conditions demands during the year.

In another invention, by Holt [23], (see Fig. (**9**)), habitable spaces of a building (100) are naturally cooled and cross-ventilated with no running energy costs. The habitable spaces (102) are located in the lower fraction of the building and their interior walls (106) form the outer boundary of a core (108) or open space. At the top of the building there is an air chamber (308) and the roof (304) of this chamber is made of transparent material, such as glass. Solar radiation (316) heats the roof (304) and the temperature of the air present in the chamber rises, this temperature is higher than the temperature of the air present in the core (108). Due to solar radiation (316), the temperature of the air at the top of the core (108) is also higher than the temperature of the air at the lower part of the core. Hence, due to buoyancy forces, air rises along the core and cold air from outside of the building is suctioned through ventilation openings (312), located in the bottom of the building, or open windows and/or voids (314) located in the exterior lateral walls of the building.

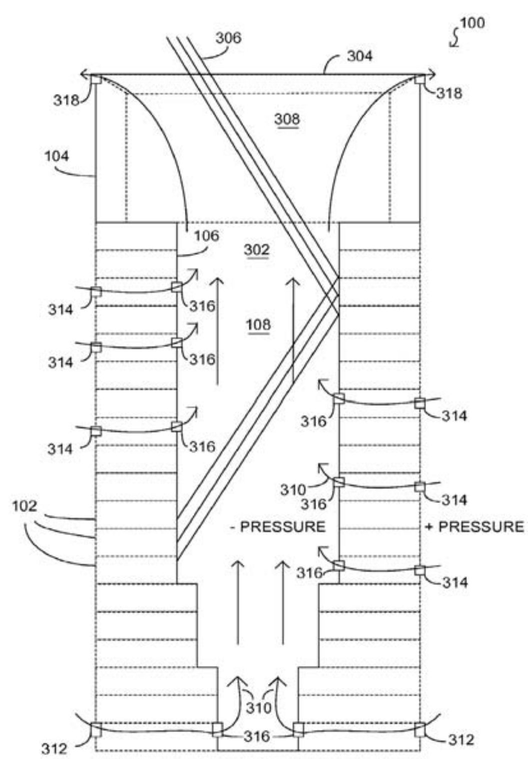

Fig. (9). Energy efficient building (for the complete description of the numbers see [23]).

Cold outdoor air enters in the core through inner ventilation openings (316), rises and then is expelled from the air chamber through one or more openings (318) located at the walls of the air chamber (308). As a result of the described air flow, the habitable spaces (102) are cooled and naturally ventilated [23].

Holt suggested [23] that the use of reflectors (located at the top of the air chamber) that reflect solar radiation to the air chamber and/or core can increase the temperature in the air chamber and/or core and, therefore, improve the performance due to higher buoyancy forces. The introduction of solar radiation into the core also beneficially illuminates the interior parts of the habitable spaces located around the core [23]. The above-mentioned researcher measured an air velocity (obtained only due to buoyancy forces), at the top of the core, of 7 m/s and 7.5 m/s in the mid-season and in winter season, respectively, and suggested that wind turbines, (Fig. (**10**)), located around the top exit of the core (108) may be used to supply electricity to the building.

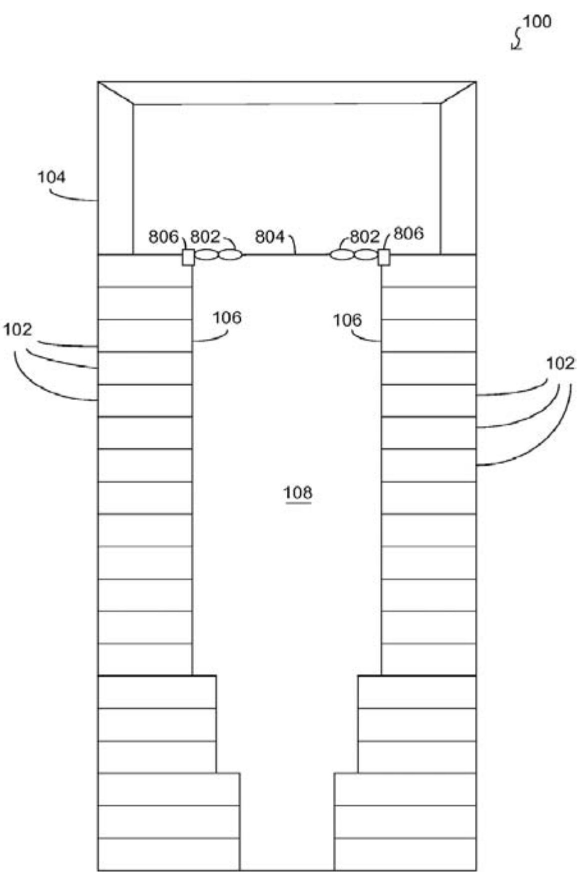

Fig. (10). Cross-sectional view of the energy efficient building with wind turbines (for the complete description of the numbers see [23]).

As the air rises toward the top of the core (108), it mixes with warmer air and increases velocity. Therefore, wind turbines (802) rotate with this moving air, driving generators (806) that convert the mechanical turning energy into electricity.

4. CURRENT & FUTURE DEVELOPMENTS

The solar collector passive technology has been slowly introduced in common buildings. Its application still faces some barriers. Nevertheless, the benefits of using solar energy and natural airflow passive principles for building indoor comfort are gaining more and more supporters [24, 25].

Chan *et al*. [3] state that the system efficiency, the aesthetics and the cost effectiveness should be future research issues. Along with the system efficiency developments, which is without any doubt is essential, the development and application of new materials for solar collection apart from the glazing is also an interesting future path. One of the major problems of some of these systems is their impact on the aesthetics of the building envelopes. Recent developments also pointed out that these systems should be conceived more embedded in building elements, for more architectural integration and economic feasibility [3, 26]. Making the passive solar systems a more integrated part of the building components without losing efficiency is something that should be developed in the future.

Also, the multi-use of the systems, for heating, cooling or ventilating improves its economical viability [11]. The research for even more multifunctional, upgradable and adaptive systems to climate changes and indoor needs should be another path for future innovation. But, as it was underlined by Selkowitz [5], these systems will be widely used if their lifecycle benefits exceed their cost.

It is also important to take into account that more than applying this technology to new buildings it is even more challenging to create innovative solutions adapted to building refurbishment where a very wide range of constraints must be faced.

Finally, it must be observed that majority of the recent patents discussed in this paper have a concern for passive cooling and ventilation strategies, besides the traditional concern for heating and it is predictable that the future R&D in solar systems will continue to follow mostly this direction.

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