# STACK VENTILATION STRATEGIES IN ARCHITECTURAL CONTEXT: A BRIEF REVIEW OF HISTORICAL DEVELOPMENT, CURRENT TRENDS AND FUTURE POSSIBILITIES

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**ABSTRACT**
Man has used the stack ventilation strategy for centuries to ensure comfortable indoor environment in their buildings. Today, in the conditions of the denser built environment and the need for deep-plan buildings seems inevitable, the application of stack ventilation strategy has become more important, especially when the natural cross ventilation has limited functions. However, realizing the fact that this strategy is very dependent on indoor-outdoor temperature differential, many innovative elements, devices and strategies based on this ventilation concept have been developed to overcome the weaknesses of this strategy, particularly in terms of its reliability and applicability in the modern building. Therefore, concerning about the potential and current limitations of this ventilation strategy, this paper presents a brief overview on various aspects of stack ventilation, covering its historical development, recent innovation and application trends as well as future possibilities for its further development.

**Keywords:** *Solar Induced Ventilation, Wind-driven Ventilation, Natural Ventilation, Renewable Energy, Green Building*

## 1. INTRODUCTION

Since many studies have shown that the wind effect is far more dominant than temperature buoyancy (stack effect) in inducing airflow [1], the application of natural cross ventilation is always the preferred choice by the architects and building designers to generate indoor air movement and improve their building thermal environment [2]. However nowadays, in the conditions of the warmer climate and denser built environment, the conventional concept of natural cross ventilation does not always successfully apply. The need for a compartmentation of spaces in a deep plan building and more compact layout of planning where buildings are laid closely like in the terrace houses have resulted in limited openings for cross-airflow [3]. For these situations, the main solution could lie on providing effective outlet area at the top of the building and use a stack ventilation strategy to induce vertical air movement.

In this context, stack ventilation can be defined as the upward movement of air through openings in a building fabric due to thermal buoyancy and/or negative pressure generated by the wind over the roof. This principle makes this ventilation strategy less dependent on outdoor wind condition and makes it more significant to improve natural ventilation in a building with limited side openings, like in a terrace house. Due to these advantages, many researchers and building designers are prompted to design and develop several innovative stack ventilation strategies as alternatives to cross ventilation in various types of buildings. This involves the development of the advanced passive stack devices, solar induced ventilation, wind-stack driven strategy and even fan induced stack ventilation strategies.

Therefore, in order to clarify about the full potential and limitations of this stack ventilation strategy, this paper reviews various aspects of its applications in the building, covering the aspect of historical development, current trends and its future possibilities.

## 2. HISTORICAL DEVELOPMENT

Historically, stack ventilation strategy has been used by mankind since ancient times to provide comfortable indoor environment in their buildings. From the literature, it was reported that earlier man of the Minoan period used wind towers and building height to induce vertical air movement [4] while rural villagers in Banpo China during 4000-5000BC used chimneys to remove the products of combustion used for heat, light or cooking from their homes [5]. On the other hand, the ventilation shafts equipped with outlet openings were used by the Anasazi Pueblo Kiva to provide ventilation air and extract combustion products from their houses [6], as shown in Figure 1(a). During the age of Roman Empire, the flat roofs above the living quarters have been discovered to have vent holes to allow smoke out from the interiors [7]. This approach is quite similar with the stack ventilation strategy incorporated in The Indian Teepee which employs thermal forces and free wind to ensure ample ventilation by the provision of a hole at the top to induce stale air out and a doorway to let fresh air in.

*(a)* *(b)*

*Figure 1: Early stack ventilation strategies in man-made structures; (a) Anasazi Pueblo Kiva [8] (b) the kiln at a malting in Essex, UK [9]*

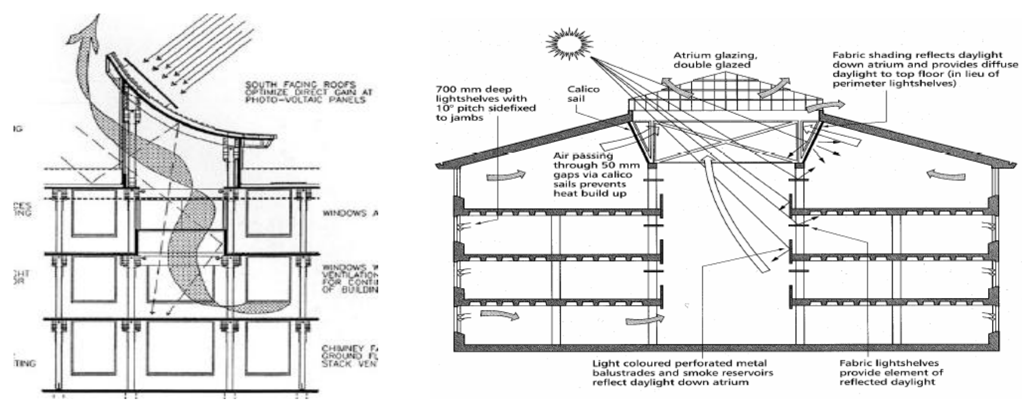
In the 19th century, the enhancement of stack ventilation strategy has been shown by the system built in House of Commons, England where open fires were used to generate a thermal draft. At the same time, exhaust openings in the upper part of the building induced a stack effect to extract hot air out through the building [10, 11].

On the other hand, the kiln-vent in the malting and a cupola in nineteenth-century American house were other relevant examples of the stack ventilation strategies used in the past. In the typical malting in the cold climate of United Kingdom, air enters the building through the large louvered windows and flows up through the flooring blocks, before exits through the kiln-vent (Figure 1(b)). In the American house, the cupola which is incorporated with a series of windows at all sides was centered over the staircases to allow the ventilation from side to side and bottom to top occurred when all the windows and internal doors on all levels are opened [12].

## 3. CURRENT TRENDS

### 3.1 Natural Stack Ventilation Strategies

Apart from the earlier mentioned strategies, there are several stack ventilation techniques inherited from vernacular architecture worldwide which are still in use today. Among the most common techniques are the static type openings on top or upper part of the building like ridge, static and dormer vent, chimney flue, jack roof and roof monitor (Figure 2(a)), which most of them deal with the function to ventilate the trapped hot air underneath the roof, thus reduce the internal heat gain [13].




*(a)* *(b)*

*Figure 2: Natural stack ventilation strategies in modern building; (a) roof monitor at CK Choi Building, USA [14] (b) double glazed atrium at PowerGen Headquarters, Coventry, UK [15]*

In some conditions, these static types of stack ventilation strategies could be enhanced by the use of atrium, stack devices and ventilation shafts. An atrium is a space with glazed roofs which is usually incorporated in the middle of a deep-plan building for both daylighting and ventilation purposes. This architectural feature could enhance the stack ventilation performance by increasing high differential pressure through the use of the glazing elements at the upper part. This element could absorb solar gain and increase the air temperature near the outlet area which in turn makes the stack flow more effective due to the increase in buoyancy-driven flow (Figure 2(b)). However, this feature has several drawbacks in terms of the noise problem, which can be transferred between adjacent rooms by reflection in the glazed cavity surface and the problem of heat radiation during the hot days [16].

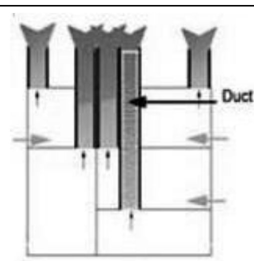
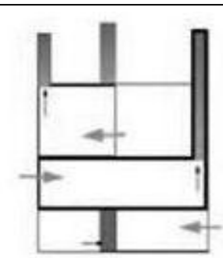
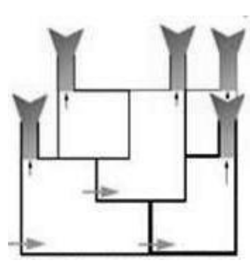
On the other hand, stack ventilation towers like a stack device is another conventional architectural feature which usually associated with stack ventilation strategy. With the high vertical façade above the roof, this element is not only effective in increasing the buoyancy pressure available to drive an upward flow, but also effective to drive ventilation in lower floors of the multi-storey building (Figure 3).

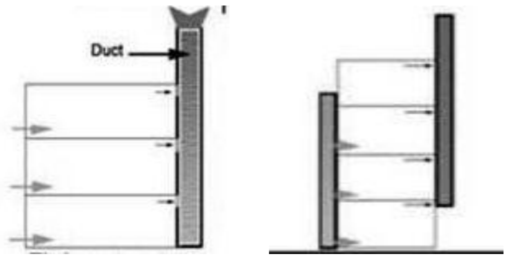
*(a)* *(b)*

*Figure 3: Actual application of stack ventilation towers at (a) The De Montfort University, UK [17] (b) Frederick Lanchester Library, UK [18]*

In contrast with stack device, ventilation shaft is a space within the building framework with the primary function is to collect, transport and sometimes distribute ventilation air to another space or outdoor. For the stack ventilation purpose, this shaft element can be applied to collect hot and stale air from the occupied spaces before extract it out to the outdoors via more suitable elements like chimney or wind tower. On the whole, Mansouri *et al.* [19] classified the stack devices and ventilation shaft strategies into three main categories i.e. fitting structure, adjacency structure and overlapping structure, as can be seen in Table 1 below.

Table 1: Spaces layout configurations of stack devices and ventilation shafts as classified by Mansouri *et al.* [19]

| | **Stack Ventilation Strategy** (in multi-storey building) | **Stack Devices** | **Ventilation Shafts** |
|---|---|---|---|
| **Geometrical Independence** | **Adjacency structure** (where each room is ventilated individually) |   |  |
| | **Overlapping Structure** (where all rooms are partially superposed although each room has a specific ventilation strategy) |  | |

| | | |
|---|---|---|
| **Geometrical Dependency** | **Fitting Structure**<br>(where similar designing rooms are superposed) |  |

### 3.2 Advanced Stack Ventilation Strategies

In an effort to make stack ventilation more significant even in low-indoor outdoor temperature difference region, some advanced stack ventilation strategies that maximize the natural energy sources available from both the sun and wind has been developed and tested. These include solar induced ventilation, wind-stack driven ventilation and even fan induced stack ventilation.

Solar induced ventilation which some of its strategies are inherited from yesteryears rely upon the heating of the building fabric by solar radiation resulting into a greater temperature difference to induce the stack effect [20]. Three main building elements which are based on this concept of ventilation are solar chimney, solar roof and double façade [21].

According to Khedari *et al.* [22], the solar chimney which relies upon the solar radiation and heat absorption to induce a bigger pressure difference between the inlet and the outlet of the element to increase the stack effect succeeded to generate ventilation rates of between 8 and 15 ACH and had induced air movement of about 0.04m/s at occupied level. Some examples if this strategy in modern building can be seen in Charles de Gaulle School in in Damascus, Syria and BRE Office Building in Herfordshire, UK, as shown in Figure 4(a).

*(a)* *(b)*

*Figure 4: Exterior view of (a) solar chimney features in BRE Office Building, Herfordshire [15] (b) double skin applications in McCann FitzGerald Offices in Dublin, Ireland [23]*

In double façade element which can be used for both ventilation and daylighting purposes, the air in the intermediate space or cavity between inner and outer glazed skin is heated due to solar radiation. The increasing pressure between inlet and upper outlet area then could induce stack effect, thus extract hot air out from the building. Based on the study by Hirunlabh *et al.* [24], this strategy is able to increase ventilation rate of their model room up to 1.65 ACH. SIDC Headquarters in Malaysia and McCann FitzGerald Offices in Dublin, Ireland are two examples of modern buildings which incorporate this element in their façade (Figure 4(b)).

Solar roof or commonly known as double roof is another example of solar induced ventilation. In this element, the large sloping roof is used to absorb solar radiation, thus heating the cavity between the outer and inner roof. As a result, the increasing negative pressure in that cavity is capable to induce upward air movement from the occupied space and thus extract it out through the upper outlet area. Based on the field study, Hirunlabh *et al.* [25] found that the roof solar collector with 14cm air gap succeeded to induce air change rate up to 4 ACH in building under tropical climate.

On the other hand, many studies revealed that the use of wind-driven ventilation techniques like wind cowl, wind tower, windcatcher and turbine ventilator are very helpful to induce vertical air movement, thus enhancing the stack ventilation significantly [26]. Due to this rationale, it sometimes termed as wind-stack driven ventilation [27], or wind assisted stack ventilation.

One of the wind-stack driven strategies that are considered appropriate to be used in high-wind velocity condition like in temperate climate region is a wind cowl. In contrast with commonly used exhaust cowl, this rotating wind cowl is proven to be more effective in inducing vertical air movement since it can maximize outdoor wind force. In this strategy, the negative pressure resulted from placing its opening to face the leeward side is capable to extract air up to 210l/s at 9m/s [28].

Another wind-driven ventilation strategy that can assist stack ventilation is a wind tower or commonly known as *'badghir'* in the Middle East. According to Bahadori [29], this ventilation strategy which can both capture the wind and extract it out within one single element is capable to induce air extraction up to 73 ACH, particulary for 4m tower head equipped with clay conduits. The IONICA building in UK is one example of the modern building which applies this feature in its design (Figure 5).


*(a)*


*(b)*

*Figure 5: Applications of wind tower in; (a) vernacular architecture in Iran [30] (b) IONICA Building, UK [31]*

As a modern version of wind tower, wind catcher uses almost the same principle with the former strategy, which is by catching the wind at the windward side of the roof, channel it downward to the occupied space before exhaust it out at the leeward side. Based on the wind tunnel and numerical simulation study, Li and Mak [32] found that the device achieved to reduce occupied space temperature up to 6°C.

On the other hand, the turbine ventilator which is considerable cheap and technological simple to operate is another wind-driven ventilation strategy that can be used to assist stack ventilation, especially in the absence of wind. According to the previous studies, this device is found effective to enhance ventilation rate [33], reduce attic and indoor air temperatures and improve indoor air quality (IAQ) in various types of building, especially in high-wind velocity region [33, 34].

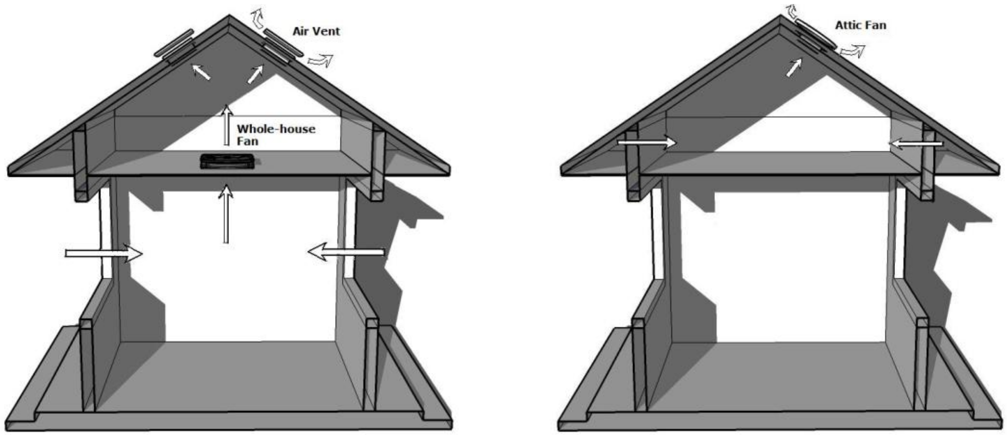
### 3.3 Fan Induced Stack Ventilation

From the review of the solar induced ventilation and wind-stack driven ventilation strategies, it is clear that those stack ventilation strategies could be a promising energy-efficient strategy since they utilize nature's power. However, for a modern building especially in hot-humid tropical climate, where certainty and efficiency are preferred, the assistance of active or forced ventilation is considered to be the best reliable mean to overcome the inadequacy of natural stack ventilation alone to effectively ventilate the building. ASHRAE [35] defined forced ventilation (or mechanical ventilation) as *"intentional movement of air into and out of a building using fans and intake exhaust vents"*.

These strategies are thought to be possible alternatives for enhancing natural ventilation especially in the cases when stack ventilation is limited by low room height, too small areas available for high outlets and also when stack ventilation structural elements like open sections, communicating levels, or ventilation chimney may not be possible. Moreover, this strategy is also significant when microclimatic condition becomes a major constraint such as when the indoor-outdoor temperature difference is too low and outdoor wind velocity is too weak to create negative pressure to assist stack ventilation [2].

#### 3.3.1 Mains Powered Stack Ventilator

In the case of this active stack ventilation strategy, generally there are two main basic types of fan induced stack ventilation that have been used to reduce air conditioning cost in the building i.e. whole-house fan (Figure 6(a)) and attic extractor fan (Figure 6(b)).




(a) (b)

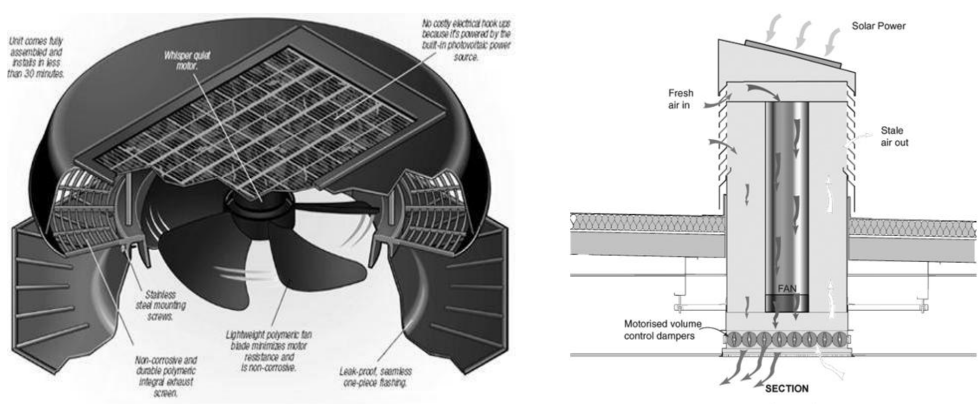
*Figure 6: Illustrative diagram of conventional active stack ventilators (a) whole-house fan (b) attic extractor fan*

Whole-house fan which is a large volume and low velocity fan that mounts in the ceiling is used to promote air exchange by drawing air from windows and exhaust from a central high point to the attic and then to outside with the help of air vent. Although this mechanical device can create some air movement and reduce air temperatures in a home, but it has several disadvantages in terms of noise, installation complexity and high electricity consumption of about 300 and 500 watts per fan.

Regarding extractor fan, Wong and Heryanto [36] and Priyadarsini *et al.* [37] clarified the advantageous of fixing the device to enhance stack ventilation in the apartment buildings in Singapore. By placing the fan at the top of the stack, Wong and Heryanto [36] revealed that strategy could significantly increase the average air velocity within the residential unit by 47% and within the particular rooms where the stack was located by 54%. On the other hand, Priyadarsini found that the strategy succeeded to induce upward air movement of between 0.26 to 0.6m/s, which is equal to 550% increased compared to velocity when the fan is not used [37].

### 3.3.2 Solar-Powered Stack Ventilators

Although the application of extractor fan is proven significant to increase stack ventilation, but the drawback of consuming a high amount of purchased energy (around 250 watts), has made the use of solar powered attic fan as a better alternative to choose (Figure 7(a)). This was confirmed by Ahmed *et al.* [38] who indicated that its application in Malaysian climate does succeed to reduce the air temperature and humidity inside a building, especially when the openings are closed. However, the study revealed that the airspeed in the indoor space was found to be very minimal and the device's total dependent on solar energy has limited its function during to the daytime only [38].

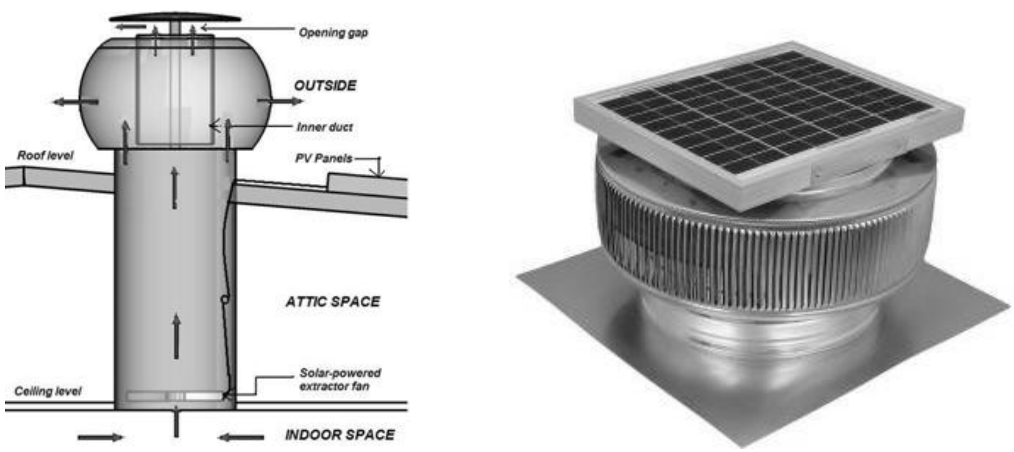



(a) (b)

*Figure 7: Solar-powered stack ventilators; (a) A 10 watt solar powered attic fan (SolarStar) from Solatube, Inc. [39] (b) A 40watt crystalline PV powered Solaboost [40]*

In an effort to prolong its operation and improve ventilation efficiency, some innovative stack ventilation strategies have been developed by combining the solar powered inner fan with wind-driven ventilation devices like wind catcher (Figure 7(b)) and turbine ventilator (Figure 13).

Based on the field study result, Khan *et al.* [41] reported that with the installation of inner fan powered by 40W polycrystalline PV panel in *Monodraught Windcatcher* (SolaBoost), 260l/s of airflow rate has been achieved. It was found that the fan started to rotate when solar panel received at least 6V. However, when it received 14V (means hotter outdoor air and more cooling is needed), the device will boost the fan power to 25V which could produce 250% increase of the rotation speed, thus inducing the flow rate significantly [41].
Regarding turbine ventilator, Lai [42] has developed a prototype ventilator which combined conventional wind-driven turbine ventilator with solar-powered inner fan and discovered that the device succeeded to increase ventilation rate ($m^3/s$), especially with a rate rotation speed of 1500rpm and battery. The study also showed that the prototype works optimally in low outdoor wind speed of not more than 5m/s, thus demonstrated its potential to be effectively used in the low-wind velocity region. This model later has been proven effective to be used in the real building when the results of field study and CFD simulation by Shieh *et al.* [43] showed that the device achieved to produce air extraction rate four times higher than the wind-driven ventilator.
In order to maximize the airflow through the turbine ventilator, Shun and Ahmed [44] also developed and studied the performance of turbine ventilator powered by hybrid solar and wind, but placing the solar powered extractor fan at the upper part of the turbine. The results also proved that at low wind velocity, such combination and configuration is capable to increase air extraction rate significantly compared with conventional wind turbine. On the hand, Ismail and Abdul Rahman [45] studied the performance of hybrid turbine ventilator (HTV) in the real building and under real climate condition. The results showed that the new configuration of the device which is equipped with with inner duct, larger upper outlet area and extractor fan at ceiling level succeeded to reduce air temperature by 0.7°C in the occupied space (Figure 8(a)). The study also recommended that the performance of such device could possibly be improved if it is applied simultaneously for both attic and indoor spaces.
Today, this innovative solar-powered turbine ventilator has been recently commercialized, with the current market is mainly for temperate climate countries. The figures of this straight vane hybrid turbine ventilator are shown in Figure 8(b).




*(a)* *(b)*

*Figure 8: Solar-powered turbine ventilator; (a) Illustrative diagram of the HTV model with inner duct and larger upper outlet area [45] (b) recently commercialized PV-wind turbine ventilator (Aura Ventilator) from Active Ventilation Products Inc. [46]*

## 4. FUTURE POSSIBILITIES

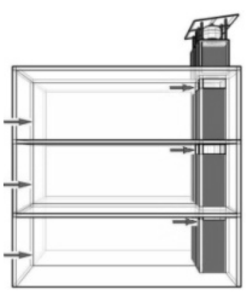
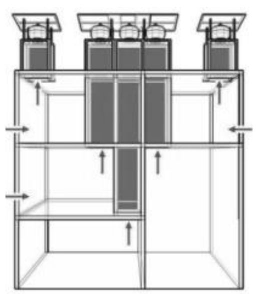
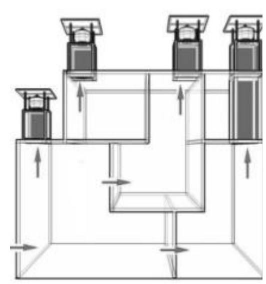
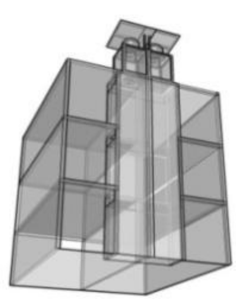
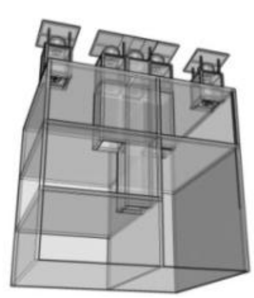
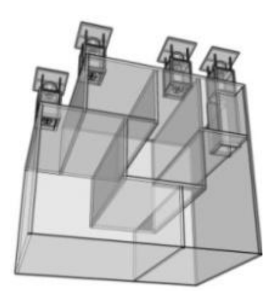
As discussed earlier, several advanced stack ventilation strategies have been developed and experimented in an effort to make stack ventilation is more reliable, consistent and efficient, even in the low indoor-outdoor temperature difference condition and low wind velocity region. One of the most potent ventilation concepts is the development fan induced stack ventilation which can maximize the natural energy sources available from both the sun and wind. This includes the prototype development of some hybrid stack ventilation devices such as solar-powered windcatcher and solar-powered turbine ventilator. In this context, hybrid energy can be described as *"a complementary operation of multiple renewable energy sources available from the local natural environment to achieve optimum energy generation"* [42]. From the previous studies, it has been proven that this stack ventilation strategy, especially hybrid turbine ventilator (HTV) is very promising and synergetic techniques since the effectiveness of the system to induce airflow increased as solar irradiation increased, which is proportional to the cooling needs of the building. Therefore, it is rationale to expect that this type of strategy could be one of the preferred ventilation choices in the near future.

Moreover, since the study by Ismail and Abdul Rahman [45] showed that the HTV configuration designed with inner duct and free upper outlet area is significant to increase air flow and improve indoor thermal environment, so it seems that it is possible to separate the top of the HTV without significantly influencing the performance of the turbine, thus could lead to more variety of the top designs and device configurations on the whole. Two lightweight solar panels could also be used as the top of the turbine itself, without necessarily to fix it on the surface of the turbine as in the case of commercially available solar-powered turbine ventilator. As a result, various design permutations of the HTV which can contribute to the enhancement of the device, both in terms of functionality and architectural aesthetic are made possible; with some design permutations are as follows (Figure 9):

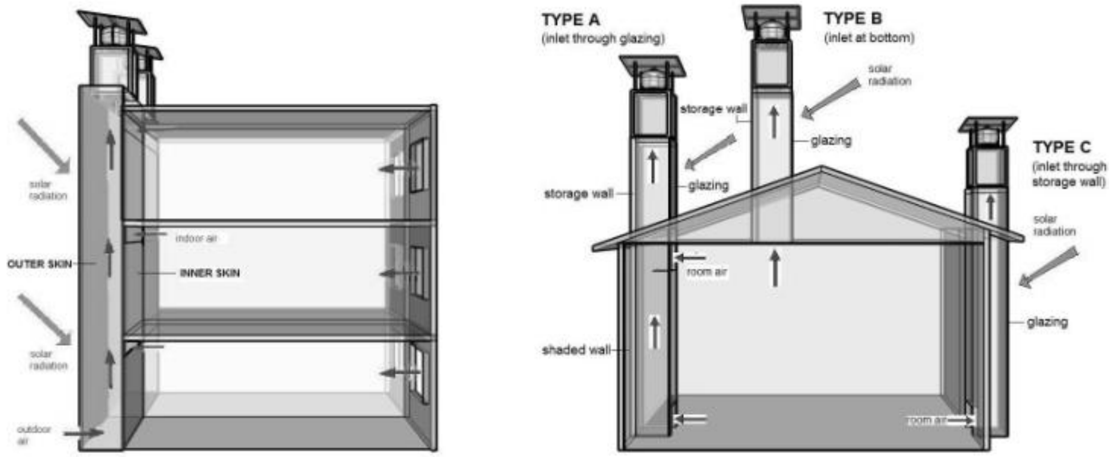
*Figure 9: Possible configurations of HTV that combined the turbine ventilator, extractor fan and solar panels as one integrated device*

With this new configuration, the HTV is also possible to be integrated with conventional stack devices which have been categorized by Mansouri *et al.* [19] into 3 main forms i.e. fitting structure, adjacency structure and overlapping structure, thus allowing it to be implemented in multi-storey building. Possible implementations are presented in Table 2.

Table 2: Possible implementation of HTV as stack devices

| **Implementation as Stack Devices** | | |
|---|---|---|
| Fitting Structure | Adjacency Structure | Overlapping Structure |
|  |  |  |
|  |  |  |

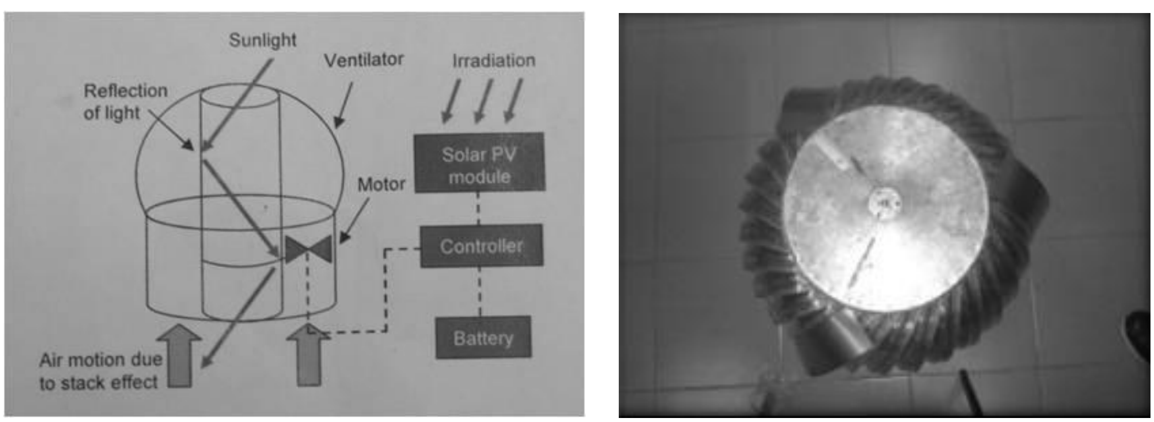
In addition to the simple HTV configuration addressed in this paper, it is expected that the combination of HTV with other design elements such as wind towers, courtyards and ventilated staircases can create an interesting integrated system in enhancing natural stack ventilation in a building. Furthermore, it is also possible to enhance its performance by combining it with other advanced solar induced ventilation strategies like the double skin façade and various types of solar chimneys proposed by Gan [47]. Such integration is shown in Figure 10.




(a) (b)

Figure 10: Possible enhancement of HTV (a) with double skin façade (b) with solar chimney

Moreover, it is also expected that for the coming future, this stack ventilation strategy like turbine ventilator is not only employed just for the ventilation purpose, but could also be used for lighting and aesthetic purposes. In order to upgrade it to be an effective multifunction device, several studies have been done to develop its prototype. This includes the study by Zain-Ahmed *et al.* [48] who developed the Photovolatic Lighting Ventilation (PVLV) which combined the lightpipe with conventional turbine ventilator to provide both daylighting and ventilation in the interior spaces (Figure 11(a)).




*(a) (b)*

*Figure 11: Innovative development of turbine ventilator (a) diagram of the Photovolatic Lighting Ventilation (PVLV) [48] (b) Power Generation Roof Ventilator [49]*

In a more recent study, Daut *et al.* [49] revealed that their prototype roof ventilator is not only effective to increase the airflow but also capable to generate the electricity from the wind by itself (Figure 11(b)). By adding some extra vanes to increase the rotation, the study showed that the prototype device achieved to produce 13 Vdc to 14 Vdc to charge the 12 Vdc batteries system, thus making it another energy efficient multifunction device to be considered in the near future.

## 5. CONCLUSION

From the literature surveys, it is confirmed that the stack ventilation strategy could be an effective strategy to ventilate the building, especially in the condition when the room is dominated by the wind effect. Historical review on its development since ancient times has proven its effectiveness, especially in temperate and cold climate region where the indoor-outdoor temperature is high enough to induce the air flow. But in some climate region like in the tropics, its effect is always considered negligible, thus prompting many researchers and building designers to develop several advanced stack ventilation strategies that can maximize both the sun and free wind force to enhance its performance. Some innovative solar-powered stack ventilators devices which uses both wind and solar energy to operate like solar-powered wind catcher and solar-powered turbine ventilator or better known as hybrid turbine ventilator (HTV) are not only succeeded to increase the ventilation rate, but also significant to ensure more consistent rotation of the device, thus make it more reliable to be used even in the low wind velocity region. Moreover, some development and recommendations to combine it with solar chimney feature and lightpipe device have also increased its potential to be utilized as multifunction device that can both daylight and ventilate the building without consuming additional energy. In fact, there have being some studies which are trying to develop the turbine ventilator which is not only can save building energy, but also can generate wind energy. Therefore, from the architectural point of view, it is quite interesting to expect that in the coming future, this stack ventilation strategy will not only be an energy efficient device to improve indoor thermal environment, but also could enhance the aesthetic appearance of the building itself.

## 6. ACKNOWLEDGEMENT

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