



A review on natural ventilation applications through building façade components and ventilation openings in tropical climates



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ABSTRACT

Energy consumption in the building sector is a major concern, especially in tropical climates where high temperatures and humidity force occupants to use electro-mechanical ventilation. Passive design strategies, in particular the application of natural ventilation, are one of the main techniques to moderate temperatures in buildings. Furthermore, many studies have shown reduced operating costs, better thermal comfort and indoor air quality, to be some of the advantages of the application of natural ventilation in buildings. Although existing studies support the efficiency of natural ventilation, the efficiency and practicability of architectural elements to maximise ventilation in buildings remains problematic. This study reviews studies on natural ventilation with other passive design strategies in tropical climates in order to support the argument for the application of natural ventilation in tropical climates. Through a review of studies on the operation of natural ventilation in buildings, it also identifies the most effective architectural elements and techniques in building façades and ventilation openings. The results indicate that ventilation shafts, window-to-wall ratio and building orientation should be applied in future construction. This study also identifies some further specific elements that are worth further investigation, including the shape of louvered windows, different forms of apertures and vernacular elements.

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1. Introduction

The high demand for building construction nowadays as a result of population increases has become a primary concern of scholars in developing countries. The availability of modern housing as a new type of construction in urban contexts has helped to meet the demand from the huge number of migrants who want to live in fast-growing cities. Although this strategy has mitigated some issues in overpopulated cities, responding to overheated indoor air temperatures in the primary stages of building design has proved a complicated challenge. As a result, most residents in modern housing rely on electro-mechanical ventilation to achieve acceptable and tolerable indoor temperatures in their units. As a consequence, the amount of energy required for cooling and heating buildings has grown to 6.7% of the total world energy consumption, with air-conditioners consuming a major part of this [1,2]. This percentage may be even higher in tropical climates, where high temperatures and humidity intensify air-conditioner usage. According to the World Business Council for Sustainable Development (WBCSD) report [3] of 2008, buildings account for 40% of the world's energy use and produce substantially more carbon emissions than the transportation sector, in order to achieve thermal comfort (cooling or heating) inside units. For instance, the carbon emissions and energy consumption of an air-conditioned house are 67% and 66%, respectively which is higher than a naturally ventilated house. This is why the WBCSD has called for the building sector to achieve greater energy efficiency through a combination of public policies, technological innovation, informed customer choices and innovative design.

In fact, scholars have expressed specific concern about the need to conserve energy in the construction and building sector to reduce air pollution and counteract global warming. Earlier studies have shown that passive cooling systems could reduce world energy requirements by 2.35% [2]. The term 'passive cooling' was coined to describe buildings architecturally designed to be responsive to local climatic conditions, creating comfortable and sustainable indoor conditions by natural means [4]. Another definition by Cook [5] describes passive cooling as any building design technique that not only prevents outdoor heat coming in, but also transfers indoor heat out to a natural heat sink.

Following extensive studies, innovatively designed natural ventilation systems have been applied in buildings in the tropics in an attempt to reduce the use of electro-mechanical ventilation [6–11]. However, the efficiency of natural ventilation in reducing the cooling load in tropical climates is highly dependent on a number of factors such as the outdoor micro-climate, the nature of the terrain, innovative techniques and the design of building elements and so on. This study reviews the literature on the underlying scientific bases for operation of natural ventilation and the related installation of architectural elements in buildings to better understand what elements and techniques are most effective in increasing indoor air velocity in tropical climates. Furthermore, in line with findings of previous studies, this study recommends certain architectural elements and strategies for natural ventilation which are worth testing.

2. Natural ventilation efficiency and precedence in tropical buildings

Studies by Kubota et al. [12–14] cite a reduction in energy consumption and greenhouse gas emissions as some of the advantages of using natural ventilation in the built environment. It further states that using natural ventilation in buildings increases the degree of thermal comfort in both indoor and outdoor environments. Another study regarding the use of fresh air in buildings

suggests that naturally ventilated buildings offer greater occupant control and higher levels of environmental quality than electro-mechanically ventilated buildings [15]. A further, comparative study of natural and electro-mechanical ventilation indicates that up to 18% savings in health costs could be achieved by regularly using natural ventilation in mixed mode systems [16]. A study of office buildings by Fisk [17] reveals that the incidence of sick building syndrome could be reduced by greater use of fresh air, saving US\$10 to 30 billion in the USA. This concept can similarly be applied to residential buildings such as apartment blocks with higher indoor air quality and a better thermal comfort being achieved through fresh natural ventilation [18]. Taking all these studies together, the overall advantages of applying natural ventilation in buildings can be summarised as follows:

- Reduced operation costs
- Increase the degree of thermal comfort
- Better air quality

Moreover, natural ventilation as a passive cooling strategy in buildings seems to offer significant advantages over other artificial cooling techniques [19], including other passive design techniques in tropical climates.

Studies on radiation cooling by Givoni [20,21] for example confirmed that this strategy does not work well in a hot and humid climate. The lack of temperature fluctuation between day and night, high humidity and cloud cover in the sky are all variables which reduce the rate of heat transfer and, also trap heat inside the building, causing uncomfortable thermal conditions. By the same token, high levels of humidity reduce the efficiency of the evaporation cooling technique. Wu and Yellott [22] point out that evaporation cooling works effectively when the tangible heat in the air stream is exchanged for the latent heat of water droplets or wet surfaces. However, in tropical regions there is a need to remove moisture from the indoor environment, where it otherwise condenses in the air or even onto surfaces, and then to apply air velocity (drafts) from outdoor in order to achieve effective evaporation.

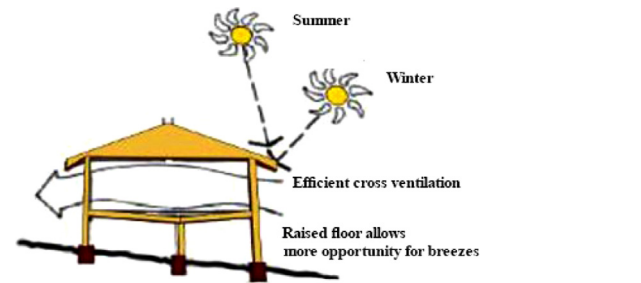
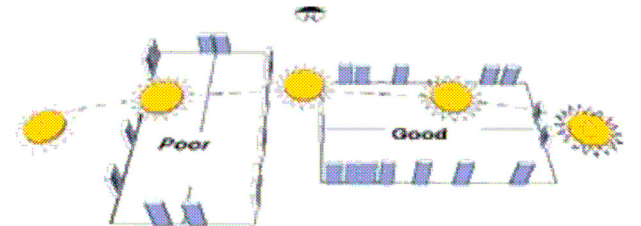
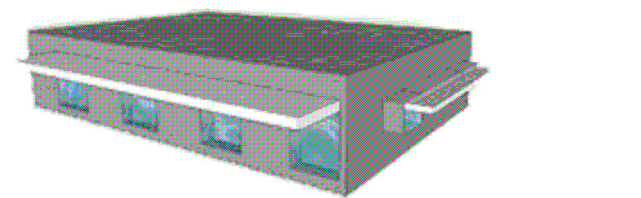

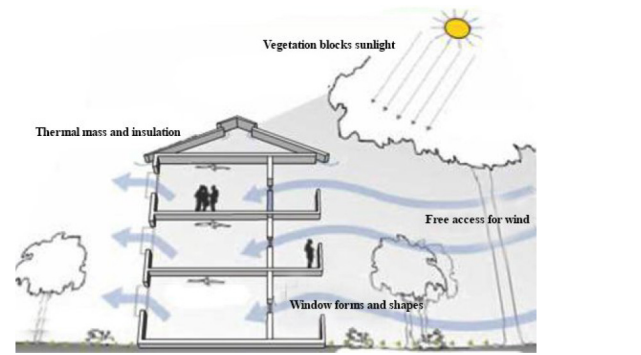
Based on above climate characteristic, it could be argued that natural ventilation is the best technique to achieve comfortable indoor temperatures and humidity levels inside buildings. However, for this technique to achieve maximum efficiency, strategies that avoid heat are also needed. In other words, natural ventilation can enhance cooling significantly, but only where attention has been paid in the primary stages of building design to minimising heat absorption from the surrounding environment. Table 1 shows some relevant heat avoidance techniques as complementary strategies to achieve effective natural ventilation [4,23–31].

3. Natural ventilation operations and principles in buildings and its application through architectural elements

3.1. Natural ventilation operations and basic principles in buildings

Air movement is the key requirement in the overall ventilation process when integrating and designing building façade, building form, apertures and building orientation [32]. In addition, a study by Chen [33] indicates that temperature, humidity, air flow patterns and air velocity are key factors to consider when collecting, measuring and evaluating data on indoor temperatures and inside air flow quality. Moreover, outdoor air velocities can also affect indoor air movements and temperatures as a result of differences in air pressure applied through building façades by the appropriate location of openings and passive design strategies [34].

Table 1
Heat avoidance as complementary techniques to increase natural ventilation.

Effective strategy for heat prevention	Drawing of scheme
<p>Shading Providing shading elements at the top of openings, especially on the east and west sides [23,24] Figure source: Authors, 2014</p>	
<p>Building orientation The building should be oriented in the direction of prevailing angles of wind and sun [25] Figure source: Authors, 2014</p>	
<p>Size of apertures and windows These should be kept small on the east and west sides, which receive twice as much radiation as north-south elevations [4] Figure source: Authors, 2014</p>	
<p>Form and shape of architectural plan. Longitudinal ends should be along the west-east axis; and should be as narrow as possible [26,27] Figure source: Authors, 2014</p>	
<p>Vegetation surrounding building, material of façade, window forms and shapes, thermal mass and insulation in external walls are significant heat avoidance techniques. [28–30] Figure source: Author, 2014 retrieved from [31]</p>	

In general, natural ventilation inside buildings can be categorised into air pressure ventilation, known as wind force, and stack effect ventilation or thermal force [34]. As explained by Szokolay [35], air pressure ventilation will occur when a flow of wind is blocked by a building's surfaces. The wind's velocity creates higher pressures on the windward side of the building, while on the leeward side, the pressure is much lower. This differential can stimulate air flow into the indoor environment and hence lower the air temperature in the building. As Fig. 1 shows below, the different air pressures outside and inside the building leads to cool air flowing horizontally through the apertures into the rooms. The patterns of such air flow can be classified into single-side ventilation and double-side or cross ventilation. Single-side ventilation is where wind velocities moves inwards and outwards through the same

apertures on the same side of a building. On the other hand, cross ventilation works efficiently where wind velocities move inwards and outwards through different windows or doors on different facades. This basic rule has been used by some scholars such as Szokolay [35] and Givoni [36] in their studies to increase air velocities inside buildings in order to produce a more comfortable indoor environment.

Building corridors are an example of architectural element which helps to create cross ventilation in buildings, by acting as connectors between outdoor environments and isolated indoor spaces. Corridors can play a significant role in channelling and delivering air flow into parts of a building.

A microclimate study by Mohamed et al. [38] found that well designed and integrated corridors inside a building can deliver

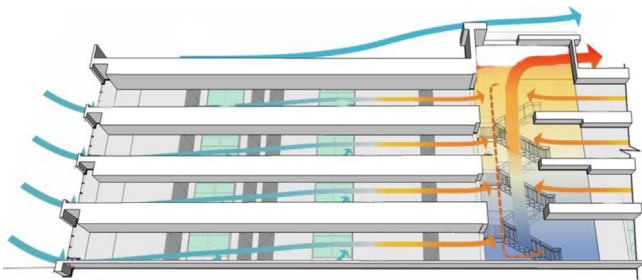


Fig. 1. Natural ventilation created by wind forces and buoyancy effect in a building. Source: Author, retrieved from [37].

adequate local air flow. According to their study, corridors transfer outdoor air by providing an air pressure zone which directs air into the building. Air pressure intensification and air change requirements can be further improved by integrating such corridors with other passive design strategies [34,39].

However, stack ventilation or thermal force can occur through vertical air movement, where cool air has been warmed up in a building by human activity or the operation of machinery. The warm air rises vertically and is discharged out from the building by architectural elements, as shown in Fig. 1. Thermal force occurs due to the difference in density between cool and warm air. Thermal force can also be created by discrepancies between outdoor and indoor temperatures [40]. Ismail and Abdul Rahman [41] in their study suggest that temperature differences between indoor and outdoor environments and differences in height between indoor and outdoor apertures are both significant factors in the application of proper stack ventilation in buildings.

Many studies have shown air wells to be an applicable technique for stack ventilation in buildings. Through the process shown in Fig. 2, this design strategy produces air flow vertically in the building, thereby replacing hot air with fresh, cool air. This passive element, long used in hot and arid climates, is known as a wind catcher. Its function is to cause wind movement which takes fresh air through the building façade and discharges warm air through a vertical duct in the building [34]. During this process, polluted indoor air can be disposed of effectively and replaced with cool air, thus creating comfortable indoor conditions [42,43]. To achieve this, chimneys and stack air ducts can be used in smaller buildings, while larger air wells or atriums can create sufficient wind flow to achieve thermal comfort in larger structures.

Stack ventilation and cross ventilation are two of the ventilation systems commonly used in traditional architectural buildings in order to cool the indoor environment and bring maximum thermal comfort to the building occupants. A study by Siew [45] reveals that various types of natural ventilation are used in vernacular architecture in tropical regions to alleviate high temperatures and humidity. However, previous researches agreed that

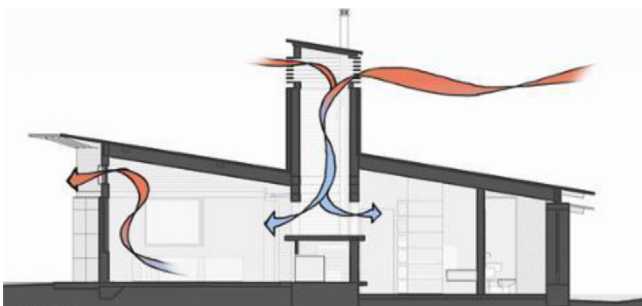


Fig. 2. The simple functions of wind catchers in buildings Source: Author, retrieved from [44].

cross ventilation is a more effective approach than stack ventilation in tropical regions, where there are generally no substantial differences in temperature between the indoor and outdoor environments [34,36].

Overall, the effective operation of natural ventilation depends on the application of various architectural elements and techniques to induce air movement inside buildings. The following sections will discuss on these components in order to understand how they interact and work together to modify indoor temperatures.

3.2. Natural ventilation application through architectural elements; alternatives in building facade and ventilation opening

Natural ventilation based on wind force and stack effect in buildings can be traced back to architectural elements in traditional buildings which were created to increase air velocity (air flow), well before active systems such as air-conditioning came into being. By reviewing recent studies, it was possible to identify the most relevant architectural elements used for natural ventilation in buildings. Generally, these elements ensure adequate air exchange and velocity rates in indoor environments through relatively simple mechanisms.

The building façade – including walls, roofs and all openings such as windows – and building layout play a significant role in controlling air flow. They are major factors and alternatives in ensuring indoor air quality is maintained through a combination of fresh outdoor air and existing indoor air. In their study on climate-responsive design for buildings, Clair and Hyde [46] used an approach of permeable wall-roof design and plan orientation to evaluate passive design concepts and their impact on thermal comfort. Their research argued that plan dimensions of more than 15 m in length reduce the efficiency of natural ventilation and consequently the degree of thermal comfort.

A study on the application of natural ventilation in high density buildings identified an ideal model for building facades to reduce environmental loads. Field experiments and computational fluid dynamics (CFD) simulations were carried out to evaluate how far CO₂ emissions could be reduced by applying different design models of natural ventilation. The results showed that CO₂ emissions could be reduced in daily operation by 30% and for the whole-life cycle of buildings by 22% when high ventilation was enhanced by optimum porous-design models [47]. Moreover, proper façade design such as thermal insulation in external walls, building materials, shading and building layout could also have a significant impact on the cooling load and minimise the usage of air-conditioning [48].

At the same time, air pressure differences between outdoor and indoor spaces and ventilation openings on the windward side are also effective ways of bringing fresh air into buildings while discharging used air on the leeward sides of buildings. A proper design and accurate location of openings, coupled with sufficient window and door areas overall, are key factors in producing the required air movement for thermal comfort [49].

A study on natural ventilation designs for houses in Thailand was conducted to evaluate what air-rates, size of apertures, form and orientation of houses were required in the Thai climate to achieve thermal comfort. This included thermal comfort and climate analysis with a CFD simulation model in order to achieve optimum site planning and design for a tropical climate. The results showed that indoor air velocity of as little as 0.04 m/s could improve indoor thermal comfort. Furthermore, it indicated that the total area of inlet and outlet apertures should be roughly 40% of the total floor area.

A simulation program used to assess a number of different variables suggested that using ceiling fans to raise air velocity could allow the total area of apertures to be reduced to 25% while maintaining the same level of thermal comfort [50]. Another study by Gratia et al. [51] concluded that a combination of these design

approaches could reduce overall cooling requirements by more than 40% per unit. Furthermore, to reduce the use of artificial lighting and ventilation, apertures such as windows, doors, vents and louvres also emerged as significant components [45,52].

4. Applied elements and techniques for effective cross and stack ventilation in tropical buildings

A review of studies on natural ventilation through architectural elements and related techniques enables us to ascertain the most effective strategies for tropical regions. Previous research have looked at a range of different elements and techniques such as retrofitting building by vegetation [53,54] internal layout and division [55] building material [56] and shape of building structure [57] to achieve better ventilation and acceptable thermal condition inside buildings. This current review, however, concentrates on studies that focus on elements related to ventilation openings with attention to size and location of apertures and specific concern on components on the building façades. These studies are classified into two categories based on principles of natural ventilation namely: cross ventilation (wind force) and stack ventilation (thermal force) and are depicted on the following Tables for comparative analysis. Whilst the first three Tables focus on the application of cross ventilation through different elements and techniques, the last Table compares some studies covering various types of stack ventilation.

4.1. Studies on cross ventilation using ventilation openings and apertures

4.1.1. Inlet and outlet size and location

As shown in Table 2, studies on cross ventilation using ventilation openings have been carried out in various tropical countries. Such studies have looked *inter alia* at inlet and outlet size and location as effective elements for cross ventilation. Studies by Sahabuddin [58] and Karava [6] suggested some guidelines for the application of cross ventilation using these elements. Sahabuddin [58] recommended perpendicular windows to increase cross ventilation and a wide plan layout for external surfaces in the south and north of building façades to increase indoor air flow in Malaysia. In a different experiment, using techniques from vernacular architecture, he utilised louvre windows above panels to raise air pressure further and hence improve cross ventilation through windows.

4.1.2. Building orientation, layout and Louvre windows

Building orientation is another design option in naturally ventilated buildings in environments where sufficient wind movement can be achieved by facing a building to the prevailing wind. A study by Al-Tamimi et al. [59] suggested that there should be no windows on the east or west sides of buildings because these orientations receive more radiated heat from the sun and less ventilation than the other two sides. In a study in Hong Kong, window position and configuration as well as the effect of surrounding blocks were evaluated in different building orientations to find out how these variables interact with each other and their impacts on indoor ventilation [60]. The results suggested that the effectiveness of natural ventilation is most sensitive to changes in window positions, followed by building orientation and door positions. An evaluation of the combined effects of different parameters further showed that choosing the right window positions and building orientation would have a positive impact on the level of natural ventilation.

A study by Burnet et al. [61] in Hong Kong found that the optimum layout and orientation of a building to the prevailing wind was $\theta = 30^\circ$. This study showed that the flats at the front have the highest potential for natural ventilation for any given angles (θ). However, proper cross ventilation can be achieved in such front-facing flats

where θ is equal to 0° , 45° and 90° . These angles are totally different in the case of flats on the central side, where optimum ventilation is achieved with θ equal to 15° , 30° , 60° and 75° . The angles of louvres, as another type of ventilation opening, are another element affecting the direction and amount of air flow inside buildings. Louvre angle of 45° affects air flow direction, while louvre angles of 0° , 15° and 30° affect air velocity volumes inside a building [9].

4.2. Studies on cross ventilation using façade elements and components

Cross ventilation through façade components have been evaluated in many studies. However, selected studies from different tropical regions of the world are analysed and presented in Table 3.

4.2.1. Balcony size and ventilated roof

Balconies and their performance as one of the elements in building façade were evaluated in a study by Ai et al. [62]. Different balcony sizes, ceiling heights and wind directions were examined in the study to understand which types of balcony provide the best ventilation. Field measurements and simulations indicated that balcony ventilation performance falls slightly as the height of the balcony ceiling increases. On the other hand, the study findings showed that the dimensions of balconies do not have a significant impact on ventilation performance.

Ventilated roofs were evaluated as a design alternative to improve ventilation inside apartment units in China and the results showed that these could reduce temperatures, especially in hot seasons. Furthermore, an integrated design study of passive cooling and design guidelines for ventilated roofs suggested that such roofs could play a significant role in creating different air pressures around the external and internal surfaces of a building [63].

4.2.2. Vernacular architectural element and thermal performance of wall

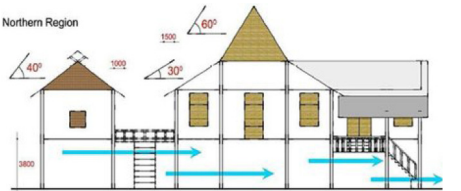
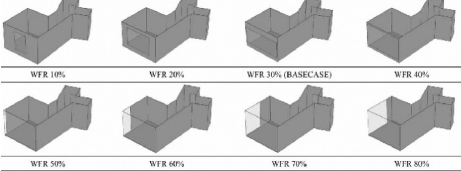
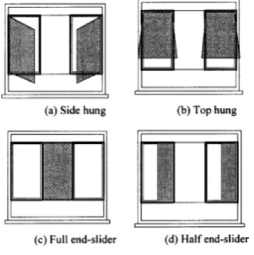
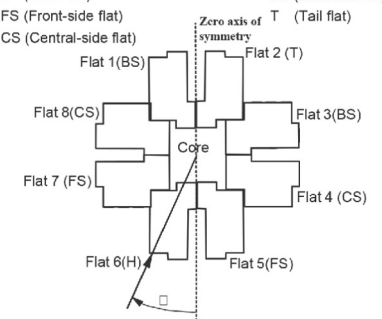

In a study in Saudi Arabia, the vernacular architectural element of wall grooves was examined in modern buildings to see how far they could improve ventilation and consequently thermal comfort. The findings showed that wall grooves caused pressure differences at the inlet side and could stimulate greater air flow inside buildings [64]. A separate study on thermal mass and insulation and their impact on outdoor air flow showed that thermal insulation effects do need to be considered along with other building elements in order to understand better the thermal performance of a building. The same study also suggested that integrating indirect and direct ventilation through heat exchangers could reduce the latent cooling load [65].

4.3. Studies on cross ventilation using complementary concept

The complementary concept of ventilation opening elements and façade components are categorised in Table 4. In their studies, Prianto and Depecker [55,66] explored the combined effects of balconies and openings on cross ventilation in buildings. These studies indicated no impact on overall ventilation from increasing balcony ceiling heights however; installing louvre windows at an angle of 45° at ceiling height beside the balcony could improve comfort levels. Furthermore, internal modifications such as raised kitchen floors, in combination with windows in an upward position (45°), could produce noticeable improvements in air velocity and comfort levels. Simulation studies have also shown that pivot windows at a 45° angle have a more significant effect on indoor air velocity than those at 30° .

In another study in Malaysia, window-to-wall ratio, thermal insulation and shading devices and their impacts on overall ventilation were evaluated by field measurements and simulations.

Table 2
Cross ventilation application using ventilation opening in various tropical buildings.

Elements and techniques established in the study and literatures	Type of architectural element	Ventilation methods	Figure of scheme
Window size/location Layout plan Vernacular elements [58]	Ventilation openings	Cross ventilation	
Building orientation Window to floor ratio Outside air velocity speed [59]	Ventilation openings	Cross ventilation	
Window type and configuration Building orientation Surrounding blocks Prevailing wind [60]	Ventilation openings	Cross ventilation	
Building orientation and layout Window and room location in units [61]	Ventilation openings	Cross ventilation	
Louvre angle (0° , 15° , 30° , 45°) Outdoor wind speed Air velocity ratio [9]	Ventilation openings	Cross ventilation	

This study showed that, with every 10% increase in window-to-wall ratio, the cooling load increases by 1.3%. With regards to thermal insulation, the same study revealed that cooling loads could be reduced from 10.2% to 26.3% by applying adequate insulation inside the external walls. On the other hand, a simulated test of different shadings (colour tones) on the external surfaces of a building showed that this had limited impact on cooling loads [67].

4.4. Studies on stack ventilation using architectural elements

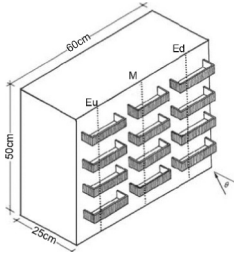
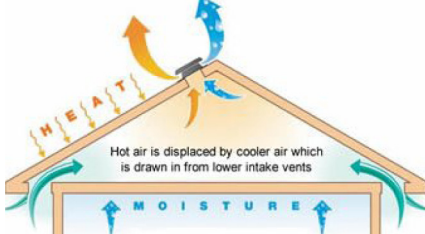
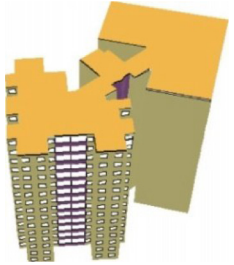
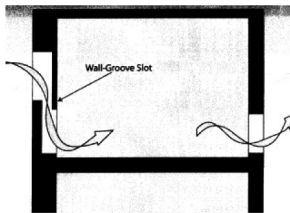
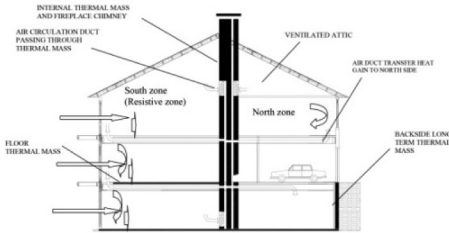
Studies on stack ventilation are shown on the Table 5, with three selected studies addressing those architectural elements which produce the maximum stack ventilation in buildings. Firstly, ventilation shafts and outdoor wind speed and direction were examined in Thailand to ascertain how far ventilation shafts could reduce cooling loads [68]. This study showed that ventilation shafts could effectively create ventilation in buildings and thereby increase

comfort hours by 37.5% to 53.6%. This extension of comfort levels could save 2700 kWh of electrical energy per residential unit.

The efficiency of ventilation shafts demonstrated in other studies persuaded other researchers to examine different sizes and locations of stacks. A study in Singapore looked at these, as well as the performance of active and passive stacks in a typical four bedroom Housing and Development Board flat (HDB) using scaled model through controlled wind tunnel and simulation.

The passive stack, 400 mm × 400 mm (the size of the stack in 1:5 scale is 80 mm × 80 mm) was located between two bedrooms. The thermocouple wires were fixed to the top and bottom of the stack to record air temperature and velocity. The wind tunnel system was allowed to reach steady state before the measurement was recorded. Also, for air flow visualisation, smoke was injected through the window of the flat. To create actual condition on top of the stack, the small sized fan (82 mm × 82 mm) which is powered by 15 V dc adaptor allowed the flow of different air speeds

Table 3
Cross ventilation application using façade components in various tropical buildings.

Elements and techniques established in the study and literatures	Type of architectural element	Ventilation methods	Figure of scheme
Impact of different balcony sizes, ceiling heights and wind directions [62]	Façade component	Cross ventilation	
Ventilated roof Special design of roof [63]	Façade component	Cross ventilation	
Four ventilation strategies Building orientation/window-to-wall ratio [19]	Façade component	Cross ventilation	
Wall groove as vernacular element [64]	Façade component	Cross ventilation	
Thermal mass/insulation Outdoor air flow rate [65]	Façade component	Cross ventilation	

(2.7, 3.7 and 5.5 m/s). The results suggested that the active stacks with a small fan on top lead to more effective ventilation and temperature comfort than passive stacks. Moreover, during evening hours, the closed doors and windows were used to simulate and understand the effect of stack on indoor air velocity. Simulation tests showed that small-sized stacks (400 mm × 400 mm) could increase air velocity by 550% and raise the maximum velocity to as much as 0.067 m/s. Also, the comparison of air speed by different size of stack in simulated model indicates that the optimum size for higher air velocities inside rooms is 400 mm × 400 mm. [69].

The application of ventilation shaft and air traps which are known as Termah and Shenashir was suggested for hot-humid region in Iran [70]. The study concludes that ventilation shaft

perpendicular to the wind breeze from the sea is an effective strategy to induce wind into the built environment. The study highlights compact urban neighbourhood with the possibility of air circulation around each building to increase wind force through indoor environment.

4.5. The most significant elements for effective indoor ventilation and subjects for further research

The overall review of studies in all Tables presents a range of architectural elements and techniques within building façades and ventilation openings which have been used to achieve natural ventilation inside buildings in tropical climates. A comparison of the

Table 4
Cross ventilation application by ventilation opening and façade components in buildings.

Elements and techniques established in the study and literatures	Type of architectural element	Ventilation methods	Figure of scheme
Balcony shape and size Opening size and form Indoor wall division [55,66]	Ventilation openings and façade component	Cross ventilation	
Window-to-wall ratio Thermal insulation Shading devices [67]	Ventilation openings and façade component	Cross ventilation	

results indicates that ventilation shafts, window-to-wall ratio and building orientation are fundamental criteria's for naturally ventilated buildings.

Critical evaluation of the studies as presented in all the Tables points out some elements and techniques for further research. For instance, the design of louvred windows for night-time flushing as the best ventilation strategy in tropical climate declared by Kubota et al. [13] or different shapes of louvre to maximise wind force ventilation are two effective strategies which are not explored in the

above mentioned studies. According to the outcomes of the study by Al-Tamimi and Fadzil [67], further research should be conducted on the impact of vertical shadings on air velocity ratios inside buildings. Another architectural element worth looking into is the effect of different shapes and forms of apertures on differences in air pressure around the external surfaces of a building. While certain specific types and configurations of windows were evaluated by Gao and Lee [60] in Hong Kong, further tests on aperture forms could well produce novel results.

Table 5
Efficient stack ventilation through application of architectural elements.

Elements and techniques established in the study and literatures	Type of architectural element	Ventilation methods	Figure of scheme
Application of ventilation shaft Outdoor wind speed and direction [68]	Ventilation openings	Stack ventilation	
Size and location of stacks Active and passive stacks Active stack and various speed tests [69]	Ventilation openings	Stack ventilation	
Use of Louvers (ventilation shaft, air trap) Wooden balconies and terraces (known as Tarmeh and Shenashir) [70]	Ventilation openings	Stack ventilation	

Finally, a study by Al-Shali [64] showed that wall grooves as used in vernacular architecture could increase natural ventilation in buildings. However, there is very little research on the application of these elements in modern architecture. It would be worth examining the shape and form of roofs and windows and specific layouts as design approaches in specific regions in modern architecture. Further research on such vernacular elements could throw light on how far these elements in building façades or openings might help to increase air velocity ratios in new buildings.

5. Conclusion and recommendation

The current study has reviewed previous research on the application of natural ventilation and found that it is the dominant technique in tropical buildings compared to other passive design strategies. Lack of temperature change between day and night, high humidity levels and persistent cloud cover, however, constrain the use of natural ventilation as a prevalent strategy in tropical regions. The study found that, to achieve maximum efficiency, this technique (natural ventilation) relies on strategies that avoid heat. Natural ventilation can increase cooling significantly where steps have been taken in building design and construction to limit heat absorption from the surrounding environment.

The review and analysis of natural ventilation in buildings showed the stack effect and wind force to be the two main and basic principles to produce air movement in buildings. However, the efficiency of these methods depends on certain factors. Differences in temperature as well as vertical distance between inlet and outlet are two important criteria affecting the efficiency of stack ventilation. On the other hand, pressure discrepancies between the windward and leeward sides of a building and openings perpendicular to each other are significant variables in the application of wind force techniques. A further examination of previous studies showed that wind force and the stack effect can be harnessed using architectural elements within building façade components and ventilation openings. Building layout, size and location of apertures, building orientation, size and form of balconies on the external surfaces of building façades and vernacular elements were the most relevant architectural variables in these reviewed studies. An evaluation of the results of these studies revealed that ventilation shafts (especially active stacks), window-to-wall ratio and window-to-floor ratio, building position and building orientation are the most important elements in order to produce effective natural ventilation. The results of studies in this review which are based on specific cases in tropical regions of the world produced guidelines that are generalisable to all naturally ventilated buildings in tropical climates.

Finally, further reviews of the variables identified in the studies recommend elements and techniques for future studies. The design of louvred windows for night-time flushing or different shapes of louvres to maximise ventilation, impact of vertical shadings on indoor air velocity, different shapes and forms of apertures to produce greater air pressure differences and the application of new vernacular elements in modern buildings, are some of the relevant architectural elements that might produce novel results in tropical climates.

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