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A REVIEW ON PASSIVE DESIGN CONFIGURATIONS EFFECTS ON NATURAL VENTILATION PERFORMANCE IN MULTI-STOREY RESIDENTIAL BUILDINGS OF TROPICAL CLIMATES

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Abstract: *Energy consumption and quality of indoor environment are the main challenges for multi-story residential buildings in tropical climates. MSRB users rely heavily on mechanical ventilation systems due to local climate conditions. Various studies revealed that natural ventilation can enhance thermal comfort indoor air quality and energy efficiency in multi-storey residential buildings. However, the application effects of passive design configurations in multi-storey residential buildings to improve natural ventilation performance for adequate thermal comfort and indoor air quality is still questionable. This paper focuses on reviewing studies that evaluated the application effects of passive design configurations on natural ventilation performance in multi-story residential buildings of tropical climates. By comparative analysis, on the efficiency and the limitation of the passive design configurations applied to achieve effective natural ventilation, suitable thermal comfort, and indoor air quality. Among the identified design configurations thermal comfort level, indoor air quality and natural ventilation performance are mostly enhanced through adequate building orientation, vertical voids, window configurations, and ventilation shafts. It was also found that studies mainly rely on CFD simulation and field measurement methods for the evaluation. Furthermore, the study highlights the importance of other passive design configurations for further evaluation in multi-story residential buildings.*

Keywords: *Energy Conservation, Multi Storey Residential Buildings, Natural Ventilation, Passive Design Configuration, Tropical Climates*

Introduction

Multi-story, high-rise or tall buildings are common solutions in the city due to high land cost, population density and demand. Multi-storey residential buildings can be classified based on the height parameter into medium rise residential building with height varies between six (6) levels as a minimum to twelve (12) level and high-rise residential building with more than twelve (12) levels (Kuan, 2013). The high-rise buildings fundamental issues are thermal comfort, indoor air quality, and energy consumption especially the ones located in the tropical climates (Niu, 2004). Occupants of residential buildings achieve thermal comfort and indoor air quality through mechanical ventilation systems, which increase energy consumption. As results, more than two-thirds (2/3) of total energy is consumed by the residential sector for heating and cooling purposes (Orme, 2001). Mechanical ventilation systems consume over half of the energy in the residential building (Bastide, Lauret, & Boyer, 2006).

S. Wong et al., (2009) indicated that occupants of high-rise residential buildings Apartments showed Sick Building Syndrome such as nasal issues as one the effects of using air-conditioned. In most developed countries, the residential building sector account of two-thirds of the total carbon dioxide emission (Nejat, Jomehzadeh, Taheri, Gohari, & Muhd, 2015). On the other hand, naturally ventilated residential buildings produce less of carbon dioxide compared to residential buildings that rely on air conditioning systems (Aflaki et al., 2015). Energy efficiency is required in the residential building sector due to the massive consumption of energy and the environmental effects of carbon dioxide (Nejat et al., 2015). Scholars indicated that there are significant potentials of reducing energy consumption, CO_2 emissions and achieve better internal environmental quality in the vital sector of residential building through passive cooling strategies. Passive cooling strategies are the methods of design that allows the building to adapt with the climatic conditions where the building located, in order to achieve energy efficiency, and suitable indoor environment quality without any cooling and heating systems (Chenvidyakarn, 2007).

Passive cooling systems used in tropical climates buildings are classified into natural ventilation cooling, cooling through radiation, evaporation and thermal mass cooling (Chenvidyakarn, 2007). The application of natural ventilation as an alternative passive strategy allows reducing energy consumption, enhancing thermal comfort and indoor air quality (IAQ) in multi-storey residential buildings (Fung & Lee, 2015). However, there are different factors that influence the efficiency of natural ventilation such as the local climatic conditions, where in tropical climates there is a lack in the temperature differences between indoor and outdoor environment (Ghiaus & Allard, 2012). The location of multi-story residential in the high-density urban area reduces airflow circulation through the building. Multi-storey residential buildings particularly high-rise residential buildings characterized by a limited design where living units are connected to the outdoor environment only by exterior façade (Gaber, Farea, & Minna, 2012). Moreover, limited form configurations reduce the living units surface where the application of passive design configuration of low-rise buildings in multi-storey residential buildings is complicated (Aflaki, Hirbodi, Mahyuddin, Yaghoubi, & Esfandiari, 2019)

This paper aims on reviewing the literature on the application effects of passive design configurations on natural ventilation performance, thermal comfort and indoor air quality in multi-story residential buildings of tropical climates. In addition, this paper recommends different building design configurations for evaluation in terms of their effects on the performance of natural ventilation in multi-story residential building of tropical climate

Influence of Natural Ventilation Cooling Strategy in Multi-story Residential Buildings

Pervious researches revealed that passive cooling through natural ventilation can improve the indoor air quality, level of thermal comfort and achieve energy efficiency (Muhsin, Yusoff, Mohamed, & Sapian, 2017). Due to the rapid growth of buildings in urban areas in most of the countries located in hot and humid, energy consumption particularly in residential building sector become significantly higher and non-negligible (Qi Jie Kwong Nor Mariah Adam B.B. Sahari, 2014). The use of natural ventilation in residential buildings located in region characterizes with high levels of temperature and humidity reduces the energy consumption and the environmental effects of carbon dioxide emissions (Aflaki, Mahyuddin, Al-Cheikh Mahmoud, & Baharum, 2015). In addition, it provide adequate environment quality in multi-story residential buildings. Graça et al., (2002) indicate that natural ventilation can achieve adequate level of thermal comfort in apartments of medium rise residential building in most of 90 % of times. In addition the study of Wei-Hwa Chiang (2012) revealed that using natural ventilation in residential building apartments situated in tropical climates has the ability to achieve better indoor air quality and transfer that heat to the outdoor environment. Furthermore, this passive cooling strategy helps in redaction of the overall energy consumption by quarter (1/4) (Yik, F. W., & Lun, Y. F.2010).

Based on the results of previous studies the application of natural ventilation in multi-story residential buildings located in the tropical climate have three main significant advantages namely the reduction of the overall energy consumption, enhance the internal comfort conditions and achieves better indoor air quality (IAQ).

Thermal Comfort and Indoor Air Quality in Residential Buildings

Thermal comfort can be defined as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 2013). Various environmental conditions effects the level of thermal comfort include the parameters of air velocity, temperature, relative humidity and radiant temperature (Ainurzaman and Jamaludin 2014; Ashrae 2010; Callejon-ferre et al. 2011). Air velocity consider as the main parameter that influence thermal comfort, in tropical climates natural ventilation can enhance air velocity and reduce air temperature in which air velocity of 2m/s reduce indoor temperature by 3.9 ℃ (Lechner, 2014). Air velocity range between 0.2m/s to 1.5m/s provide optimum thermal comfort in residential buildings of the hot and humid climate (ASHRAE 2004). According to Srivajana (2003) air velocity above 0.9m/s is considered to be undesirable for occupants.

Furthermore indoor air quality can be achieved through movement of air fresh in the indoor spaces (Wood & Salib, 2012). Ventilation rate is the main parameter to achieve adequate indoor air quality (F Allard & Ventilation, 2006; Francis. Allard, Santamouris, & Alvarez, 1998; Carrilho da Graça & Linden, 2016).Ventilation rate can reduce level of internal pollution1 (Francis. Allard et al., 1998). The required ventilation rate varies from country to countries based on the local climate condition. In tropical climates of Malaysia the minimum required of ventilation rate to achieve indoor environment quality is 0.14 -m^3 per minute per construction area m^2 (UBBL 2013). The airflow rate required for the residential buildings in United Kingdoms is 0.4-1 ACH Air change per hour per m^2 (CIBSE GUIDE A, 2006) and 2.5 L/S and 0.3L of fresh air per second per m^2 construction area in United States of America (ASHRAE 2011).

Natural Ventilation Principles in Multi-Story Buildings

The pressure differences occurred on the apertures of building envelope generates natural ventilation due to the effects of external wind forces, temperature differences or both of them, where ventilation forces divided into wind-driven ventilation that resulted from wind forces and buoyancy driven ventilation that resulted from temperature differences (Wood and Salib 2012). Khan, Su, and Riffat (2008) clarified that pressure differences generated on the building envelope and around the apertures allow fresh air to enter the indoor space through the apertures located in the wall with positive pressure zone and move out from the apertures in the wall with negative pressure zone. (Wood & Salib, 2012).

Natural ventilation describes as the air flow movement to internal space between inlet and outlet where its divide into cross ventilation, single-sided ventilation, and stack ventilation (Wood & Salib, 2012). In single-sided ventilation, airflow is derived from internal spaces and extracted from side opening. Stack ventilation generated due to the temperature and pressure difference between interior and exterior in a particular area in the building. Pressure difference moved the airflow to the interior from the aperture located at a lower level and extracted from an aperture located in the upper level (Wood & Salib, 2012). Cross ventilation is the airflow moving through the apertures through both sides of the envelope dues to pressure difference effects around the apertures located in windward and leeward sides (Kleiven, 2003).

Different studies highlighted the effectiveness of ventilation strategies for adequate thermal comfort and indoor air quality in the multi-storey residential buildings. Fung & Lee, (2015) revealed that ventilation performance in high-rise residential building is mostly affected by ventilation mode. A comparative study by Sara Omrani, Garcia-Hansen, Capra, & Drogemuller (2017) on the cross and single sided ventilation performance and thermal comfort level in high-rise residential buildings revealed that cross ventilation achieved thermal comfort for 70% of the time while single sided ventilation it was 1 % of the time and enhanced indoor air velocity by double in cross ventilation compared to single-sided ventilation. Ai, Mak, & Cui (2013) examined airflow rate in units of high-rise residential building with single-sided ventilation. The results showed that external wind speed of 3.0m/s achieved better air change per hour (ACH). Aflaki et al. (2016) investigated the single-sided ventilation effects on relative humidity, indoor temperature and air velocity in high-rise residential building, Results of field measurement showed that single sided ventilation achieved thermal comfort in 90 % of the time in the units located at a higher level perpendicular to the prevailing wind. The assessment of airflow rate in an isolated high-rise building with single-sided ventilation, using wind tunnel revealed that the wind direction effects the dominant driving forces of both temperature and wind speed (Larsen & Heiselberg, 2008).

Stack ventilation showed efficiency in the multi-storey residential building designed with atria where it can remove the trapped heat in the internal spaces and enhance natural ventilation performance. Wei-Hwa Chiang (2012) indicated that stack ventilation in medium rise residential building designed with atria reduce indoor air temperature in the adjacent units and increase indoor air velocity level.

Application Effects of Building Design Configuration on Natural Ventilation in Multi-Story Residential Buildings

The following review focus on studies that evaluated the application effects of passive design configurations on natural ventilation performance in multi-story residential buildings of tropical climate. The reviewed studies are classified into five (5) main categories based on the most effective design configurations on natural ventilation performance, thermal comfort and indoor air quality in both medium and high-rise residential buildings as showed in tables 1,2,3,4 and 5. All tables contain the design configuration variables, ventilation strategies, methods of evaluation and design effects. The identified design configurations include:

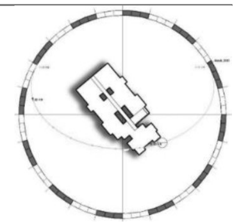
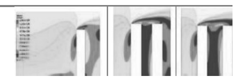
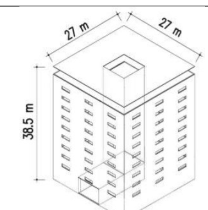
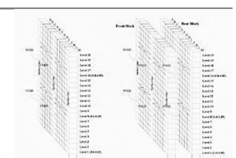
i. The application effects of void configurations on natural ventilation performance in multi-story residential buildings.
ii. The application effects of building height and orientation configurations on natural ventilation performance in multi-story residential buildings.
iii. The application effects of balcony configurations on natural ventilation performance in multi-story residential buildings.
iv. The application effects of window configurations on natural ventilation performance in multi-story residential buildings.
v. The application effects of ventilation shafts configurations on natural ventilation performance in multi-story residential buildings.

The Application Effects of Void Configurations on Natural Ventilation Performance in Multi-Story Residential Buildings

The existing of the vertical void, atria or courtyard as a passive design configuration in multi-story residential building enhance natural ventilation and lighting in the units of multi-storey residential buildings (Gaber, Remaz, Alkaff, & Kotani, 2015; Ismail, 1996; Kotani, Narasaki, Sato, & Yamanaka, 2003). Different void configurations such as size and position were examined in various studies to assess its effects on natural ventilation performance, thermal comfort, and indoor air quality as shown. Muhsin, Yusoff, Mohamed, and Sapian (2017) examined vertical void sizes with different wind directions to find which types of vertical void provide the optimal natural ventilation performance in seven (7) story residential building located in Malaysia. Results of CFD simulation and site measurement revealed that increased the size of the central vertical void by 50% of the unit's surface improved the air velocity significantly in the adjacent units Furthermore, the study found that perpendicular wind to the building is the optimal wind direction to enhance air velocity. A study by Muhsin, Yusoff, Mohamed, Rasani, & Sapian (2017), clarified that vertical void enhanced ventilation rate in medium-rise residential buildings of Malaysia. However, application of large vertical void reduce the ventilation rate.

In analysing of horizontal voids effects, Wei-hwa & Anh (2012) used the CFD simulation to assess natural ventilation performance of horizontal voids connected to central vertical void in a medium-rise residential building. The ground floor horizontal void in windward façade and top horizontal void in leeward façade connected to central vertical void and enhanced air velocity and improved stack ventilation performance, an exterior wind of 1m/s is sufficient to extract the heated air from the central void to the outdoor environment. Sapian (2004) evaluated the horizontal voids integrated into the high-rise residential building of Kuala Lumpur Malaysia. With a view of improving indoor air velocity for suitable thermal comfort. The outcomes of the simulation demonstrated that horizontal voids located in ground floor, middle and higher level enhanced slightly the indoor air velocity with a vertical void created between two buildings blocks designed with horizontal voids at different heights reduced; the indoor air velocity in the building situated on the back of the front building.

Table 1: Summary of the Application Effects of Void Configuration in Multi-Story Residential Buildings

Building Type	Design variables	Ventilation Strategy Method	Design Effects	Illustration Images
Medium rise residential building (MRRB)	Vertical void size	Cross ventilation Site measurement CFD simulation	Wind angle of 0°,increase void size by 50 % enhance air velocity by 50.88% to 0.44 m/s Wind angle of 45°,increase void size by 50 % enhance air velocity by 48.56% to 0.07m/s	 (Muhsin, Fatimah, Yusoff, Mohamed, & Sapian, 2017)
Medium rise residential building (MRRB)	Vertical void size	Cross ventilation CFD simulation	Wind angle of 0° , void in building increased ventilation rate by Wind angle of 0° , Increased void size by 50 % reduce ventilation rate by 1.03%	 (Muhsin, Yusoff, Mohamed, Rasani, & Sapian, 2017)
Medium rise residential building (MRRB)	Horizontal void position	Wind-driven ventilation Buoyancy-driven ventilation CFD simulation	Improve stack ventilation performance and enhance air velocity by 38 % to1.6 m/s.	 (Wei-Hwa Chiang, 2012)
High rise residential building (HRRB)	Horizontal voids position	Cross ventilation CFD simulation	Wind angle of 0°, Building without voids achieved air velocity of 0.95m/s Wind angle of 0° horizontal void in levels 16 achieved air velocity of 0.96m/s Wind angle of 0°, voids in 1 and 16 level achieved air velocity of 0.22m/s in the back building	 (Sapian, 2004)

Source:(Muhsin, Fatimah, et al., 2017; Muhsin, Yusoff, Mohamed, Rasani, et al., 2017; Sapian, 2004; Wei-Hwa Chiang, 2012)

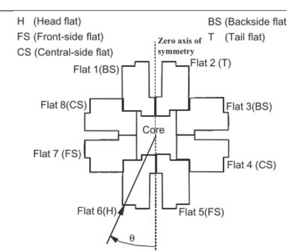
Table1 summarized studies that examined natural ventilation performance in multi-story residential buildings designed with voids. The literature review showed limited multi-storey residential buildings with central vertical void (Muhsin, Yusoff, Mohamed, & Sapian, 2017; Muhsin, Yusoff, Mohamed, Rasani, et al., 2017; Wei-Hwa Chiang, 2012). Furthermore, only one distinctive study assessed the horizontal void connected to vertical void in medium rise residential building in a hot and humid climate (Wei-Hwa Chiang, 2012). In addition, a study by Sapian (2004) highlighted horizontal voids integration in different levels in high-rise residential buildings in Malaysia. The parameter of air velocity used to evaluate thermal comfort. The study conducted by Wei-Hwa Chiang (2012) achieved the highest indoor air velocity among the previous studies. The ventilation rate was 1.36 m^3s^{-1} in (Muhsin, Yusoff, Mohamed, Rasani, et al., 2017).

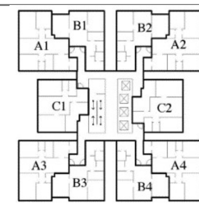
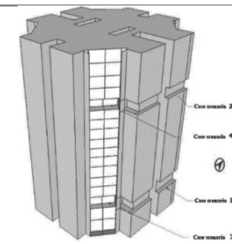
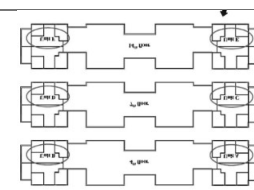
The outcomes of the previous studies revealed that voids as passive design configuration especially a combination of both horizontal and vertical void are the most effective design configuration to improve natural ventilation performance regarding thermal comfort and indoor air quality.

The Application Effects of Building Orientation and Height on Natural Ventilation Performance in Multi-Storey Residential Buildings

Burnett, Bojić, & Yik (2005) assessed the effects of high-rise residential building orientation on cross ventilation performance in Hong Kong. The results of analysis on façade pressure revealed that suitable building orientation to dominant wind is 30^0, furthermore, units located in front achieved higher performance of cross ventilation in all orientation, although the study recommended orientation of 0^0 45^0 and 90^0 for the front living units and 15^0 30^0 60^0 and 75^0 for center living units. A study conducted by Zhou, Wang, Chen, Jiang, & Pei (2014) highlighted the importance of building design modification due to the insufficient wind speed, in high rise residential building of Chongqing, China, the simulation results revealed that orientation effects significantly natural ventilation performance and enhances the ventilation rate in the units. Aflaki, Mahyuddin, & Baharum (2016) assessed the orientation and height on the efficiency of natural ventilation in high rise residential building of Malaysia. The site measurement results showed that units located in the higher level of windward and leeward sides and units in the lower level of windward side achieved better indoor thermal comfort. In Singapore, the measurement of the external wall temperature of units located on different height levels in high rise residential building showed that units located in the lower and middle levels achieved higher wall temperature than the units located in the top (Wong & Li, 2007).

Table 2: Summary of the Application Effects of Building Height and Orientation in Multi-Storey Residential Buildings

Building Type	Design variables	Ventilation Strategy /Method	Design Effects	Illustration Images
High rise residential building (HRRB)	Building orientation	Cross ventilation CFD simulation	Optimal cross ventilation performance achieved with Building orientation of 30^0 Optimal cross ventilation performance in windward units achieved in 0^0, 45^0 and 90^0 Optimal cross ventilation performance in center units achieved in 30^0 60^0 and 75^0	 (Burnett et al., 2005)

High rise residential building (HRRB)	Building orientation	Cross ventilation CFD simulation Site measurement	Achieved Mean air change rate 11.5 h^{-} in east orientation	 (Zhou, Wang, Chen, Jiang, & Pei, 2014)
High rise residential building (HRRB)	units level and orientation	Single side ventilation Site measurement	Achieved adequate thermal comfort almost 90 % in the interior spaces Achieved adequate thermal comfort with an air velocity of 0.52ms^{-1}	 (Aflaki, Mahyuddin, & Baharum, 2016)
High rise residential building (HRRB)	units level and orientation	Cross ventilation Site measurement Energy simulation	North/south reduce the cooling load by −11.54% Achieved lower temperature in units located at a higher level than units located in lower and middle levels	 (Wong & Li, 2007)

Source: (Aflaki et al., 2016b; Burnett et al., 2005; Wong & Li, 2007; Zhou et al., 2014)

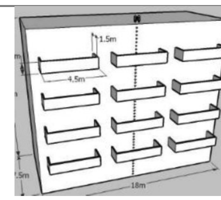
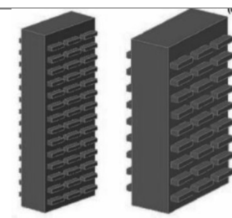
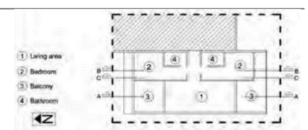
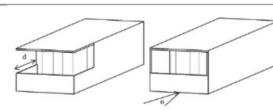
Most of the previous studies highlighted the advantages of orientation and height for effective natural ventilation in high-rise residential buildings as showed in table 2. The highest air velocity achieved is 0.52ms^{-1}Also, thermal comfort of 90 % through orientation of north-east in higher units was found in (Aflaki et al., 2016a). Building orientation to north/south reduce the cooling loads by −11.54 % (Wong and Li,2007). Furthermore, mean air change rate of (11.5 h^{-}) was found in (Zhou et al., 2014).

Based on the previous research findings it can be concluded that appropriate building orientation is significantly indispensable for effective natural ventilation, where adequate building orientation depend mainly on the local climatic conditions where the building located (Aflaki et al., 2016).

The Application Effects of Balconies Configurations on Natural Ventilation Performance in Multi-Storey Residential Buildings

The ventilation performance of balcony in medium rise residential building with single-sided ventilation showed that the introduction of a balcony in the building façade reduced the wind driven ventilation effectiveness and air flow movement inside the units (Mohamed, Prasad, King, & Hirota,2009). Ai et al., (2011) studied the introduction effects of different balcony sizes in medium rise residential building with different height and orientations, simulation results revealed that the increase in the balcony size does not enhance cross and single sided ventilation performance, furthermore the performance decreased at higher levels of the building. Garcia-hansen (2015) studied the impacts of balcony types on air velocity and airflow at high rise residential building in a sub-tropical climate. The results showed that semi-enclosed balcony enhanced indoor air velocity and airflow movement, on the other hand, open balcony with 0° wind angle decreased indoor air velocity, airflow and Air Change per hour (ACH). A recent study conducted by Omrani, Garcia-hansen, et al. (2017) evaluated balcony configuration effects and orientation and wind-driven ventilation mode. CFD and site measurement results showed that building orientation to the prevailing wind and balcony type achieves adequate single sided ventilation performance. With full open balcony single sided ventilation performance improved up by 80 % compared to the semi-enclosed balcony, while cross ventilation performance decreased with the introduction of semi and full opened balcony.

Table 3: Summary of the Application Effects of Balcony Configuration in Multi-Storey Residential Buildings

Building Type	Design variables	Ventilation Strategy/ Method	Design Effects	Illustration Images
Medium rise residential building (MRRB)	Balcony dimension	Single-sided ventilation CFD simulation	Air velocity reduced below 0.02m/s and increase slightly mean age of air to 1500s with balcony width of 1.25m	 (Mohamed et al.2009)
Medium rise residential building (MRRB)	Balcony dimension	Single sided ventilation Cross ventilation CFD simulation	Decreased pressure distribution in front façade designed with balcony in lower and top levels	 (Ai et al., 2011)
High rise residential building (HRRB)	open/semi -enclosed balcony	Single side ventilation CFD simulation	Enhanced air velocity to 1.6m/s and airflow in the semi-enclosed balcony Decreased Air change per Hour (AHC) to 3%in semi-enclosed balcony Reduced air velocity to 1.3m/s, airflow and (ACH) to 24 % with an open balcony	 (Garcia-hansen, 2015)
High rise residential building (HRRB)	Balcony dimension /length open/semi enclosed balcony	Single sided ventilation Cross ventilation CFD simulation	Enhanced single sided ventilation by 80 % with a full open balcony Decreased cross ventilation performance in both balcony types	 (Sara Omrani, Garcia-Hansen, et al., 2017)

		Site measurement	Wind angle influence the ventilation performance	

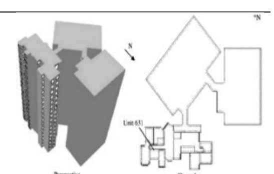
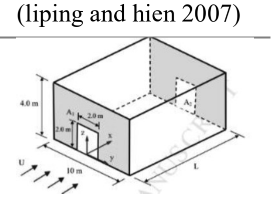
Source : (Ai et al., 2011; Garcia-hansen, 2015; Mohamed et al., 2009; Omrani et al., 2017)

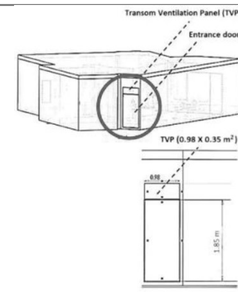
Table 3 summarized indoor thermal comfort and indoor air quality investigations in naturally ventilated medium-rise residential buildings designed with balconies. The finding of previous studies showed in table 3 revealed that the introduction of balcony does not enhance natural ventilation performance (Mohamed et al.2009; Ai et al., 2011; Garcia-hansen, 2015). However, Sara Omrani, Garcia-Hansen, et al., (2017) emphasized that building orientation to prevailing Wind improve significantly single sided ventilation performance with open balcony by 80% and indoor air speed by six times.

The Application Effects of Window Configurations on Natural Ventilation Performance in Multi-Storey Residential Buildings

The window as a building envelope component includes different design configurations such as the ratio of the window to the wall (WWR), window to floor ratio (WFR) and window position in the wall (Elshafei et al., 2017). Chu & Chiang (2014) recommended that the adequate position of the windows in the center of the leeward and windward walls enhance cross ventilation performance, the results of CFD simulation revealed that corner windows achieved 15.5% less regarding ventilation rate compared to the central windows. On the effects of window position on top of the main opening door known as "Transom Ventilation Panel (TVP)" on wind driven-ventilation performance in units of high-rise residential building located in Kuala Lumpur Malaysia. Results of simulation and site measurement conducted by Aflaki, Hirbodi, Mahyuddin, Yaghoubi, & Esfandiari (2019), showed that cross ventilation performance enhanced significantly compared to single-sided ventilation. In addition to the window positions, Studies evaluated window size impacts on natural ventilation performance. In units of high-rise residential building of Singapore, window to wall ratio of 24 % enhanced indoor air velocity for better thermal comfort, where the north/south is the optimum window orientation (Liping & Hien, 2007).

Table 4: Summary of the Application Effects of Window Configurations in Multi-Storey Residential Buildings

Building Type	Design variables	Ventilation Strategy/ Method	Design Effects	Illustration Images
High rise residential building (HRRB)	Window size window to wall ratio(wwr)	Cross ventilation CFD simulation	Improved thermal comfort by 13.09% in (WWR) of 24 % with shading device.	 (liping and hien 2007)
High rise residential building (HRRB)	Window position	Cross ventilation CFD simulation	Reduced ventilation rate by 15.5% in the window located in the corner compared to the central window in leeward and windward façades	 (Chu & Chiang, 2014)

High rise residential building (HRRB)	Window position and size	Cross ventilation Single-sided ventilation CFD simulation Site measurement	Enhanced air velocity by four (4) times in cross ventilation compared to single-sided ventilation Enhance Mean Air change per Hour (ACH) by 27 % with a low air velocity of 0.02m/s in cross ventilation compared to single-sided ventilation	 (aflaki et al. 2019)

Source: (Aflaki et al., 2019; Chu & Chiang, 2014; Wang, Wong Nyuk, & Li, 2007)

Table 4 summarized the works conducted on different window configurations effects on thermal comfort and indoor air quality. The window position on the top of main entrance improved air change per Hour (ACH) by 27 % and indoor air velocity by four (4) times in cross ventilation as shown in (aflaki et al. 2019). Furthermore central window in leeward and windward façade considered as the optimum position and improved ventilation rate as demonstrated in (Chu & Chiang, 2014). On the other hand, proper window size enhanced thermal comfort by 13.09% in (liping and hien 2007).

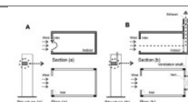
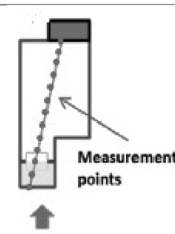
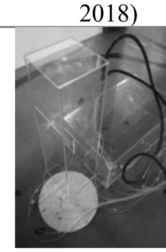
The results of previous studies showed that adequate window configurations including position, size, and orientation are fundamental passive design configuration to enhance the wind driven ventilation performance, thermal comfort and indoor air quality in multi rise residential buildings.

The Application Effects of the Ventilation Shaft Configurations on Natural Ventilation Performance in Multi-Story Residential Buildings

Different studies examined ventilation shafts in order to improve the ventilation performance in the multi-story residential building of the hot and humid climate (Priyadarsini et al., 2004; Prajongsan & Sharples, 2012; Fahmi et al., 2018). A study by Priyadarsini et al. (2004) assessed the influence of active and passive stacks in the unit of high rise residential building in Singapore. Results of CFD and wind tunnel experiment demonstrated that active stack with a top fan near the inlet with a dimension of 0.4m×0.4m enhanced indoor air velocity and achieved better indoor thermal comfort compared to passive stack. The CFD simulation results of ventilation shafts performance in high rise residential building located in Bangkok, Thailand with different wind speed and direction showed that ventilation shafts improved stack ventilation performance, enhance air velocity and indoor thermal comfort level (Prajongsan & Sharples,2012**).** Fahmi et al., (2018) assessed the impacts of different ventilation shaft opening on cross ventilation in the units of high-rise residential building in Indonesia. Results revealed that the increase in the size of the internal opening of the ventilation shaft improved indoor air speed in a room located in lower level while it decreased in a room located in higher level and improved air movement while the decreased the ventilation rate.

On the other hand, wind catchers used mainly in low rise residential buildings in the hot climatic region (Jomehzadeh, F., Nejat, P., Calautit, 2017). Gharakhani, Sediadi, Roshan, & Sabzevar (2017) evaluated the effects of wind catcher on natural ventilation performance in a high-rise residential building of tropical climate using a wind tunnel experiment. Results showed that wind watcher could enhance natural ventilation performance regardless of the low external speed and provide fresh air in the indoor spaces.

Table 5: Summary of the Application Effects of Ventilation Shaft Configuration in Multi-Story Residential Buildings

Building Type	Design variables	Ventilation Strategy/ Method	Design Effects	Illustration Images
High rise residential building (HRRB)	Active stack/fan on the top Passive stack/without the top fan	Stack ventilation Wind tunnel experiment CFD simulation	active stack with top fan Enhanced air velocity by 550% to 0.67 m/s.	 (Priyadarsini et al., 2004)
High rise residential building (HRRB)	Room with and without ventilation shaft	Stack ventilation CFD simulation	Increased Air velocity by 60% to 67% and the percentage of thermal comfort hour is by 37.5% to 56.3%.	 (Prajongsan & Sharples, 2012)
High rise residential building	Ventilation shafts internal opening size	Cross ventilation CFD simulation	Enhanced air velocity in the room at a lower level by 80 % and decreased by 52% in a room located in high level ventilation rate decreased by 28%	 (Fahmi et al., 2018)
High rise residential building (HRRB)	Windcatcher height	Stack ventilation Wind tunnel experiment	Enhanced the pressure coefficient in the measured model designed with wind catcher	 (Gharakhani et al., 2017)

Source: (Fahmi et al., 2018; Gharakhani et al., 2017; Prajongsan & Sharples, 2012; Priyadarsini et al., 2004)

Table 5 summarized different studies that assessed the performance of ventilation shafts in the multi-story residential buildings. Ventilation shafts in high rise residential building enhanced indoor air velocity by 60% to 67% which increased the percentage of thermal comfort hours by 37.5% in (Prajongsan & Sharples, 2012). Furthermore, the effects of ventilation shafts at different levels showed that ventilation shafts improved air velocity in lower rooms by 80 % and decrease by 52% in the room located in a high level (Fahmi et al., 2018).

The results revealed that ventilation shafts are an effective passive design configuration which improves natural ventilation performance especially stack ventilation performance in high-rise residential buildings.

Conclusion

The review paper aim is to provide a summary of previous studies that evaluated the passive design configurations effects on natural ventilation performance, thermal comfort and indoor air quality in natural ventilated multi-storey residential buildings of tropical climates. Previous literature reviews addressed the passive architectural design strategies impacts on natural ventilation performance in low-rise residential buildings.

For that, current review provide comparative analysis on the efficiency and the limitations of different passive design configurations performance applied to achieve effective natural ventilation suitable thermal comfort and indoor air quality in multi-storey residential buildings in tropical climates. It was found that despite the design limitations of multi-story residential buildings, the surrounding environment and the climatic conditions of tropical climates and the introduction of passive design configurations improved the efficiency of natural ventilation as a passive cooling strategy to achieve adequate thermal comfort and indoor air quality. The comparative analysis of reviewed studies findings on natural ventilation performance for suitable thermal comfort and indoor air quality showed that configurations such as window size and position, vertical void size, the horizontal void connected to the vertical void and building orientation are the most effective design configurations that enhanced wind-driven ventilation performance. Balcony configurations do not show any significant effects on wind driven ventilation performance. The ventilation shafts configurations are mostly effective in buoyancy driven ventilation.

The reviewed studies carried out research through CFD simulation, which provides a precise prediction of indoor and outdoor airflow. However, the experimental methods need to be validated by field measurement methods or wind tunnel experiment. Tables 1,2,3,4 and 5 summarise the design configuration applied and the impacts in the wind-driven ventilation and buoyancy driven ventilation performance in the multi-story residential buildings.

Further studies are recommended to be conducted in order to improve the efficiency of natural ventilation, thermal comfort and indoor air quality in multi-storey residential buildings of tropical climates .The design of vertical void segmentation with horizontal void to enhance ventilation in units in different level and orientation, the effects of internal layout design on cross and single sided ventilation performance, the size, and position of windcatchers influence on pressure differences for both single-sided and cross ventilation, and effects of window position designed with horizontal and vertical shading devices, moreover the assessment of passive design configuration performance in the CFD simulation with the real surrounded environment.

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