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Thermal Performance of a High-Rise Residential Building with Internal Courtyard in Tropical Climate

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Abstract
Natural ventilation is an effectual passive design approach to create a better indoor thermal condition as well as energy efficiency. The primary goal of building design is providing a healthy and comfortable indoor environment titled as sustainable architecture. Literature suggests that the significant feature that alteration has to take place on for better energy performance is the envelope design. This paper aims to augment the Window to Wall Ratio (WWR), orientation and courtyard corridor size for improving the design of naturally ventilated courtyard high-rise residential buildings. Briefly, the findings indicate that contending with WWR, orientation and courtyard corridor size could increase the potential of improving its natural ventilation and thus, thermal performance.

Keywords: Thermal Performance; Residential High-rise buildings; Air Velocity, Courtyard

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1.0 Introduction
Comfort is defined as the condition of the mind which expresses satisfaction with the surrounding environment. In architecture science, thermal comfort can be achieved by heat transfer mechanisms in buildings, which are conduction whereby heat energy is transmitted between two bodies in direct contact. (Auliciems, 2007) A building in tropics means a conflict of construction and function with the acute climatic condition. (Saberi, 2006) Tropical climate regions described as high humidity, intemperate rainfall, and substantial sunshine. There are negative impacts and positive impacts on the building design because of the typical features of tropical climate. The extreme effects caused by the tropical climate through its climatic parameters such as temperature, solar radiation, relative humidity, rainfall, and the wind. It is an ideal medium state for rich of tropical plants and rainforest. A successful indoor environment depends more on the understanding of the environmental factors, including building design and setting. (Moore, 1993) Some factors affect thermal sensation which are air temperature, humidity, air velocity, mean radiant temperature, clothing levels and metabolic rate (Finger thermal equations 2001).

The technique of attaining thermal comfort in architecture is reinforced by scientific theories, but it is still art. (Olgyay V., 1963) It is undeniable that buildings are facing numerous design issues. Buildings are overheated during the day due to solar heat gain through the building envelope and radiant solar penetration through windows. Traditionally, by applying passive design concept, this heat can be eliminated partly.

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2.0 Literature Review

A building in the tropics means a confrontation of construction and function with the intense climatic condition. Tropical climate regions characterized by high humidity, excessive rainfall, and considerable sunshine. (Auliciems, 2007) Typical features of tropical climate have the negative impact and positive impact on the building design. The extreme effects caused by the tropical climate through its climatic parameters such as temperature, solar radiation, relative humidity, rainfall, and the wind. It is an ideal medium state for rich of tropical plants and rainforest. (Al-Tammi & Syed Fadzil, 2011) The favorable indoor environment much depends on an understanding of the environmental factors, including building design and setting. Healthy and comfortable indoor environment have become essential in the sustainable built environment. (Givoni, 1976) Even though the full features of the climate are out of our control, the design of a building can affect its climatic performance significantly.

2.1 Building form

Oral and Yilmaz (2002) report that building form has a significant influence on the total heat loss of buildings. Conversely, overall heat transfer coefficient (U-value) determines heat loss through the building envelope. Therefore, heat loss for different building forms should be determined about U-value of the building envelope. The authors say that the shape factor (the ratio of building length to building depth), height and roof type are the parameters defining building form.

2.2 Orientation

According to Givoni (1976), the effect of building orientation on indoor climate can be understood taking account two distinct climatic factors. Firstly, solar radiation and its heating effect on walls and rooms facing different directions. Secondly, ventilation problems resulting from the relation between prevailing winds and the building orientation. For example, in a building with insulated walls of light external color, and efficiently shaded windows, indoor temperature distinction depending on orientation may be ignored. Under these conditions, indoor climate dramatically depends on ventilation, and thus the orientation of prevailing winds is more critical than solar radiation patterns.

2.3 Thermal mass

Moore (1993) mentions that buildings having mass effect employ their thermal storage capabilities in four ways: by dampening interior daily temperature fluctuations; by delaying daily temperature extremes, by ventilating the building at night; and by earth, contact to provide seasonal storage.

2.4 Windows

According to Givoni (1976), heat gain through a window is much higher than that through an identical area of the ordinary wall, and its effect is felt rapidly without any time lag. This can be observed particularly in buildings with lightweight materials. On the other hand, the combination of shading devices and glass can optimize the thermal effect of windows. Another way of controlling the thermal effect of windows is to use of special glasses or glass treatments. Shading devices can be applicable externally, internally or between double-glazing. They may be fixed, adjustable or retractable.

2.5 Thermal insulation

According to Straaten (2007), a thermal insulator for buildings can be defined as any material blocking heat transfer and having a thermal conductivity value not exceeding 0.5 Btu/ft.H deg. F. per in. Thickness. Thermal conductivity value alone is not enough in choosing of an insulation material.

Some researchers stated that Building form specifically the building envelope has a significant influence on total heat loss/gain of buildings. Others mentioned that it is more related to the building orientation. According to a few, from a thermal point of view, the cube is the optimum building form which can be stretched to form a rectangle, and that heat gain or loss is higher in reticular forms. The majority agreed that buildings with a higher ratio of glazing area on their façade, which is more sensitive to climate conditions. However, it is possible to enhance it by getting all the benefits of passive design concepts.

Therefore, the principal feature that alteration has to take place on for better energy performance is the envelope design. The building envelope modifications such as, are the ratio of window to the wall (WWR), different categories of glazing and several kinds of shading system. The effect of natural ventilation and building orientation is also investigated considering these design concepts at the early design stages; it is firmly believed that an acceptable indoor thermal environment is achieved with low energy consumption. Hence, the finding addresses the issues of thermal discomfort condition in a residential building at different scenarios of Window Wall Ratio (WWR) and corridor widths within the same building but with opposite orientations.

3.0 Methodology

This study aims to analyze the most critical factors that have a significant effect on building thermal performance and energy consumption of residential envelope under tropical climate condition. Fig. 1 presents the scope of this research and the overall framework of the complete working evaluation model.

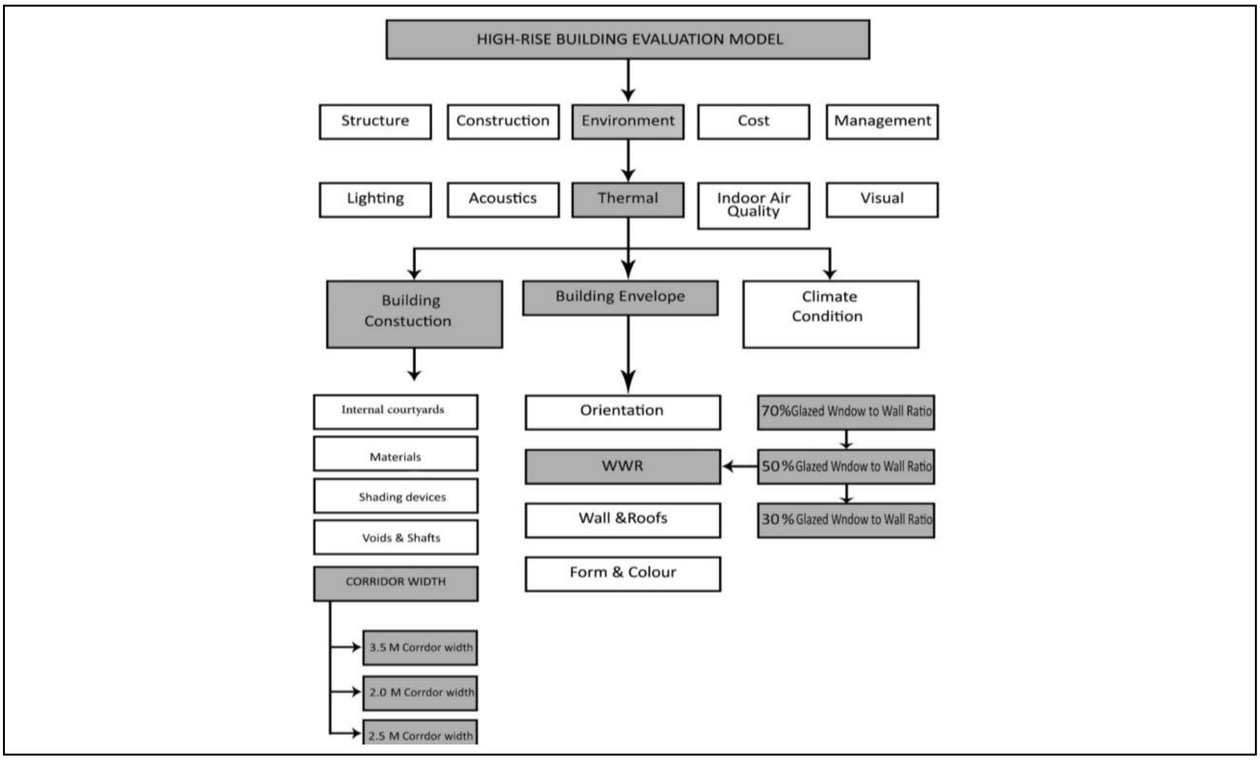


Fig. 1: Research Overall Framework
(Source: Author)

The chosen building for this study is a high-rise residential building nestled in Cyberjaya, Malaysia. It consists of 600 units which are sprawling over from blocks. It offers various build-ups ranging from 965 *ft*^{2} to 3,527 *ft*^{2}. The high-rise building features a high window to wall ratio which imposes the worst problems regarding thermal environments in the tropics, alongside alternative scenarios in comparison.

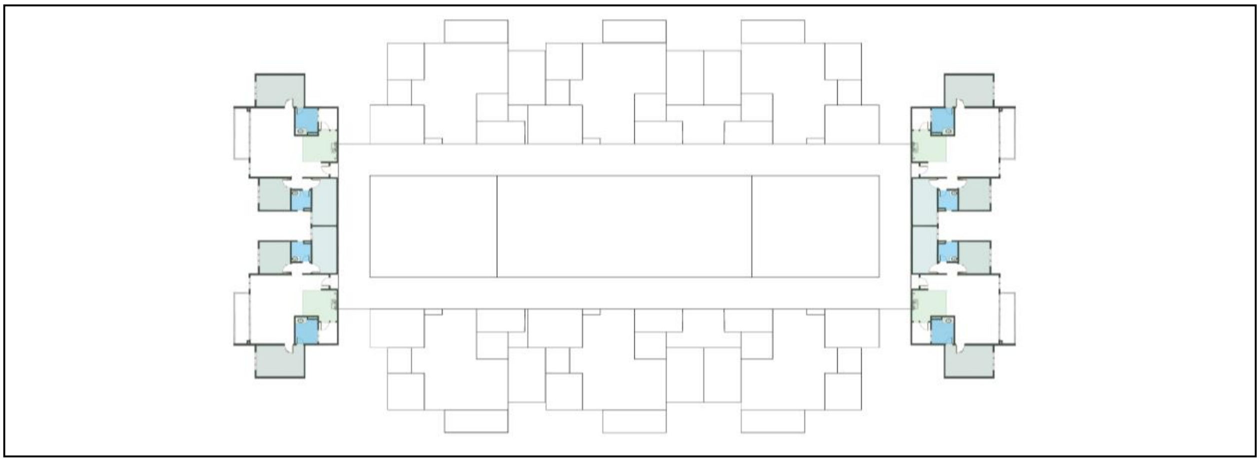


Fig. 2: Experiment Zone Floor Plan
(Source: Author)

Within the building environment aspect, the research is conducted by measurement methods, questionnaire template and other necessary information are derived from the literature review. The field study consists of two parts: a questionnaire survey and an on-site measurement campaign. In the experimental period, the measurement campaign records the building measurements, which is used in the building modeling process. Contrariwise, the questionnaire survey focuses on the subjective feeling of the residents, which can be used to verify the objective thermal sensation and compare it with the CFD simulation results.

With the aid of CFD simulation, it's possible to evaluate the building thermal performance and addresses the building envelope and the construction of the building. For the building envelope, the research studies the window to wall ratio. The evaluation of the construction layout includes the natural ventilated corridors width differences being investigated.

3.1 Data collection

The measurements field study is conducted at the residence apartment in Cyberjaya. The collected data was used to give a comprehensive picture of the building sizing for CFD modeling purposes in the month of July. Although there are many thermal modelling programs in the market, simulations were confined to just Integrated Environmental Solutions <Virtual Environment> IES<VE> which was being purchased by the university for academic research purposes. IES<VE> program was thoroughly tested and calibrated for use in the research. However, some technical limitations arose while using this software, which required co-operation between the researcher and the supervisor's support.

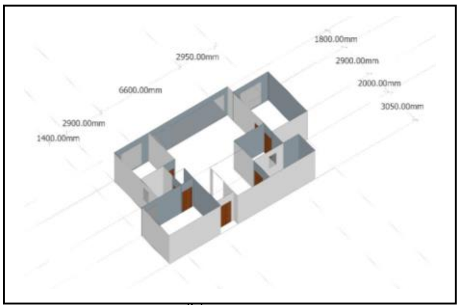
3.2 Data analysis

The results of the questionnaire are analyzed in a statically. SPSS and EXCEL are simultaneously used to process the data. Satisfaction rate, the central complaints, the gender, the age, and other related parameters are analyzed at this stage. In total, more than 80 parameters can be derived from the questionnaires. The onsite- measured data is the basis for the thermal comfort analysis and CFD simulation model purposes. For the thermal comfort analysis, the data can be processed by EXCEL and SPSS, like with the questionnaire. The data for CFD simulations are derived from the on-site measurements and later analyzed to gain suitable boundary conditions.

3.3 Model scenarios

The CFD simulation model helps to understand the indoor airflow and the temperature distribution. The model for this research is built with SKETCHUP and been analysed using <Virtual Environment> IES<VE>, which is one of the best CFD simulation soft wares at present. The below figures show the interior of one of the units facing east. The layout of the unit is regular and compact. Fig. 3 (b) shows the 3D model of the unit; the area of the unit is around 1151 *ft*^{2} of including three rooms and two bathrooms. Table 1 illustrates the different scenarios of the corridor width dimension and Window to wall ratio percentages that are eventually examined.

(a)



(b)

Fig. 3. (a) Experiment Unit Plan; (b) Experiment Unit 3D Model.

(Source: Author)

Table 1. Boundary conditions of different scenarios

Variables	Scenario 1	Scenario 2	Scenario 3	Scenario 4
WWR (%)	70	30	70	30
Corridor Width (m)	2.0	2.0	3.0	3.0

(Source: Author)

4.0 Results and Discussion

4.1 Overall Comfort Level

The comfort level is determined by many factors, including the objective ones and subjective ones. Thermal comfort is, however, the focus of this research.

Table 2. Overall comfort in July

	1	2	3	4	5	6	7	
Unsatisfacory	☐	☐	☐	☐	☐	☐	☐	Satisfactory

(Source: Author)

To begin with, how do the occupants feel in this building. The question above is mentioned in the questionnaire. On a 7-point scale, one means dissatisfied and seven means satisfied. From Table 2, it can be found that the general comfort level in July was only around 3.1. It is evident that residents are more dissatisfied during this time of the year.

Table 3. Statistic results of general comfort classified by gender

Gender	Mean	N	Std.Deviation
Male	3.04	45	1.856
Female	3.18	99	1.568
Total	3.14	144	1.650

(Source: Author)

There is also a subtle difference between genders. A woman always graded lesser comfort level lower than men. Apart from general comfort, thermal comfort might also differ by gender. The question above was mentioned in the questionnaire to assess the subjective thermal comfort of the residents.

Table 4. Statistic results of Thermal comfort classified by gender

Gender	Mean	N	Std.Deviation
Male	5.50	45	1.291
Female	5.94	99	0.959
Total	5.81	144	1.080

(Source: Author)

Table 4 shows the mean thermal comfort vote for men is 5.50, while that for women is 5.94. While the standard deviations are 1.291 and 0.959 respectively. Residents coming from different regions might have different perceptions of the overall comfort level. From Table 5, it is noticed that Yemeni residents were relatively more satisfied with the overall comfort than residents coming from India and Syria who feel overall comfort more dissatisfied. The standard deviation ranged from 1.5 to 1.9, which is the same as that in gender classification.

Table 5. Overall comfort distribution by selected nationality

Home Country	Mean	N	Std.Deviation
Yemen	4.27	46	1.831
India	2.50	14	1.522
Syria	2.90	34	1.969

(Source: Author)

To make the statement specific, thermal comfort is further analyzed. On a 7-point scale, one means cold and seven means hot. Table 6 shows the mean thermal comfort level of the residents classified by unit orientation. It is shown that residents residing in the units facing west experience lower temperatures than those are residing in units facing east, who experience higher and hotter temperatures.

Table 6. Mean temperature according to orientation

Orientation	Mean	N
East Units	5.59	81
West Units	3.65	63

(Source: Author)

According to the results above, a general idea about the comfort level in the building can be drawn, and the reasons of discomfort are analyzed. The general comfort and thermal comfort level were analyzed by gender, nationality and unit's orientation. Although the mean value differs by gender and nationality, there is no significant statistical relationship found. "Too hot" was found to be the main reason of discomfort for most residents in the building, which verifies the necessity to improve the thermal comfort level in this building.
Meanwhile, 1/3 residents complained that they could not use the natural ventilation system freely or there is difficulty to do that. The main reason is about privacy.

4.2 Units Scale Analysis

The thermal comfort level is analyzed at unit scale. As a result, it focuses more on the thermal comfort of the residents. Temperature and air velocity are separately analyzed in this section. Simulation is simultaneously applied in this section to verify differences in thermal performance between east and west orientations. To simulate the model in CFD software, the researched units needs to be simplified and modeled. As shown in Fig. 4, the unit is regarded as a continuous space with inlets and outlets in the CFD model, which has specific boundary condition. A typical room in the researched building can be simplified as a space made up of several boxes.

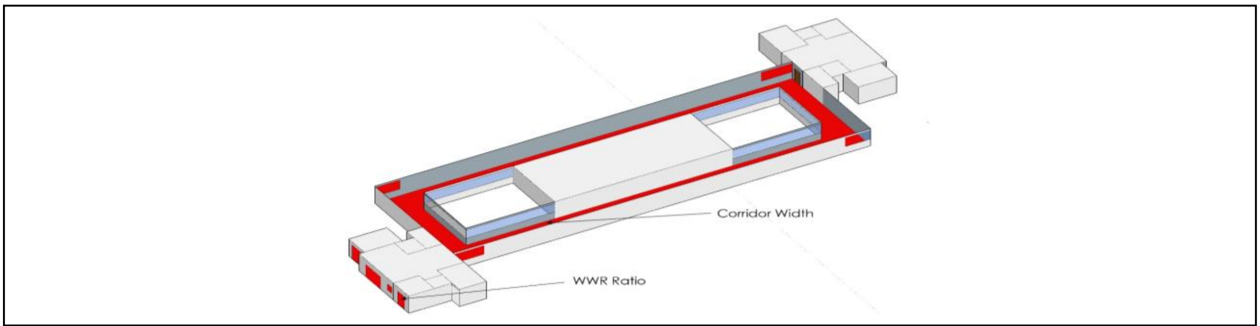


Fig. 4: Diagram of the CFD Model
(Source: Author)

4.3 Accuracy Analysis

CFD simulation is one kind of FEM (finite element method) calculation method to simulate real fluid on a computer. According to previous researchers' experience and comparison, there is always a difference between reality and simulation. To assess the validity of the simulation in this research, the reasons for accuracy are analyzed below.

(1) Inaccuracy caused by simplification

The most accurate way for natural ventilation simulation is to build a wind tunnel in CFD software and put the building in it. That kind of model is usually on an urban scale (1000m). If it is expected to simulate precisely in that way, a massive number of cells is needed. The software and hardware condition are not able to support us to do such colossal calculation, so a less but acceptably precise method is chosen.

The furniture and residents themselves have volume, which can affect the path of the air flow. In the simulation, the room is assumed to be an empty one without any furniture. Fewer obstructions in the rooms allow the wind to flow more freely, and this might result in higher air velocity in the simulation result.

(2) Mesh Quality

Since the number of cells is limited, it is not possible to have the finest cells in all the parts of the model. Therefore, the cells are reduced by modifying and rebuilding the model within the <Virtual Environment> IES<VE> software.

(3) Quantity of Iterations

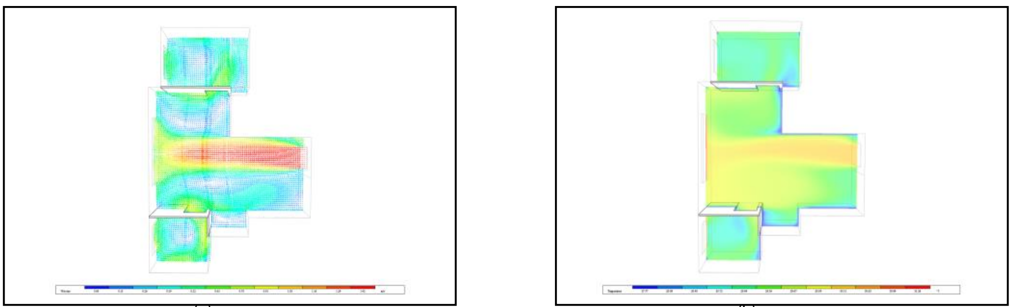
For the calculations, 200 iterations were performed. However, more iteration would allow a more accurate result. As shown in Fig. 5, the Residual decreases sharply from iteration 1 to iteration 100, and then it keeps decreasing but with a very slow speed. Since the scaled residential does not vary drastically after 250 iterations, perhaps more times in iterations are not necessary. It is important to note, that while more iterations may produce a better visual result, this is also a lot more time-consuming. As the model is to verify the measurement, the number of iterations here is acceptable.

Fig. 5: Residuals graph of simulation
(Source: Author

4.4 Simulation Results

Scenario 1: Window to wall ratio 30% + 2.0m Corridor width

To start the simulation process, both units facing east and west, are simulated separately, with the results of the air velocity and air temperature distribution. This scenario case is the current condition of the high-rise building design, whereby the existing WWR is 30%, and the corridor width dimension is 2.0m. From Fig. 6 (a), the Air velocity contours in the west unit indicate high-velocity rates of 1.03 to 1.42 m/s with air patterns directing from the corridor and exiting the unit throughout the Window openings.

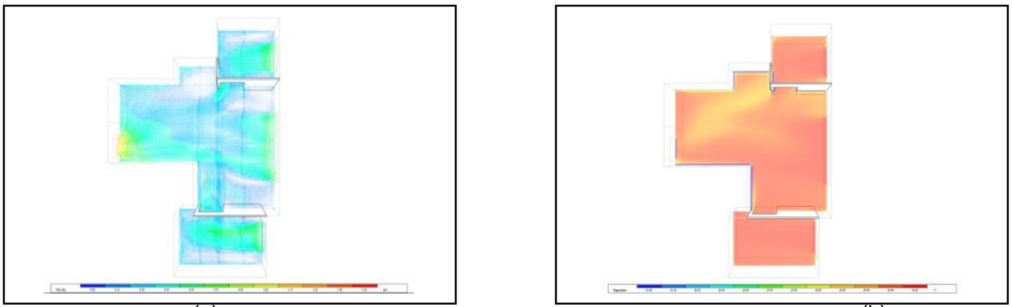


(a) (b)

Fig. 6. (a) Air Velocity patterns (West Unit) simulation results; (b) Air Temperature Contours (West Unit)
(Source: Author)

With regards to the air temperature, the contours indicate clearly that the temperature in most parts of the unit varies between 28.72 to 30.31 °C as shown in Fig. 6 (b). Interestingly, the coolest parts are in the side rooms, which is indirectly connected to the inlet opening experiences temperature variations between 29.14 to 30.32 °C. Apparently, the wind-driven effect in which air is drawn into the building courtyard on the high-pressure windward side and is drawn out of the unit window on the low-pressure leeward side.

In contrast, the east unit simulation results show the opposite, whereby, the air velocity rate tends to be lower marking 0.34 to 0.48 m/s and the air patterns flow from the windows (outlet) towards the opening (inlet) towards the corridor. Fig. 7 (b), shows the air temperature distribution in the east unit. From the temperature contours shown, it can be found that the air temperature in most parts of the unit fall between 30.48 and 31.80 °C higher than the wall temperature which is around 29.48 °C. Apparently, the cooling effect is not useful in this situation. Hence, the air velocity rate is slower, and due to gravity, the cool air falls and cools the ground, which does not contribute to improving the thermal level at human height.



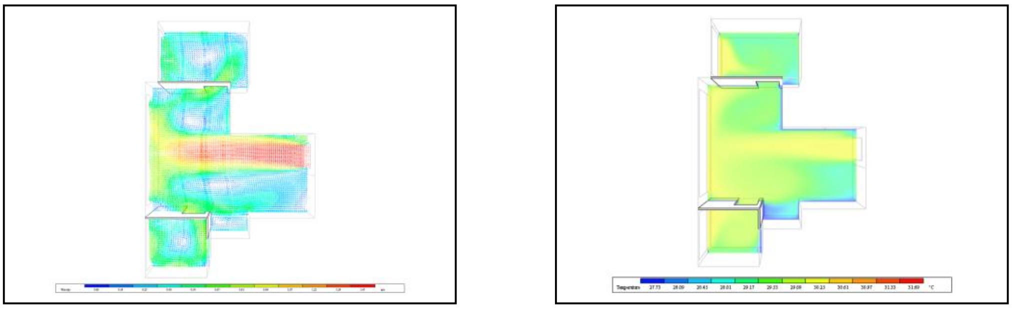
(a) (b)

Fig. 7. (a) Air Velocity patterns (East Unit) simulation results; (b) Air Temperature Contours (East Unit)
(Source: Author)

Scenario 2: Window to wall ratio 70% + 2.0m Corridor width

To examine variations of simulation results to have a valid comparison the second scenario includes the same 2.0m corridor width as scenario 1, but with 70% of the wall to window ratio. The figure below shows the air velocity increases between 1.07 to 1.47 m/s with the change of a higher WWR percentage.

This shows that, the wider the outlet dimension, the higher the air velocity rate. Fig. 8 (a) shows that, with the increment of Air velocity rate, the air temperature of the unit rises respectively. Mainly, the living area marks the highest air temperature, while the rooms mark lower air temperature rates. The air temperature close to the inlet varies from 29.17 to 29.25 °C, while in the rooms; it varies from 28.81 to 29.89 °C.

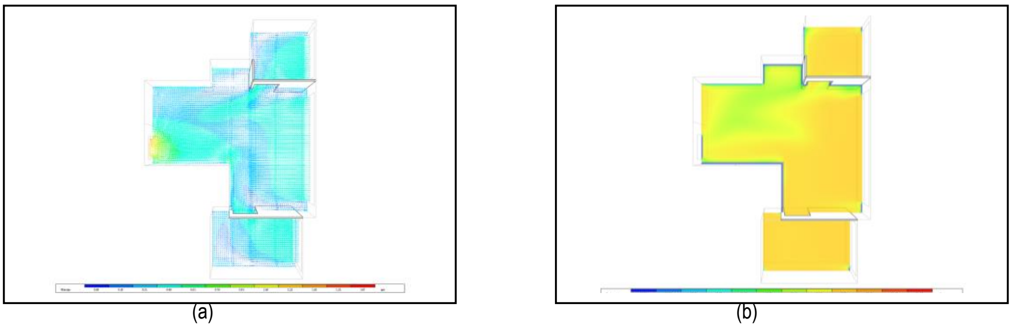


(a) (b)

Fig. 8. (a) Air Velocity patterns (West Unit) simulation results; (b) Air Temperature Contours (West Unit)
(Source: Author)

On the contrary, the east unit simulation results show the higher air velocity patterns in comparison to scenario 1. Whereby, the air velocity rate tends to be higher marking 0.31 to 0.46 m/s and the air patterns flow from the windows (outlet) towards the opening (inlet) towards the corridor as shown in Fig. 9 (a). As shown in Fig. 9 (b), it is evident that the temperature distribution in scenario 2 is significantly better than scenario 1.

Fig. 9 (b) demonstrates the temperature in most parts of the unit in green, which represent 28.17 °C. That is 1 °C lower than the temperature results in scenario 1. Hence, the distribution of air temperature is also much better. There is no apparent blind corner for ventilation.



(a) (b)

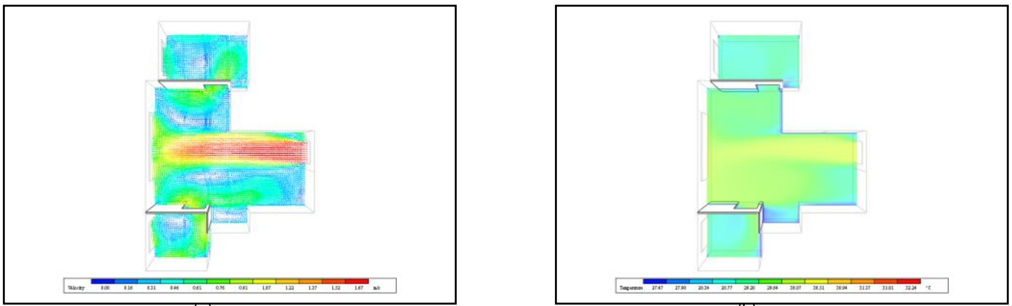
Fig. 9. (a) Air Velocity patterns (East Unit) simulation results; (b) Air Temperature Contours (East Unit)

(Source: Author)

Scenario 3: Window to wall ratio 30% + 3.0m Corridor width

Scenario 3 and 4 are relatively different from the rest of scenarios. Hence, the corridor width is considered 3.0m, which is not the existing case of the residential building. However, the window to wall ratios will be assumed to vary between 30% and 70% as well as in the previous scenarios. Fig. 10 (a), shows relatively higher air velocity patterns in comparison to scenarios 1 and 2.

The air velocity marks between 1.07 to 1.67 m/s, the air patterns flow from the corridor (outlet) towards the opening (inlet) towards the window openings. Concerning the temperature, Fig. 10 (a) shows the lowest temperature in comparison to the rest of scenarios, as the temperature falls between 28.77 °C to a maximum of 29.07 °C. The natural air velocity cools down most parts of the room in this case, and the potential is primarily utilized. There is an apparent cold flow from the openings, and it forms a “cold band,” where the air is the coolest. As a result, the areas directly affected by the wind are around 1°C colder than the others are.



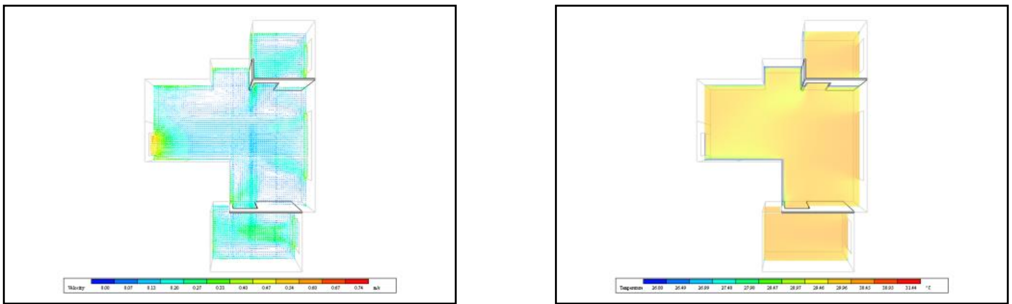
(a) (b)

Fig. 10. (a) Air Velocity patterns (West Unit) simulation results; (b) Air Temperature Contours (West Unit)

(Source: Author)

Moreover, air velocity patterns in Fig. 11. (a) is distributed chaotically. The figure also shows the lowest air velocity in comparison to the rest of scenarios, as the velocity falls between 0.13 to 0.27 m/s. This has eventually resulted in an overall higher temperature rates as shown in Fig. 11. (b). The temperature contours as shown below do not vary much.

The temperature varies between 29.96 °C to 30.45 °C. With a low air velocity, it is hardly providing extra cooling feeling. This scenario simulation shows that, the lower the air velocity, the higher the temperature distribution across the unit.



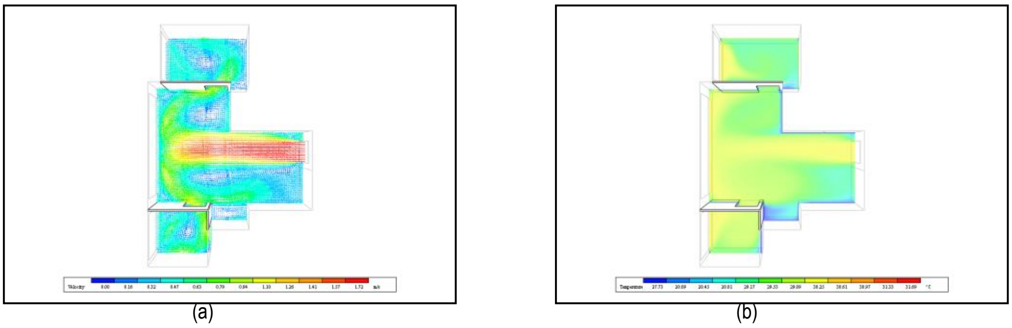
(a) (b)

Fig. 11. (a) Air Velocity patterns (East Unit) simulation results; (b) Air Temperature Contours (East Unit)

(Source: Author)

Scenario 4: Window to wall ratio 70% + 3.0m Corridor width
In this scenario, the air velocity is much higher than all other scenarios. This scenario revolves around the widest corridor width and the largest Window to Wall Ratio in this CFD simulation. As shown in Fig. 12 (a), the air velocity patterns scores between 0.94 to 1.72 m/s, which is recorded the highest wind speed recorded in all scenarios. It is also found that the air velocity reaches 1.26 m/s in most of the areas in the unit the direct wind even makes the indoor air velocity exceeds 1.72 m/s in the living area, which falls directly between the outlet and the inlet openings.

The same conclusion can be drawn from Fig. 12 (b). The temperature is well distributed, and it is not so high anymore. The temperature close to the opening is the lowest. Hence it is the primary air inlet, and the thermal insulation of the windows are not as good as the walls. This is also verified by the measurements. The temperature in the rest area is around 28.03 °C. There are areas that are slightly colder close to the corners and dead ends, but the difference is very subtle and neglectable.

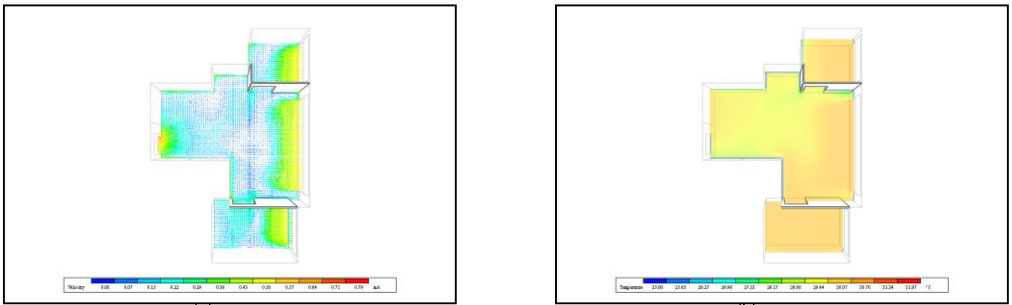


(a) (b)

Fig. 12. (a) Air Velocity patterns (West Unit) simulation results; (b) Air Temperature Contours (West Unit)
(Source: Author)

In Fig. 13 (a) and Fig. 13 (b), it is shown clearly, that scenario 4, which examines WWR of 70% and corridor width of 3.0m is the most favorable results amongst the rest of scenarios. Fig. 13 (a) shows highest air velocity patterns at the east unit marking 0.30 to 0.50 m/s. As shown in the figure, there are greener zones towards the openings of the inlet and outlet.

Correspondingly, the air temperature contours respond to the high air velocity recorded scoring the lowest temperature recorded at the east unit of 29.44 °C to 29.70 °C. As shown in the Fig. 13 (b), the majority of the color zones are in yellow, centered in the middle of the unit, which shows cooler temperature mainly in the living area. This is ideal from a thermal perspective; however, this unstable pattern might vary in reality.



(a) (b)

Fig. 13. (a) Air Velocity patterns (East Unit) simulation results; (b) Air Temperature Contours (East Unit)
(Source: Author)

5.0 Summary and Conclusion
In the four cases of CFD simulation, the indoor temperature was found to be ideal in scenario 4 and worst in scenario 1, and the indoor air velocity can be efficiently increased using increasing both the WWR percentage and the corridor width of the courtyard. It has also been concluded that the closer the openings, the more is the area influenced by the outside conditions. The air velocity in the inner parts of the living was found to the highest than other parts of the unit. When the natural wind is dominating, the distribution of temperature and air velocity tends to chaotic in the east units. This indicates the possibility of turbulence in the room. This might be occurring because the air patterns flow from the windows (outlet) towards the opening (inlet) towards the corridor.

The exact opposite happens in the west unit, whereby the air patterns flow from the corridor (outlet) towards the opening (inlet) towards the windows. However, it is concluded significantly that, the ratio between the WWR percentage and the corridor width is relatively related. Hence, the wider the corridor width and the larger the WWR percentage is the higher air velocity patterns and the lower the indoor temperature.

Comparing the results of the CFD simulation results and the conducted quantitative research executed; The Questionnaire. The CFD Simulation results correspond with how the residents actually experience inside the block. The east unit residents experience hotter

Air temperatures conditions throughout the year. As the CFD simulation results in Scenario 1 (the existing building condition) state that, the east unit hottest temperature scores 31.80 °C in the month of July. Whilst the west unit air temperature varies between 29.14 and 30.32.

Thermal comfort in a high-rise residential building is closely related to the spatial location, the background of residents, and the status of the ventilation system. To provide better thermal comfort, all these factors should be considered simultaneously. However, it is concluded that the higher the WWR percentage and the wider the corridor size in a courtyarded high-rise, the better the air velocity patterns, and indoor air temperature.

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