PART B / TROPICAL CLIMATE

§ 5.7 Tropical climate: KOMTAR building

This study is a follow-up of chapter 4 regarding energy-saving solutions for the envelope design of high-rise buildings in tropical climates. In the first part, energy-saving measures such as shading elements, glazing type, window-to-wall ratio (WWR), service core placement and roof design were investigated with a special focus on cooling and electric lighting. For this purpose, the KOMTAR tower was selected as a conventional design for tall office buildings in the tropical climate and the energy use prior to and after refurbishment was compared through computer simulations with DesignBuilder version 4.7. DesignBuilder is a powerful interface that incorporates the EnergyPlus simulation engine to calculate building (energy) performance data. The simulation model in DesignBuilder was validated using metered energy data of the KOMTAR building in 2004.

The follow-up study presented here aims to address the potential use of natural ventilation (NV) as a replacement for or supplement to mechanical ventilation using the base validated model of the KOMTAR building. In order to minimise the impact of the reference building's poor performing envelope on the results of the investigation, two external envelope measures have been upgraded. Their selection was based on our findings from the previous chapter that showed these two envelope aspects have the highest influence on building's energy performance. For the simulation model, the single pane 6 mm clear glass of the reference design is therefore replaced with double-glazed spectrally selective glazing. Additionally, external shading elements (louver and overhang) are employed as a replacement for the reference building's low-performance indoor blinds.

§ 5.7.1 Building design

The KOMTAR tower is a 65-storey commercial building with a conventional design that uses air-conditioning system year-round for providing comfort conditions for the occupants. The building has a twelve-sided plan shape that measures 60 m from façade to façade. The building features an open-plan layout and a central service core, as shown in Figure 5.14. From the total gross floor area on each floor (2894 m^2), the share of the service core is around 22%. The service core houses lift lobbies, stairways and sanitary spaces. The 12-sided central core is enclosed by three banks of lifts and is only open on three sides where the office zone is connected to the corridor; one on the north, one on the south-east, and one on the south-west. The building has a high percentage of glazing that is evenly distributed across the external façade on all orientations and accounts for 80% of the external envelope surface area.

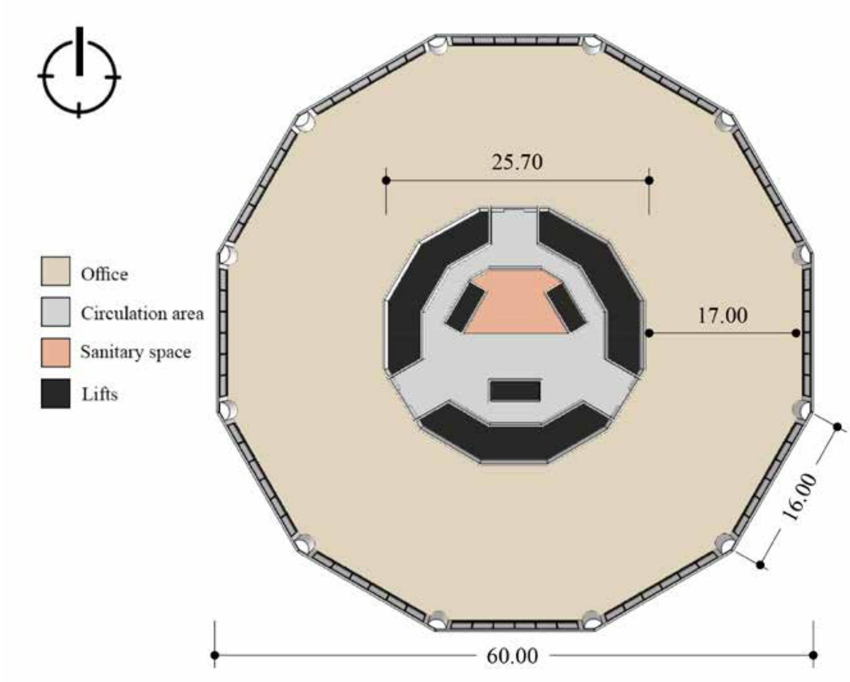


FIGURE 5.14 A simplified typical floor plan of the KOMTAR tower.

§ 5.7.2 Climate

The KOMTAR tower is located in George Town, a city in Malaysia with a tropical climate (Latitude 5°17´N and Longitude 100° 27´E). This climate features high daily mean air temperatures and a high relative humidity throughout the course of the year. The climate of this region is influenced by the proximity to the equator and the surrounding sea; this results in relatively small annual temperature variations, considerable humidity and occasionally high wind speeds. The annual average day-time and night-time temperatures is 29.3 °C and 26.8 °C respectively (Figure 5.15). Winds may blow from all directions but the pre-dominant wind direction is north and the annual average wind speed is around 1.5 m/s (Figure 5.16). Occasionally, during the monsoon seasons (May-September and November-March) wind speeds of up to 6 m/s can be expected from south-west or north-east. During the course of the year, the humidity fluctuates in a range between 60 – 90%. For this study, weather data were obtained from the nearby Bayan Lepas weather station at Penang Airport (20 km south-west of the location) (US Department of Energy). Since the energy consumption data measured were obtained in 2004, the weather data were also acquired from 2004.

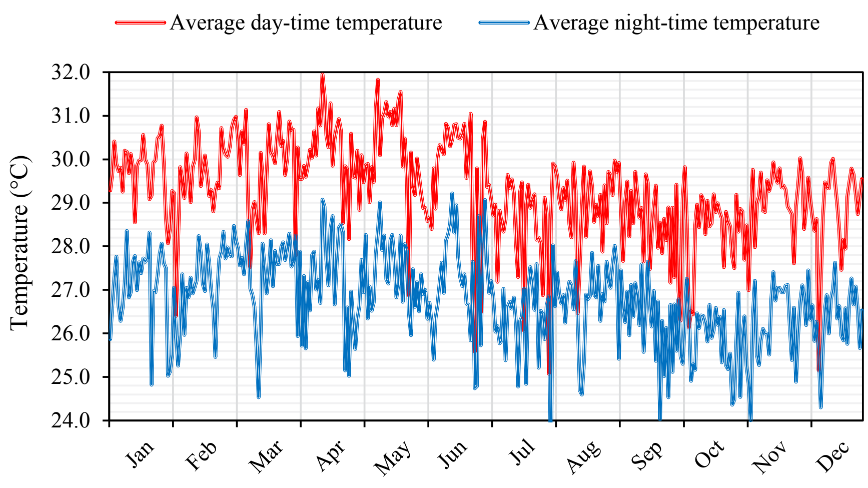


FIGURE 5.15 The average daily values of the dry-bulb temperature for day-time (7:00-19:00) and night-time (19:00-7:00) at Penang Airport in 2004.

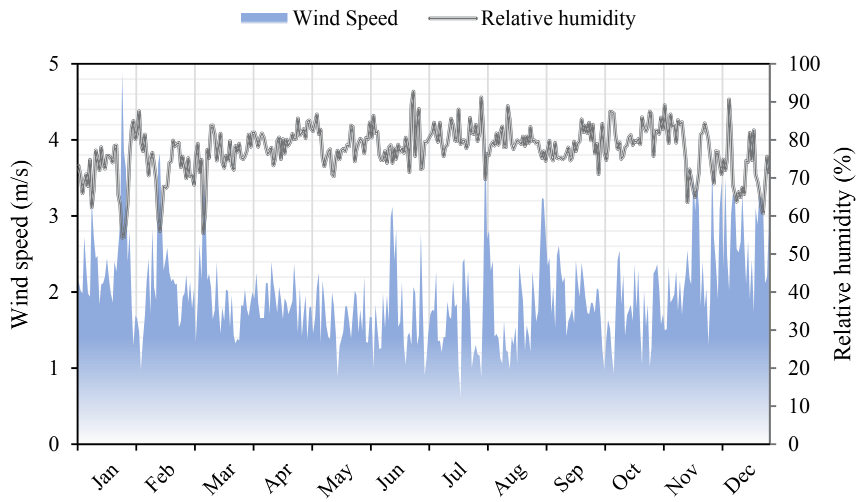


FIGURE 5.16 The daily values of wind speed and relative humidity at Penang Airport in 2004.

§ 5.8 Methodology

The objective of this study is to determine the potential use of natural ventilation (NV) as a replacement for or supplement to mechanical ventilation for high-rise office buildings in the tropical climate. For this purpose, three natural ventilation strategies were developed for the base case by changing several design parameters including the size of air inlets/outlets (the percentage of operable window area), and the application of vertical shafts. Through the application of different ventilation strategies, this research aims to address the following questions:

- What percentage of office hours can natural ventilation provide sufficient fresh air in the office area?
- What percentage of office hours can natural ventilation provide enough cooling to keep the indoor temperature in the office areas within the (adaptive) comfort range?
- Among the considered alternatives, which of the natural ventilation strategies can improve the comfort area (and the energy performance) in the office zone more than others?

In this study, the investigation of NV strategies comprises of two main steps, as shown in Figure 5.17. In the first step, the amount of fresh air changes per hour and the operative temperature is calculated during one year (2004). The EnergyPlus calculation engine within DesignBuilder simulation software was used to run the calculations. For this purpose, three office floors at different heights (low-, mid- and top-level) were selected and the results of the simulation were used to calculate the percentage of the occupancy time during which comfort conditions can be provided by the application of NV. These results were assessed according to the ASHRAE 62.1 standard (ASHRAE, 2004) and the adaptive thermal comfort model for calculating the minimum fresh air requirements and the higher limit of comfort temperature respectively. The number of discomfort hours during the occupancy time in one year determines the number of hours that active cooling or mechanical ventilation is necessary to provide comfort conditions on the test floors. A lower number of discomfort hours means that the ventilation strategy performs better, hence saves more energy.

In the second step, the CFD code in DesignBuilder was used to compare the air velocity and temperature among the three NV strategies on the proposed three office floors under three different weather conditions: no wind (0 m/s), average wind speed (1.5 m/s) and high wind speed (6.0 m/s). The average and maximum indoor air velocities, as well as the office floor area with an indoor operative temperature higher than the upper comfort limit were calculated. Then Szokolay's physiological cooling equation (Auliciems & Szokolay, 2007) was employed to measure the potential cooling effect of elevated air velocities for different NV strategies. Finally, the increased area of comfort (%) due to elevated air flow for the 27 CFD simulations was calculated and compared with the reference design.

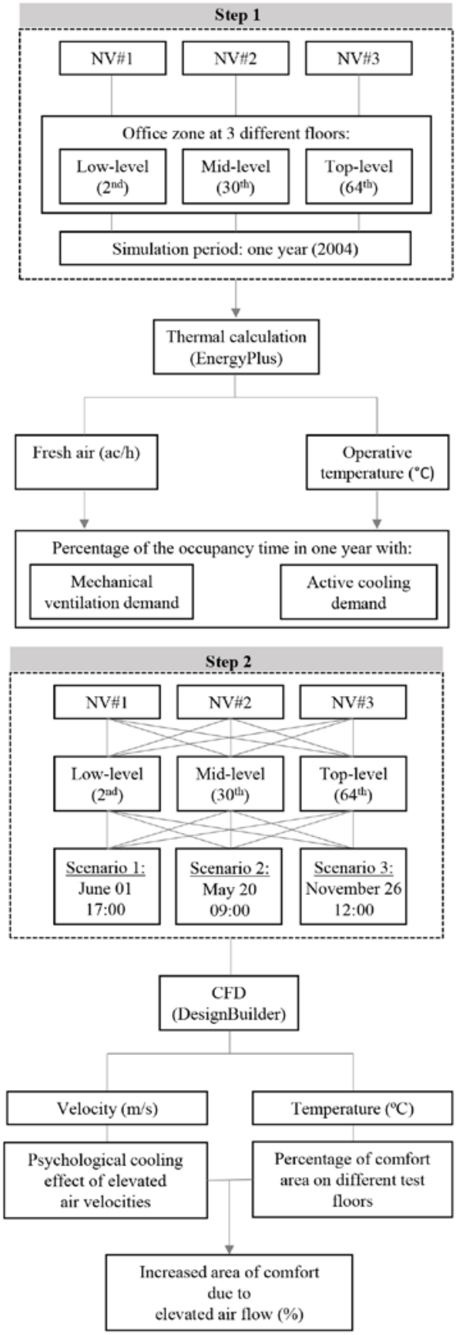


FIGURE 5.17 Methodological scheme of research.

§ 5.8.1 Fresh air calculation

For the proposed NV strategies, it is assumed that the external windows are controlled entirely by a schedule and are not affected by temperature controls or occupants. Therefore, all the external openings are constantly open during the occupancy hours (8:00 – 17:00) for the operation of NV. The building- and occupancy-related parameters with selected values used for the simulations are summarised in Table 5.5.

PARAMETER	VALUES
External wall insulation (U-value)	2.05 W/m²-K
Roof insulation (U-value)	2.13 W/m²-K
Glazing type	Dbl LoE Spec Sel Clr 6mm/13mm Arg
U-value of glass	1.34 W/m²-K
SHGC of glass	0.42
Light transmission of glass	0.68
Shading	Combined external shading devices: Overhang (1 m) + Louver (0.5 m)
Metabolic rate	0.9 met (average value for men and women)
Occupancy density	0.1 person/m²
Occupancy schedule	7:00 – 19:00 h (Mon-Fri)

TABLE 5.5 Building and occupancy parameters and the proposed values for the simulation.

According to the ASHRAE Standard 62.1-2004 (ASHRAE, 2004), the fresh air minimally required for light office work is around 8.5 l/s per person. For the purpose of the fresh air calculation, the occupancy density was assumed to be 0.1 person/m^2. This is equivalent to 222 people per office floor (2223.6 m^2). Therefore, a total amount of 1887 l/s (222×8.5) of fresh air is needed to ventilate 7382 m^3 of space. This means that the office zone at each floor requires a minimum of 0.92 ac/h to provide enough fresh air for the occupants. The total amount of fresh air changes per hour in the office zone was simulated in EnergyPlus for different NV strategies. The percentage of hours in which the air change rate was equal to or higher than this minimal value was obtained for the three ventilation strategies for the year 2004.

§ 5.8.2 Comfort temperature calculation

The impact of ventilation strategies on the occupants' thermal comfort during one year (2004) was assessed using the adaptive equations for thermal comfort in free running buildings from the European standard EN15251 (European Standard EN15251, 2007). Two comfort temperature ranges were selected with 80% and 90% acceptability limits. The 80% acceptability limit introduces a bandwidth around the comfort temperature of ±3 K, while the 90% acceptability limit covers a narrower bandwidth around the comfort temperature of ±2 K. The average percentage of the hours with thermal comfort was assessed for the three ventilation strategies in the proposed test floors, based on these 80% and 90% acceptability limits.

§ 5.8.3 Computational Fluid Dynamics (CFD)

As an alternative, the CFD technique was employed to have a more detailed examination of the velocity and temperature distribution inside the KOMTAR building at three different heights, and under three different wind scenarios. The CFD simulations were carried out for three distinct scenarios: a typical condition and two extreme conditions (see Table 5.6). The first scenario (01 June, 17:00) represents a typical day with an outdoor air temperature of 29.5 °C and wind (speed: 1.5 m/s) coming from the prevalent direction (north). The performance of the NV strategies was also tested for two extreme weather conditions: 0 m/s wind speed (20 May, 9:00) and 6.0 m/s wind speed (26 November, 12:00). Since the air flow patterns might be affected by variations in temperature between the inside and outside, the time snaps were selected on three distinct times during a day; morning, mid-day, and evening.

According to the yearly wind rose diagram at Penang Airport, a wind speed of 1-2 m/s from the north is the most frequent throughout the course of the year while for higher wind speeds (such as 6.0 m/s), the south-west is the dominant direction (see Figure 5.18).

WEATHER SCENARIO	Date / time	Outdoor dry-bulb temperature (°C)	Wind speed (m/s)	Wind direction (degree)
S.1. Typical condition	01 June / 17:00	29.5	1.5	360 (N)
S.2. No wind	20 May / 9:00	29.0	0.0	---
S.3. High wind	26 November / 12:00	30.0	6.0	225 (SW)

TABLE 5.6 The proposed weather scenarios for CFD simulations.

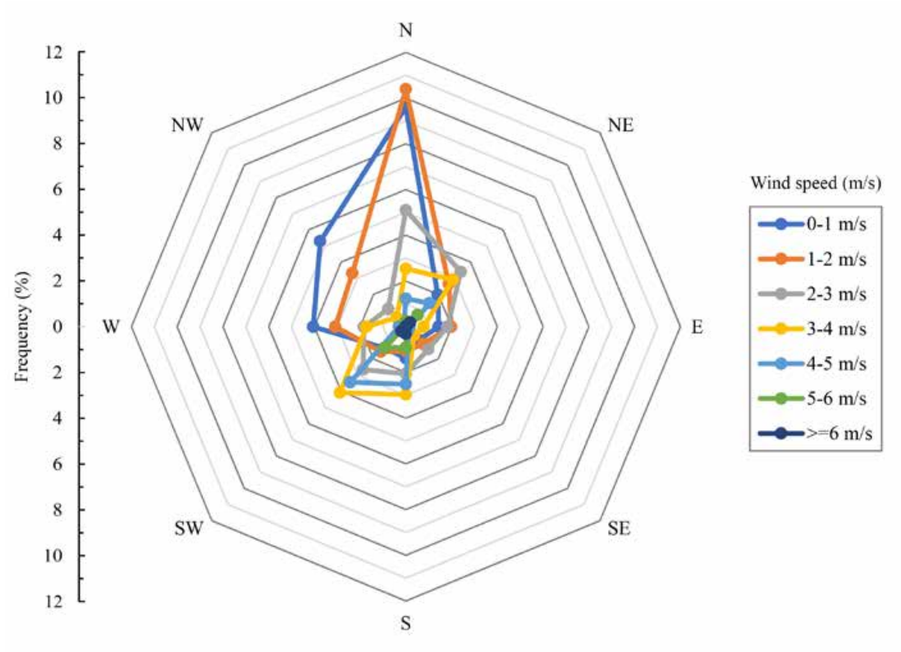
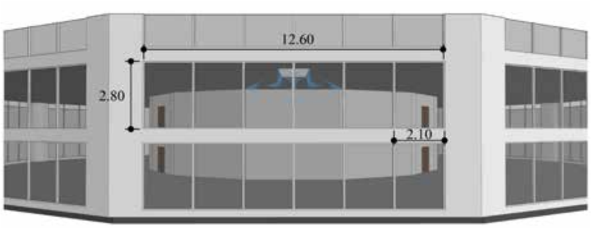


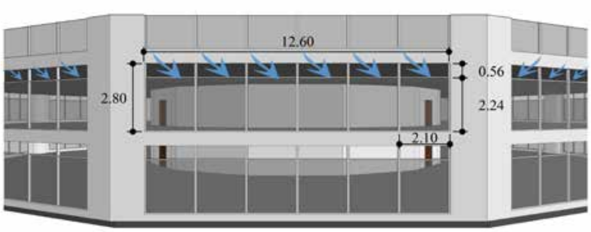
FIGURE 5.18 Frequency distribution of wind speed and direction at Penang Airport in the year 2004.

§ 5.8.4 Proposed natural ventilation strategies

In the KOMTAR building (reference design), the external windows are not operable and the building fully relies on fans and air-conditioning for providing comfort conditions. On a typical floor, each group of windows located on one side of the dodecagon has a size of 12.6 × 2.8 m (W × L) and is located 0.7 m above the floor in the centre of the external wall (Figure 5.19a). In order to provide natural ventilation for this building, the fixed external windows are changed to operable windows. The position of the aperture of all operable windows is located at the top and the aperture size is 20% of the total window area. The air flow opening is assumed to be a gap in the window. This means that 7 m^2 of window area – on each side of the plan – can be opened for the purpose of ventilation (Figure 5.19b).



(a) Fixed external windows in the reference design



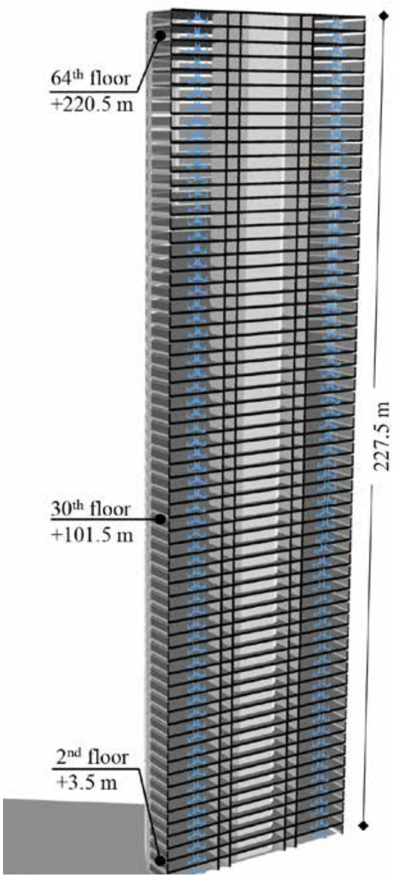
(b) 20% operable external windows for natural ventilation

FIGURE 5.19 The size of external windows and the openable window area.

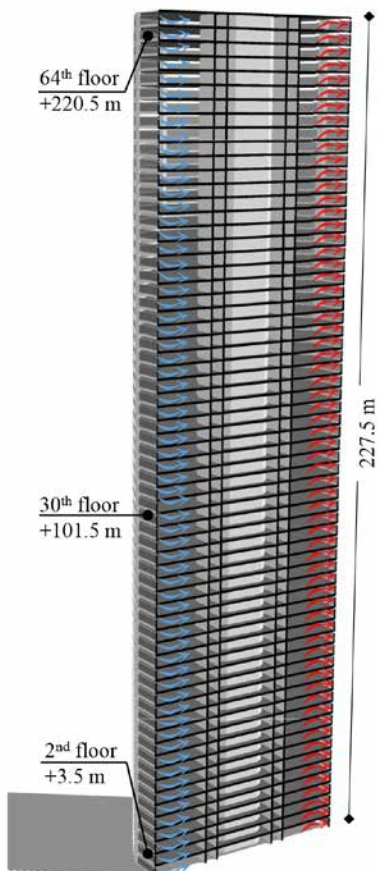
In this study three different ventilation strategies were developed for the base case using cross or stack ventilation or a combination of them. A visual representation of the three ventilation strategies and of the reference building, along with the intended air flow patterns across the ventilated spaces, are provided in Figure 5.20. Vertical distances between the investigated floors and ground level are measured at around 3.5 m for the base-level (2nd), 101.5 m for the mid-level (30th), and 220.5 m for the top-level (64th).

For the reference design, the HVAC system delivers the cool supply air from the area above the suspended ceiling into the office zone (Figure 5.20a). In NV#1: cross ventilation, the main driving force for ventilation is wind. Fresh air can enter the building through the operable windows on the windward side and exit the building from the external openings on the leeward side (Figure 5.20b). The potential of stack ventilation through the application of a vertical shaft is tested in NV#2 and NV#3. For this purpose, an atrium (3.3×5.4 m) is added in the centre of the service core with an exhaust opening at its top. A 3-storey extension is also added on top of the roof which has the same floor area as the service core. This extension is added with the aim of improving the air extraction and reducing high temperatures in the top floors. On lower floors, the outdoor air is expected to enter the building through the 20% of the operable window area along the external façade. The stale air is then sucked into the corridor, pulled up through the vertical shaft, and finally escapes the building through the operable windows on the outer façade perimeter of the rooftop extension of the central core. The external façade of this extension has large openings on all sides and the window-to-wall ratio (WWR) is set to 80%, while only 20% of the total window area can be opened for ventilation as shown in Figure 5.21a.

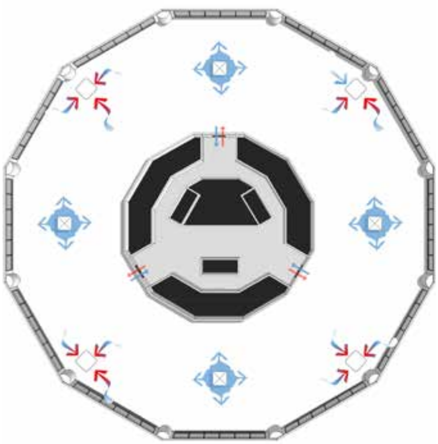
The impact of the shaft's height on natural ventilation is tested for a full height and a segmented atrium. In NV#2, the vertical shaft is extended along the entire building height (Figure 5.20c). In NV#3, the atrium has a segmentation at mid-height (34th storey). A 3-storey wind floor (on top of the 30th floor) divides the vertical shaft in two parts that are isolated from one another (Figure 5.20d and Figure 5.21b). In order to minimise the resistance, the air flow encounters between the office zone and the service core, big openings (4.80×3.20 m) are created on three sides along the core perimeter. The size of the external windows and the openable area on the rooftop extension and on the wind floor are presented in Figure 5.21.

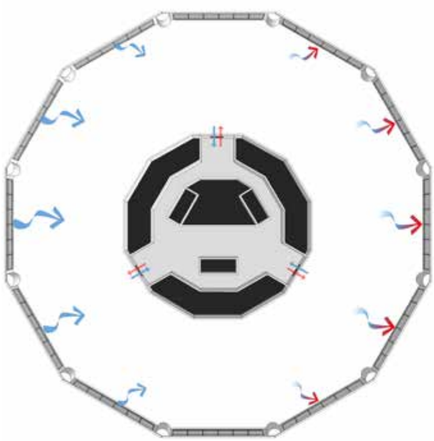


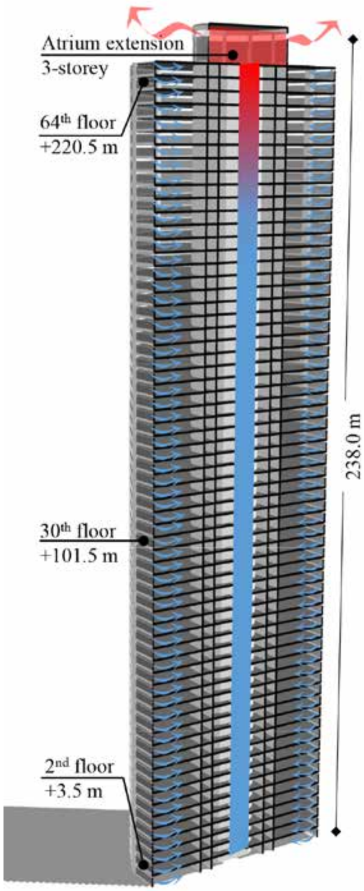
(a) Reference: mechanical ventilation



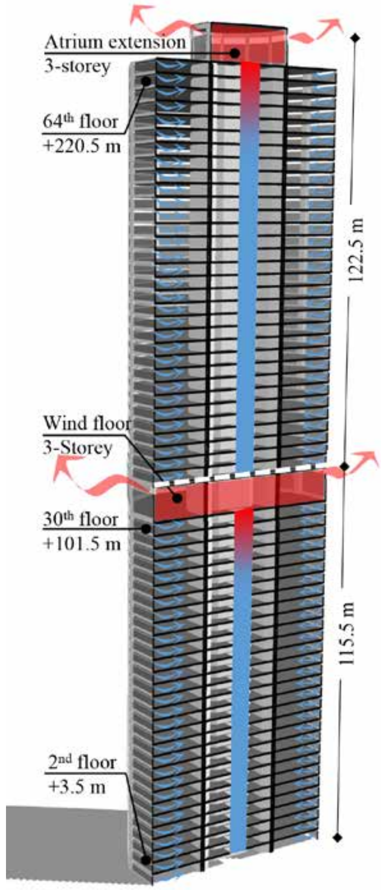
(b) NV#1: cross ventilation


Typical floor plans (reference)

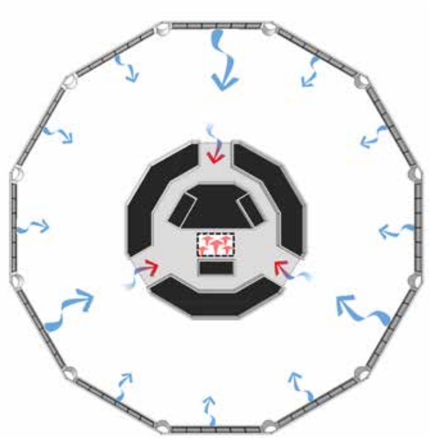

Typical floor plans (NV#1)



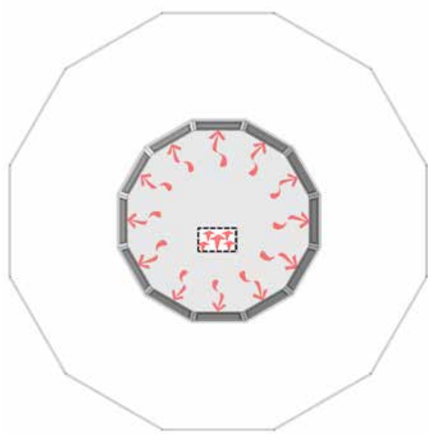
(c) NV#2: stack ventilation



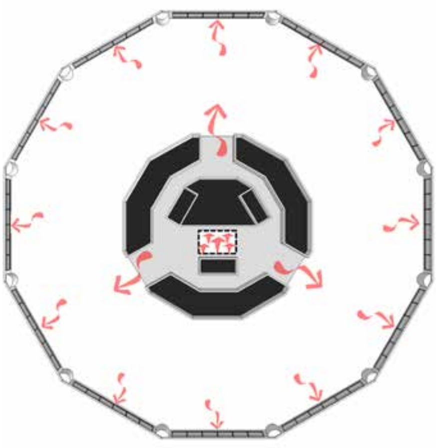
(d) NV#3: stack ventilation



Typical floor plans (NV#2 & NV#3)

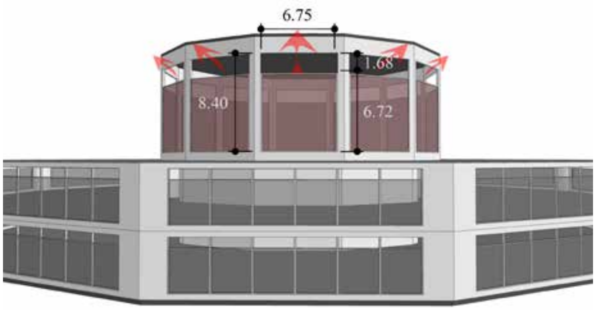


Atrium extension (NV#2 & NV#3)

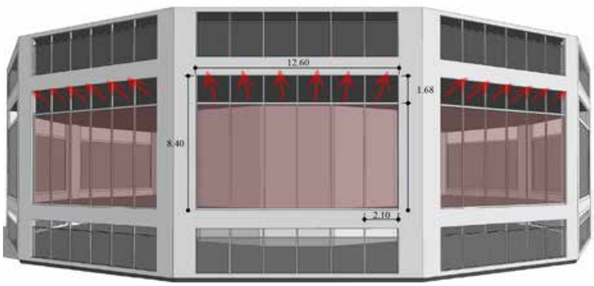


Wind floor (NV#3)

FIGURE 5.20 Proposed ventilation strategies and the reference design. Arrows show the intended flow pattern within the ventilated spaces on a typical floor plan and through the building height.



(a) Rooftop extension of the central core in NV#2 & NV#3 (20% operable external windows)



(b) Wind floor in NV#3 (20% operable external windows)

FIGURE 5.21 The size of external windows and the openable area on (a) rooftop extension, and (b) wind floor.

§ 5.9 Results and discussion

§ 5.9.1 Indoor comfort

Thermal comfort and fresh air are among the main indoor comfort indicators. Using natural driving forces, comfort conditions can be improved to a different extent depending on the design and local weather conditions. Three ventilation strategies were simulated in the EnergyPlus calculation core of DesignBuilder. The amount of discomfort hours during the occupancy time in one year determines the number of hours that active cooling or mechanical ventilation is necessary to provide comfort conditions on the test floors. A lower number of discomfort hours means that the ventilation strategy performs better, hence saves more energy.

§ 5.9.1.1 Fresh air changes

The percentage of hours in which the ac/h was equal to or higher than the minimum required value (0.92 ac/h) was obtained for the test floors (2^{nd}, 30^{th}, and 64^{th}) at different heights, as shown in Table 5.7. This table shows the percentage of time during office hours (8:00 – 17:00) in which natural ventilation alone can meet the minimum requirement for fresh air and, therefore, supplementary mechanical ventilation is not needed. Windows are scheduled to be constantly open during the occupancy time. It is probable that when the required fresh air cannot be generated it is due to low wind speed and the failure of the NV strategy to increase the flow rate in such conditions.

NV STRATEGY	Base floor (2^{nd})	Middle floor (30^{th})	Upper floor (64^{th})	Average value
NV#1	90.4%	99.9%	100%	96.8%
NV#2	99.8%	100%	96.8%	98.9%
NV#3	100%	100%	99.5%	99.8%

TABLE 5.7 The percentage of hours when natural ventilation can provide the minimum fresh air on the test floors for three ventilation strategies in the year 2004.

The simulation results for the ventilation strategies are quite promising. The need for mechanical ventilation is reduced to less than 4% of the occupancy hours when taking the average value of the three test floors, while no test floor has a value lower than 90%. The need for mechanical ventilation is different depending on the location of the test floor and the driving force for natural ventilation. The results show that NV#3 and NV#2 can provide the minimum fresh air requirement during a higher percentage of occupancy time. This can be attributed to the application of a vertical shaft that enhances supply of fresh air in a calm day with no particular wind. The best performance, however, is achieved by using a natural ventilation strategy with a segmented atrium (NV#3). Segmenting the atrium can minimise the variation of the fresh air entry rate on different floors (Etheridge & Ford, 2008), as compared to a full-height atrium. The results show that the top floor of a building that employs a full height atrium (NV#2) needs supplementary mechanical ventilation during a higher percentage of occupancy time (about 3%) than a segmented atrium. However, the segmentation of the vertical shaft may limit the full effect of buoyancy and result in a reduction of indoor air velocity on particular levels.

Among all ventilation strategies, the base floor (2^{nd}) in NV#1 is in highest demand for mechanical ventilation by around 10% of the occupancy hours, while there is no need for a supplementary mechanical system on the middle and upper floors (30^{th} and 64^{th}). In NV#2 and NV#3, the top floor (64^{th}) needs mechanical ventilation for a higher percentage of occupancy time. When the stack effect is the dominating driving force for natural ventilation (in the absence of wind), the air that enters the upper floor comes from the shaft and is therefore stale air. As a result, it could be questionable to use this air as fresh air. In such conditions, the integration of sky gardens into atrium -for air supply and exhaust- and segmentation of atrium along the building height are passive strategies that can effectively reduce stale air accumulation on the upper floors. When comfort conditions are not achievable through passive techniques, an assistant mechanical ventilation system besides natural ventilation might be essential for certain floors depending on the physical mechanism driving the air movement during some periods in the course of a year in the tropical climates; the lower floors of a building with a wind-induced ventilation strategy, and the middle floors (and the upper floors) of a building with a buoyancy-induced ventilation strategy. The 3% higher demand for mechanical ventilation on the top floor compared to the middle floor of this building with a full height atrium is probably caused by design specifications of this particular building; otherwise it is generally expected to have lower air exchange through the windows at the height close to the neutral pressure plane.

§ 5.9.1.2 Comfort temperature

The average percentage of thermal comfort hours is calculated for the proposed NV strategies at different test floors in one year. The results are presented for two sets of acceptability limits as shown in Figure 5.22. The 80% acceptability limits are for normal expectations that introduce a boundary around the comfort temperature of ±3 K. When a higher standard of thermal comfort is desired, the 90% acceptability limits can be used that involve a narrower comfort temperature range of ±2 K.

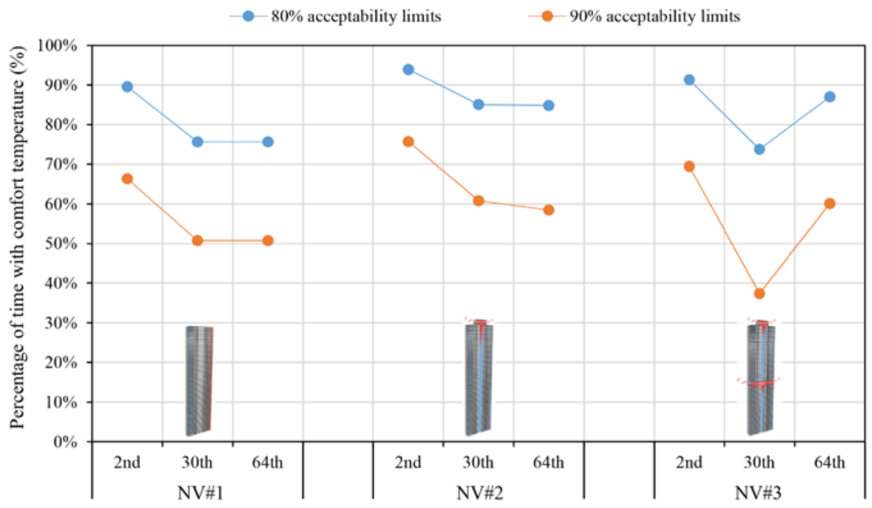


FIGURE 5.22 The average percentage of thermal comfort hours for three ventilation strategies on the proposed test floors based on 80% and 90% acceptability limits.

If the wider comfort temperature range (±3 K) is selected, natural ventilation strategies will be able to keep the indoor temperature within the comfort limit during the majority of occupancy hours (ranging from 74% to 94%). Depending on the location of the test floors, in NV#1, the number of comfort hours is between 76%-90%. The results show that adding a vertical shaft into the central core (NV#2 and NV#3) can extend the percentage of comfort hours by up to 10%. The highest number of comfort hours is achieved by using a full height atrium (NV#2). The three test floors, in NV#2, have a temperature which is comfortable for 85-94% of the occupancy time. For the same ventilation scenario, these figures will reduce to a range between 58-76% if the narrower comfort temperature range (±2 K) is selected.

In NV#2 and NV#3, the heat stratification through the vertical shaft results in higher indoor temperatures on the upper floors in comparison with the lower zones. For this reason, the upper floors have a lower percentage of comfort hours. In NV#2, the percentage of comfort hours on the top-level is lower than on the base-level by around 9% and 18% respectively, with 80% and 90% acceptability limits. Generally, for all NV strategies, the middle floors have thermal conditions almost similar to the upper floors, with the exemption of NV#3. In NV#3, the middle floor is directly located under the wind floor level where the atrium is segmented, and therefore the indoor air temperature on this floor is highly influenced by the high temperatures of the floor above it and the warm stale air that enters this floor through the shaft. As a result, the mid-floor has the lowest percentage of comfort hours among the three test floors in NV#3. With the narrower comfort temperature range, the percentage of comfort hours for the mid-level in NV#3 is 14% less than in NV#1, and 24% less than in NV#2. In NV#3 with a segmented atrium, the number of comfort hours on the upper test floor is higher than on the middle one. This can be explained by a further distance (one storey or 3.5 meter) between the 64th storey and the location of air outlets on top of the vertical shaft (at atrium extension level) as compared to the 30th storey which is located in close proximity to air outlets on the wind floor. In NV#3, the top floor has the highest value of comfort among the top-floors in all NV strategies. This shows that segmentation of the vertical shaft might reduce the uncomfortable conditions on the upper floors. However, it is important to increase the height of the wind floor to more than 3 stories (10.5 m) or add more segmentations along the building height to lessen the effect of heat stratification on the top floors and to reduce the wind speeds inside the atrium.

When the outdoor air temperature is higher than the indoor air temperature, higher fresh air changes can cause lower number of comfort hours, and vice versa. In NV#1, the base floor has a higher percentage of comfort hours, which can be related to inefficiency of this ventilation scenario in an increasing velocity and fresh air supply at this floor. This is in line with the results of fresh air calculation that is presented in Table 5.7 (Section 6.8.1.1).

§ 5.9.2 Air flow patterns and indoor air temperature

The following section includes a detailed investigation on the NV strategies by using the CFD code in DesignBuilder. Under three weather scenarios, velocity and temperature simulations were carried out on the working planes at a height of 1.2 meter above the floor; again the 2nd, 30th and 64th floors were analysed. Accordingly, the average and maximum value of air velocity, and the percentage of floor area −excluding the service core – with an indoor air temperature higher than the upper comfort temperature range (based on 90% acceptability limits) was calculated for the three test floors. The comfort temperature was calculated using the adaptive equations for comfort in free running buildings (see Table 5.8).

WEATHER SCENARIO	T_{out} (°C)	T_{comf} (°C)	$T_{comf-upper}$ (°C)
01 June / 17:00	29.5	28.0	30
20 May / 9:00	29	28.0	30
26 November / 12:00	30	28.1	30.1

TABLE 5.8 The outdoor air temperature (T_{out}), comfort temperature (T_{comf}), and the upper limit of the comfort temperature ($T_{comf-upper}$) based on the narrower comfort temperature range for the three weather scenarios.

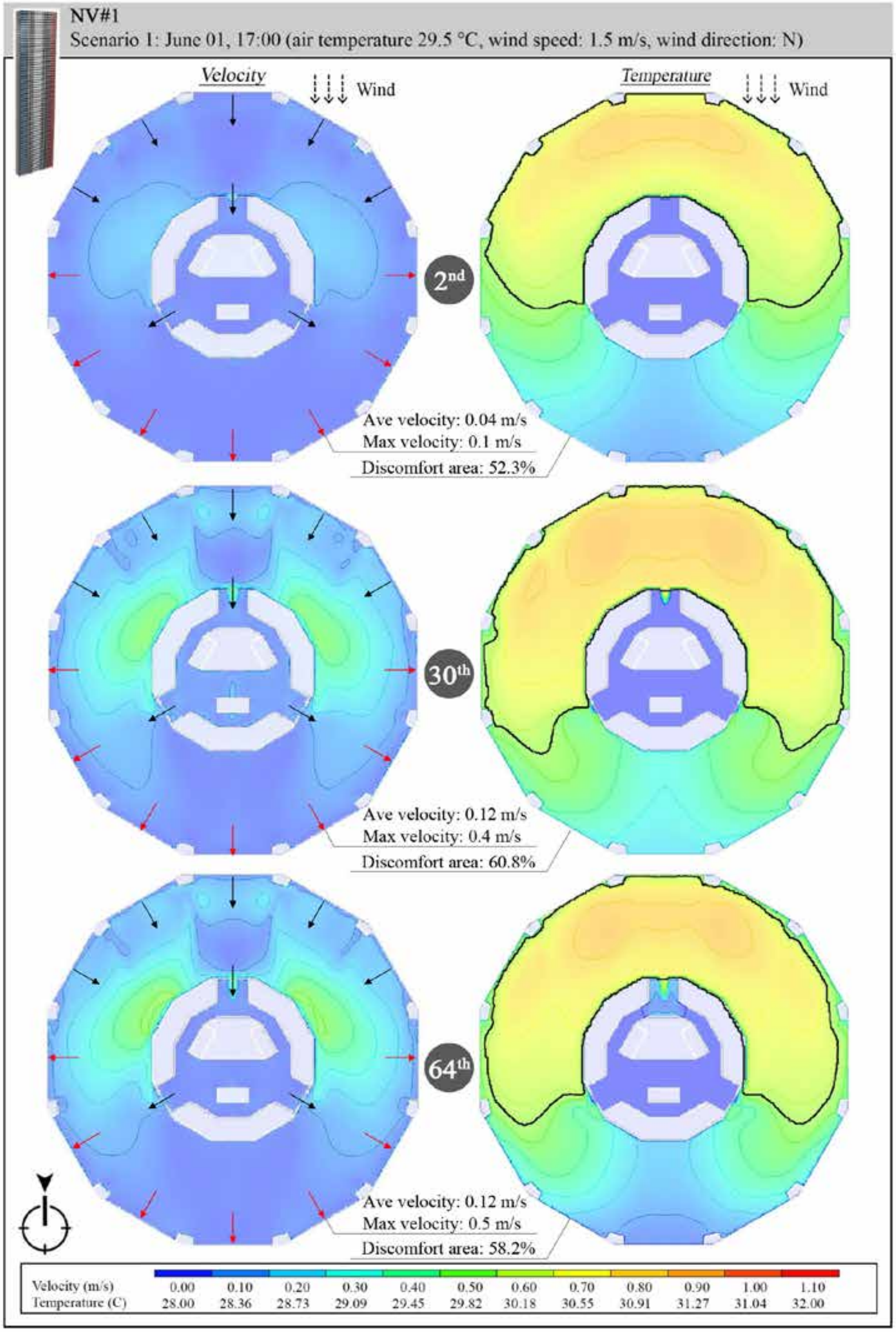
Since each category of air velocities has a different percentage value (of discomfort area), the weighted average method was used to calculate the average velocity on the working planes. In order to calculate the average weighted value, each category value (of air velocities) was multiplied by its percentage (of its share from the total area) and then all the values were added together. In this study, the internal surface temperatures for each surface in the domain and the airflow rates through open windows, vents, doors and holes were calculated first using an EnergyPlus simulation which was then imported as boundary conditions for the internal CFD analysis. Generally, in hot and humid climates, an indoor air movement of up to 1 m/s is pleasant. Even higher velocities may be perceived as acceptable by the occupants as they can help to extend the comfort temperature limits (Szokolay, 1997).

§ 5.9.2.1 Scenario 1 (average wind speed)

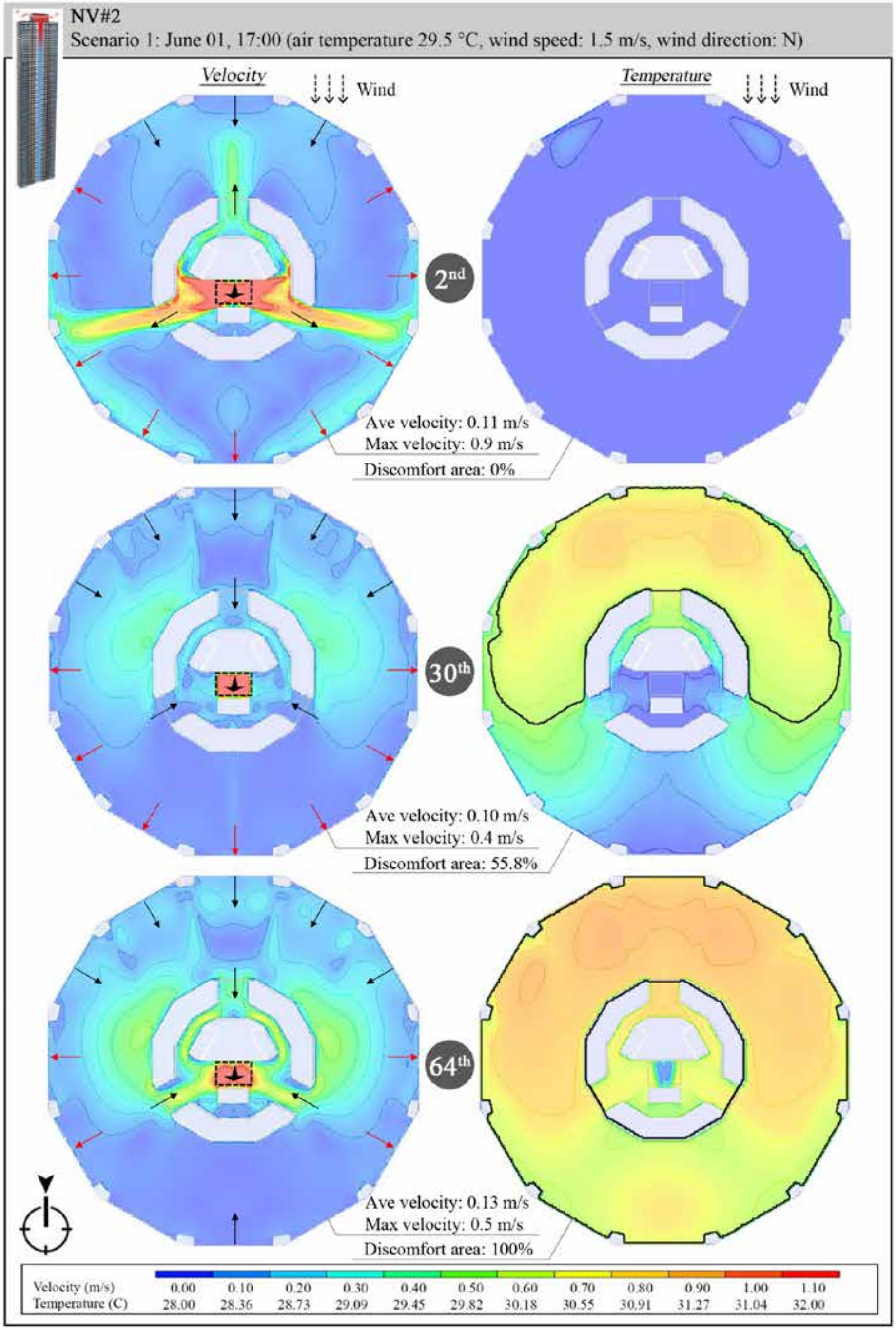
The first scenario represents a typical weather condition in George Town: a wind speed of 1.5 m/s coming from the prevalent direction (north) and an outdoor air temperature of around 29.5 °C. w 5.23 shows the air velocity and the temperature contours for different natural ventilation scenarios on three test floors at different levels: base level (2nd floor), mid-level (30th floor), and top-level (64th floor). In NV#1, the pressure differentials between the openings on the windward and leeward sides are the driving force for natural ventilation. However, the floor plates are too deep for natural ventilation to reach deep zones. Therefore, the areas of higher velocities would be limited to the office zones that are located between the external windows and the service core on the northeast and northwest of the floor plan. Moreover, the pressure across the envelope increases at higher altitudes, therefore the top floors exhibit higher indoor air velocities. On the upper floor level and mid floor level in NV#2 and NV#3, the fresh air flows in through the openings on the windward side (north) and flows out mostly thought the openings on the leeward side and partially through the atrium. The results show there is a downward flow through the atrium, so that part of the used air of the upper levels flows into the lower levels through the vertical shaft. A reverse stack effect occurs when the outdoor air temperature is higher than the indoor air temperature (Wood & Salib, 2013). The existence of this reverse flow could deteriorate the indoor air quality, especially for offices in the lower zones of the building. This scenario thus leads to a combination of cross ventilation with a small amount of reverse stack ventilation.

According to the CFD results, the average air velocities on the working planes are in a range of 0.04-0.12 m/s in NV#1, 0.11-0.13 m/s in NV#2, and 0.09-0.12 m/s in NV#3. In regards to average air velocities (on the middle and upper floors in particular), no significant differences are found between the performance of ventilation strategies with or without a vertical shaft, under typical weather conditions. This is due to a number of reasons such as small differences between indoor and outdoor air temperature (and therefore limited stack effect), and presence of wind (1.5 m/s). The combination of these factors makes the buoyancy force play a minor role in driving the natural ventilation. The maximum velocities on the base floor (2nd) in NV#2 and NV#3 are nine times of the maximum velocity on the equivalent floor in NV#1 due to the formation of pressure gradients along the vertical shaft. However, the air distribution is not uniform throughout the entire plan and there are areas with particularly higher velocity such as in the corridor openings and their adjacent external windows. Slight differences can be observed between the performance of a full-height and a segmented atrium. The application of a full-height atrium (NV#2) can increase the average velocity slightly more than a segmented atrium design (NV#3); by around 0.02 m/s for the base floor and around 0.01 m/s for the top floor.

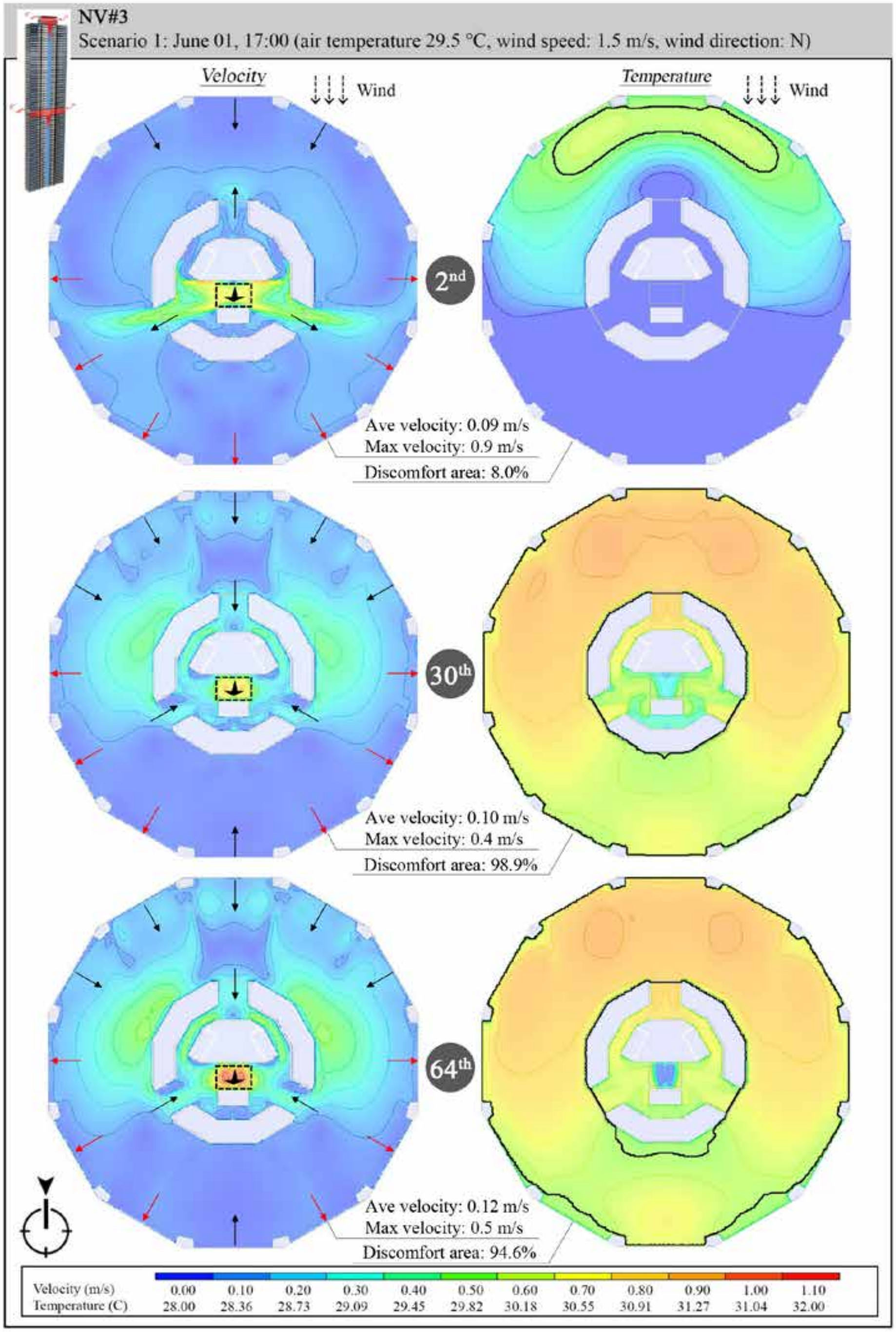
The CFD study of the temperature distribution shows that areas of the office zone close to the external windows on the northern part of the plan, where fresh air is entering the building, have a higher temperature that exceeds the upper limit of the comfort range (30 °C) in weather scenario 1. In NV#1, the average discomfort percentage is about 60% which is almost within the same range among all floors at different heights. In NV#2 and NV#3, the majority of office areas on the base floor are within the comfort range. In a full-height atrium, the agglomeration of heat on the top levels causes the highest percentage of discomfort (100%) to be formed on the upper floor. In NV#3, both the 64th and 30th floors are located at close distance from the air outlets of the vertical shaft. As a result, the middle floor has the same comfort conditions as the top floor in NV#3, with almost the entire apace within the discomfort range. Our findings show that there is a certain degree of difference between the results from the two modelling tools (EnergyPlus and CFD). Generally, EnergyPlus and CFD provide a very different approach to the modelling of natural ventilation. In particular, horizontal and vertical stratification are not taken into account in most of the EnergyPlus airflow models. When using the EnergyPlus model, the average operative temperature of the entire office zone was used for the calculation of thermal comfort conditions on each test floor. However, by using the CFD model, air temperatures at the individual points throughout the working plane can be generated which let to measure the areas of comfort in a relatively more accurate way.


NV#1
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.04 m/s
Max velocity: 0.1 m/s
Discomfort area: 52.3%
30th
Ave velocity: 0.12 m/s
Max velocity: 0.4 m/s
Discomfort area: 60.8%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.5 m/s
Discomfort area: 58.2%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(a) NV#1


NV#2
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.11 m/s
Max velocity: 0.9 m/s
Discomfort area: 0%
30th
Ave velocity: 0.10 m/s
Max velocity: 0.4 m/s
Discomfort area: 55.8%
64th
Ave velocity: 0.13 m/s
Max velocity: 0.5 m/s
Discomfort area: 100%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2


NV#3
Scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed: 1.5 m/s, wind direction: N)
Velocity
Wind
Temperature
Wind
2nd
Ave velocity: 0.09 m/s
Max velocity: 0.9 m/s
Discomfort area: 8.0%
30th
Ave velocity: 0.10 m/s
Max velocity: 0.4 m/s
Discomfort area: 98.9%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.5 m/s
Discomfort area: 94.6%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

FIGURE 5.23 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 1.5 m/s and outside air temperature of 29.5 °C (June 01, 17:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

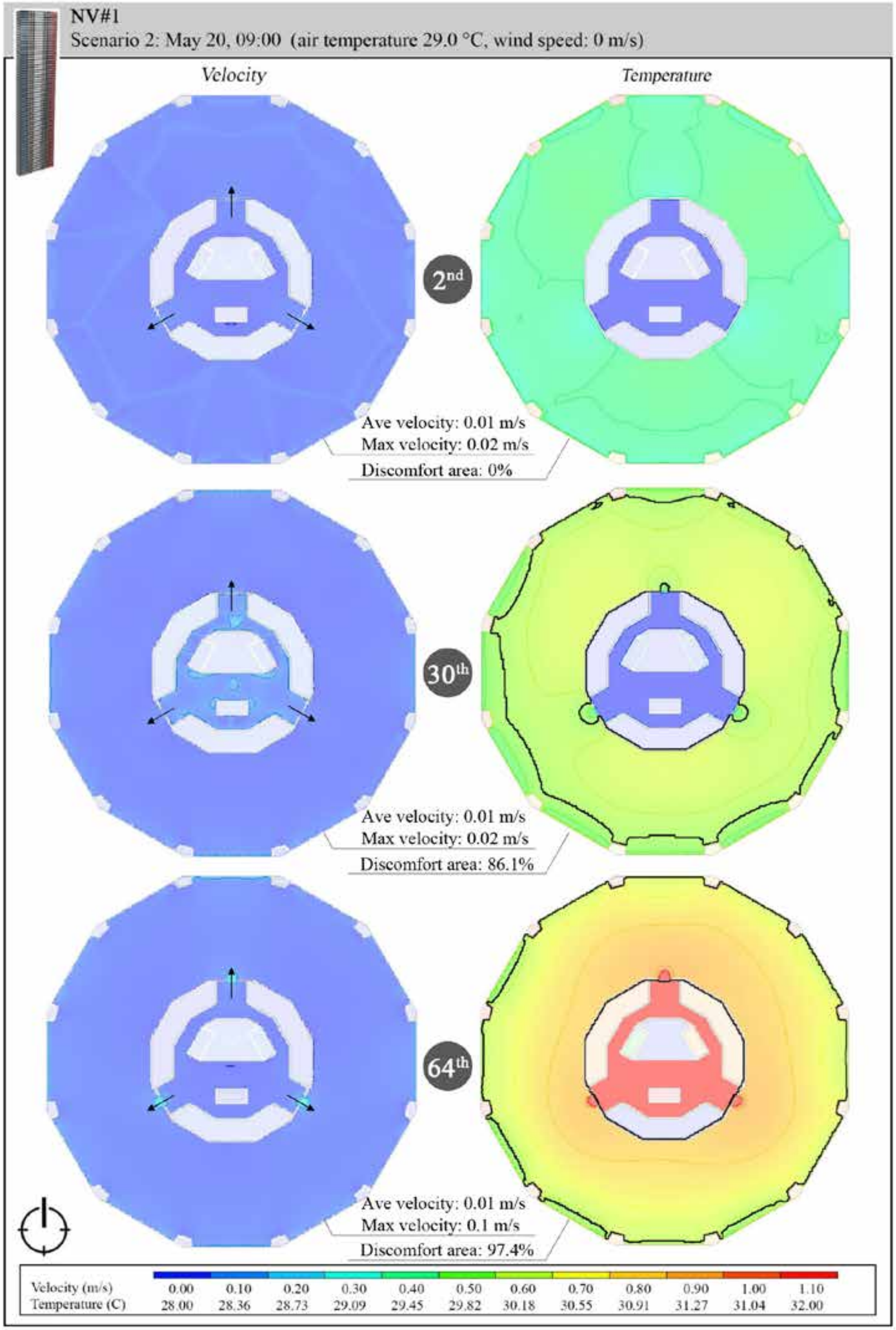
§ 5.9.2.2 Scenario 2 (no wind)

In scenario 2, the effectiveness of the buoyancy-induced versus the wind-induced ventilation was tested on a calm day with no wind. CFD simulations were carried out for an early morning hour (9:00) when the outdoor air temperature was around 29 °C. During the operation of the windows for natural ventilation (8:00-17:00), the outdoor air temperature is most likely to be most of the time higher than the indoor air temperature. The only time period when the outdoor air temperature is lower than the indoor air temperature is during early morning hours, usually between 8:00 to 10:00. The results show that when the indoor air temperature exceeds the outdoor temperature, an upward airflow will form in the vertical shaft in NV#2 and NV#3. This is caused by the formation of an under-pressure zone in the lower levels of the building, which pulls air inwards through the openings on the external façade. As the air moves through the building height it gains heat (by equipment and occupants) and creates an over-pressure zone at the top of the building. The differences in density between the indoor and outdoor air results in a different pressure gradient across the height of the building. The over-pressured areas at the top of the building drive air out of the openings, while the under-pressured areas at the base of the building pull air inwards through the openings. In case of NV#2 the height of the neutral pressure plane is at around 116 m above the ground, which is roughly halfway the height of the building.

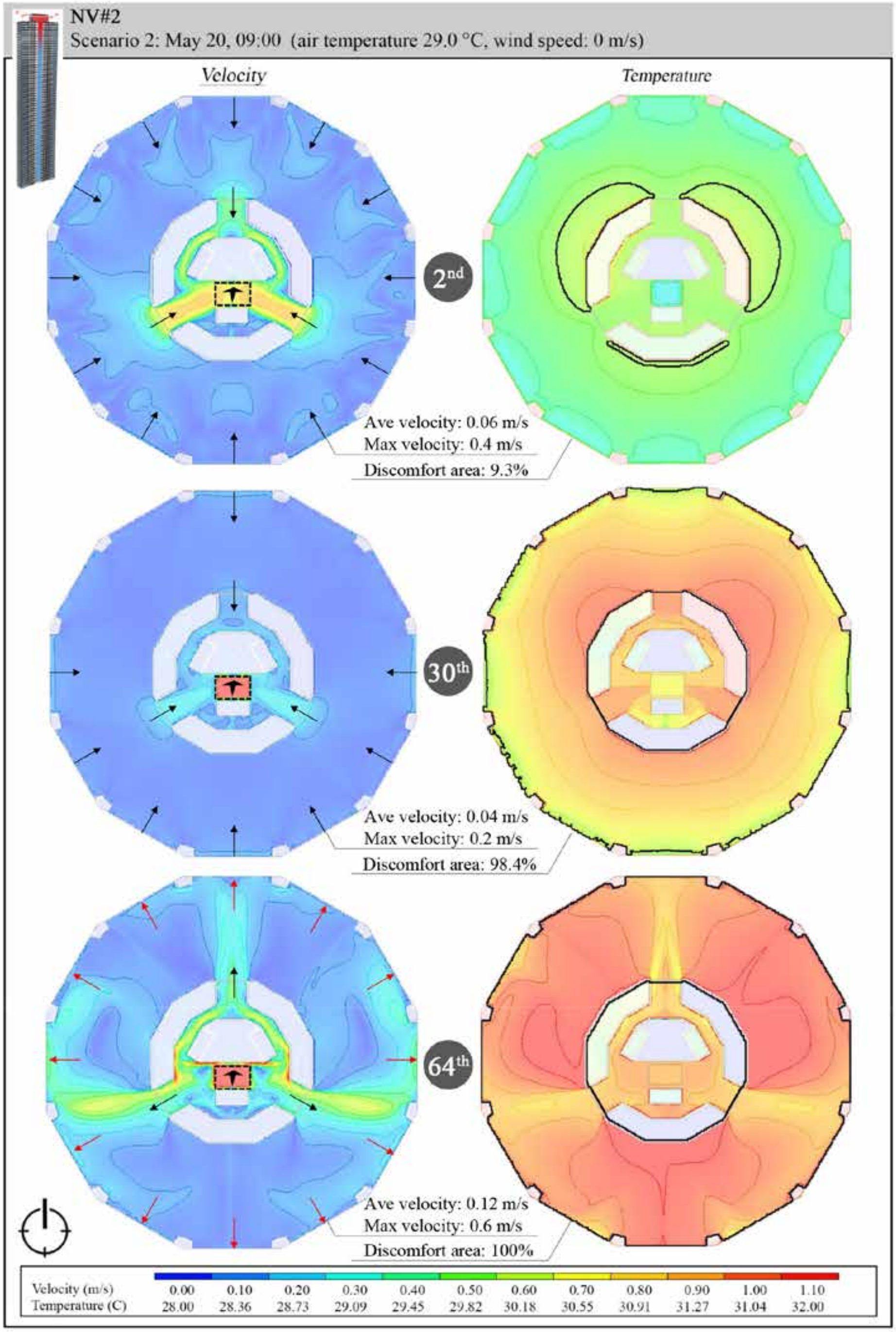
In the absence of wind, cross ventilation will hardly occur (NV#1). Moreover, in order to achieve effective cross ventilation, the room depth should not exceed roughly five times its height (Wood & Salib, 2013). In case of the KOMTAR building this ratio is about three times higher than recommended. In NV#1, the average air velocity is equal to or less than 0.01 m/s on the three test floors. The results show that the application of the vertical shaft can increase the average velocities in a range between 0.04-0.12 m/s in NV#2, and 0.05-0.08 m/s in NV#3. This shows that the stack effect is the dominating driving force for natural ventilation in scenario 2. Furthermore, on a calm day stack ventilation is able to increase the indoor air velocity better than wind-driven ventilation.

A full height atrium (NV#2) in comparison to a segmented atrium (NV#3), can make higher pressure differentials along the vertical shaft and therefore it can induce higher indoor air velocities on the base floor and the top floor. At mid-height (30th floor), however, the average and maximum velocities are lower in NV#2 compared to NV#3. The reason is that this floor is located at a close distance from the neutral plane (32^{nd} floor in case of NV#2), so that the indoor pressure and the outdoor pressure are almost equal to each other at this height in NV#2. Ventilation short circuits can be observed in the over-pressured areas on the upper levels such as the 64^{th} floor in NV#2, or 30^{th} and 64^{th} floor in NV#3. Generally, air flows through the path of least resistance, so the areas of plan that are closer to the corridor openings exhibit higher air velocities. In this study, the effect of occupants and furniture layouts on air flow patterns are not taken into account for the office zones. Adjusting the layout of the furniture might be an effective solution to avoid short circuiting of natural ventilation.

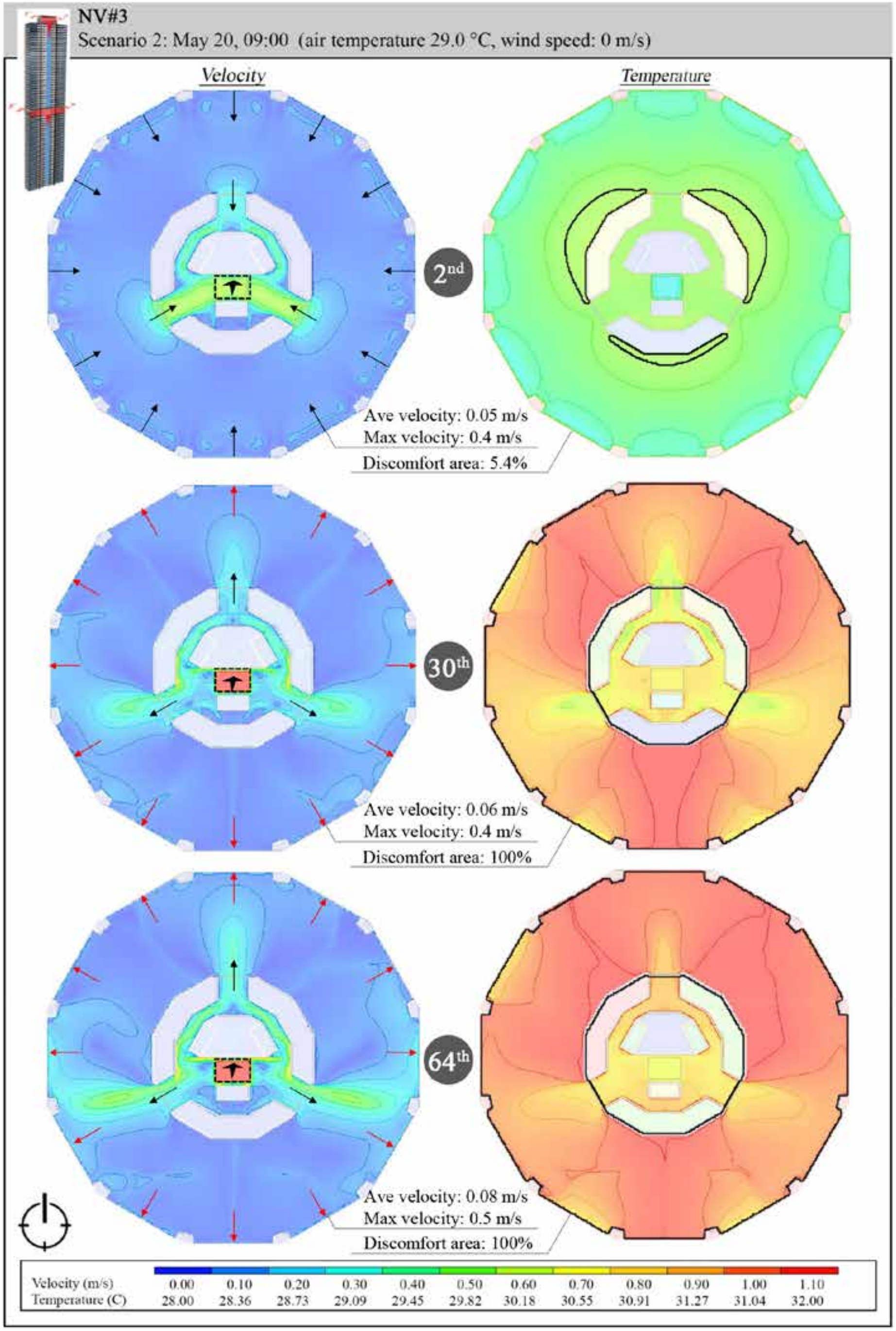
On the base level (2^{nd}), the indoor air temperature is within the comfort boundaries for the majority of the office zone, while on the higher levels (30^{th} and 64^{th}), the indoor temperatures are beyond the upper limits of comfort temperature (30 °C) for almost the entire zone. During the morning hours, the cooler air flows inside the building through the openings on the lower floors and decreases the warmer indoor air temperature. The used (and warmed) air subsequently is being sucked out through the vertical shaft and exits the building from the openings on the upper floors, so that the upper levels would have a higher percentage of discomfort area. The results indicate that the average indoor air temperature for the three test floors in weather scenario 1 (June 01, 17:00) is relatively lower than the equivalent floors in scenario 2 (May 20, 09:00), despite a higher outdoor air temperature (0.5 °C) on June 1. In tropical climates, outdoor air temperatures are close to the upper comfort temperature range (or sometimes even higher). While lightweight constructions respond quickly to cooling breezes, heavyweight constructions delay the decrease of indoor air temperature. The heavyweight concrete structure of the KOMTAR building, besides the absence of wind, might be the reason for a higher percentage of thermal discomfort during the morning hours in scenario 2.


NV#1
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.01 m/s
Max velocity: 0.02 m/s
Discomfort area: 0%
30th
Ave velocity: 0.01 m/s
Max velocity: 0.02 m/s
Discomfort area: 86.1%
64th
Ave velocity: 0.01 m/s
Max velocity: 0.1 m/s
Discomfort area: 97.4%
Velocity (m/s)
Temperature (C)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(a) NV#1


NV#2
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.06 m/s
Max velocity: 0.4 m/s
Discomfort area: 9.3%
30th
Ave velocity: 0.04 m/s
Max velocity: 0.2 m/s
Discomfort area: 98.4%
64th
Ave velocity: 0.12 m/s
Max velocity: 0.6 m/s
Discomfort area: 100%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2


NV#3
Scenario 2: May 20, 09:00 (air temperature 29.0 °C, wind speed: 0 m/s)
Velocity
Temperature
2nd
Ave velocity: 0.05 m/s
Max velocity: 0.4 m/s
Discomfort area: 5.4%
30th
Ave velocity: 0.06 m/s
Max velocity: 0.4 m/s
Discomfort area: 100%
64th
Ave velocity: 0.08 m/s
Max velocity: 0.5 m/s
Discomfort area: 100%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

TOC

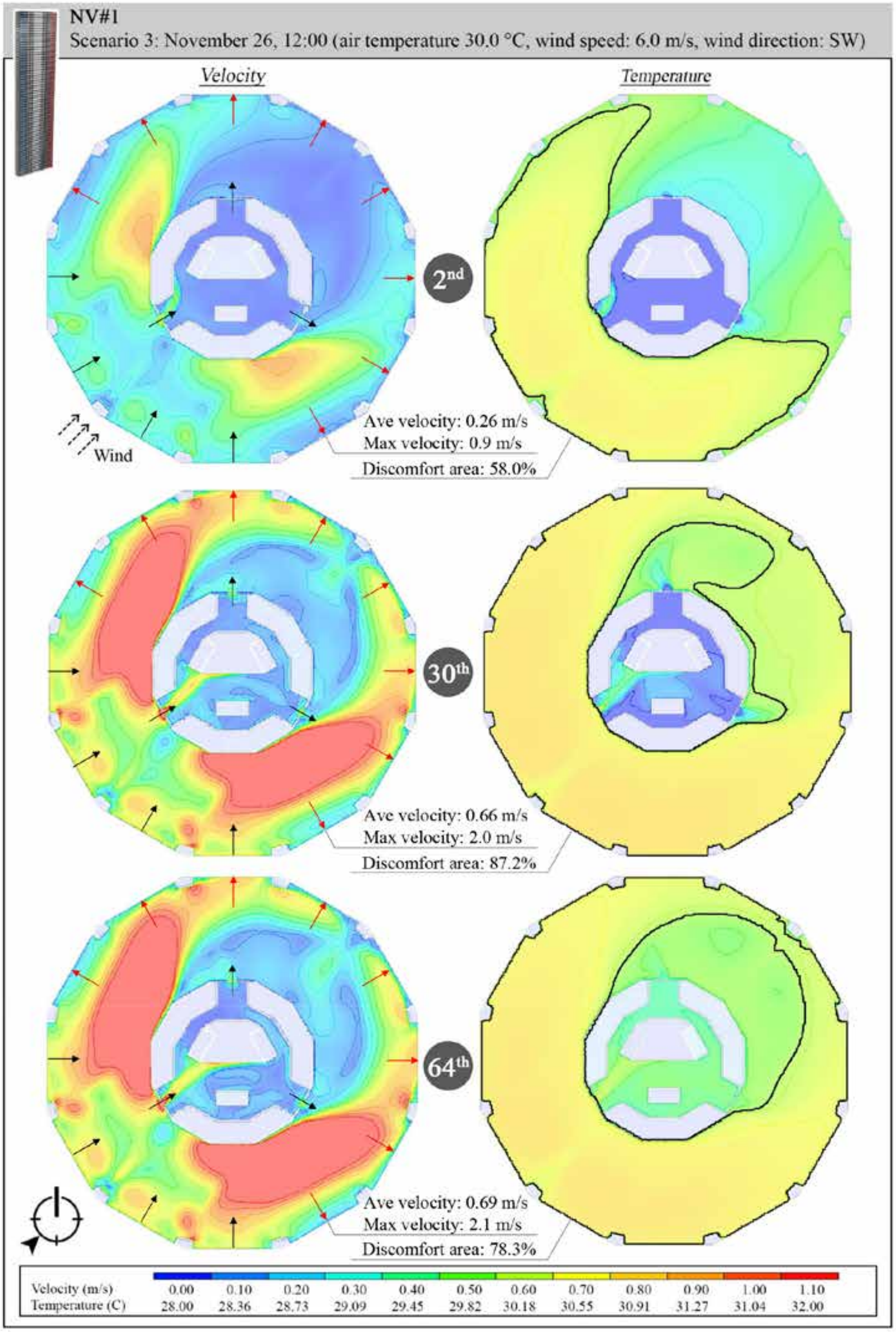
FIGURE 5.24 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 0 m/s and outside air temperature of 29.0 °C (May 20, 09:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

§ 5.9.2.3 Scenario 3 (high wind speed)

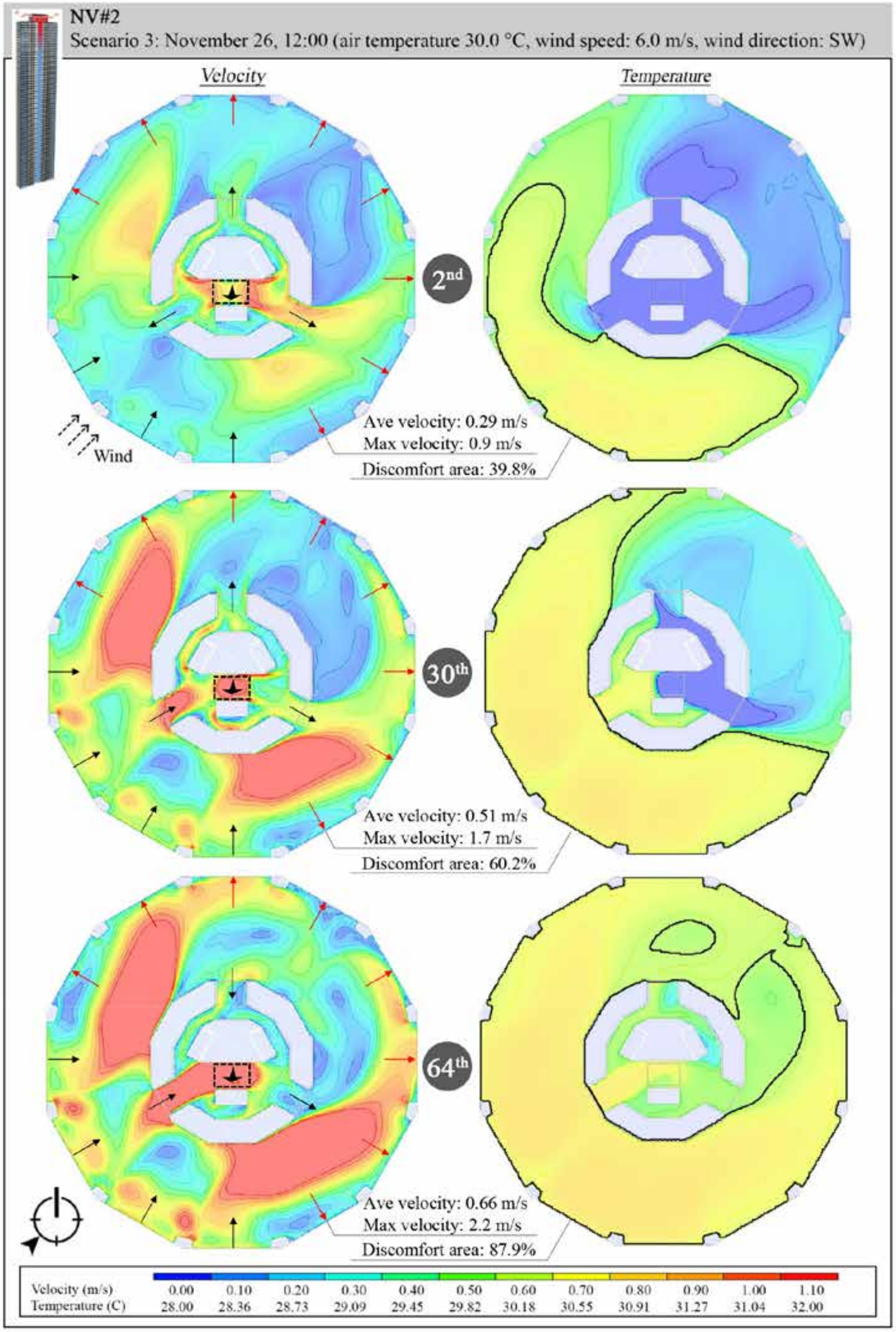
In scenario 3, the effectiveness of NV strategies was tested for extreme weather conditions when the wind speed is 6 m/s and it is coming from the south-west direction. Among all weather scenarios, the highest indoor air velocities are achieved in scenario 3. The average velocity reached a peak of 0.69 m/s in NV#1, while the maximum velocity reached a peak of 2.2 m/s in NV#2. The results show that the average and maximum velocities are significantly higher on the upper floor (64^{th}) and the middle floor (30^{th}) than on the base floor (2^{nd}) for all NV strategies.

In NV#2, the air in the atrium moves down whereas in NV#3 it moves up. In NV#3, the indoor air temperature is warmer than the outdoor air temperature which would suggest an upward movement. Furthermore, the results show that the air flow through the vertical shaft in NV#2 and NV#3 is being disrupted by high winds passing through the corridor from the windward side. As a result, the buoyancy force plays a minor role in driving the natural ventilation and the pressure differentials generated by wind are the dominating driving force on a windy day. A comparison of the indoor velocity results between the three NV strategies shows that the average velocity and maximum velocity are both lower by about 0.15 m/s and 0.3 m/s in NV#2 and NV#3 as compared to NV#1. This means that buoyancy slightly counteracts cross ventilation here.

Since the outdoor air temperature is higher than the indoor air temperature, fresh air enters the building and a higher percentage of the office zone will be under the influence of high temperatures. For this reason, the mid-floor in NV#1 has the maximum discomfort area (87.2%) in comparison with the equivalent floors in NV#2 and NV#3. Furthermore, the minimum and maximum discomfort area belongs to NV#2; the lowest discomfort area is achieved for the 2^{nd} floor (about 40%), while the highest discomfort area is achieved for the 64^{th} floor (about 88%).


NV#1
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Ave velocity: 0.26 m/s
Max velocity: 0.9 m/s
Discomfort area: 58.0%
Wind
30th
Ave velocity: 0.66 m/s
Max velocity: 2.0 m/s
Discomfort area: 87.2%
64th
Ave velocity: 0.69 m/s
Max velocity: 2.1 m/s
Discomfort area: 78.3%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

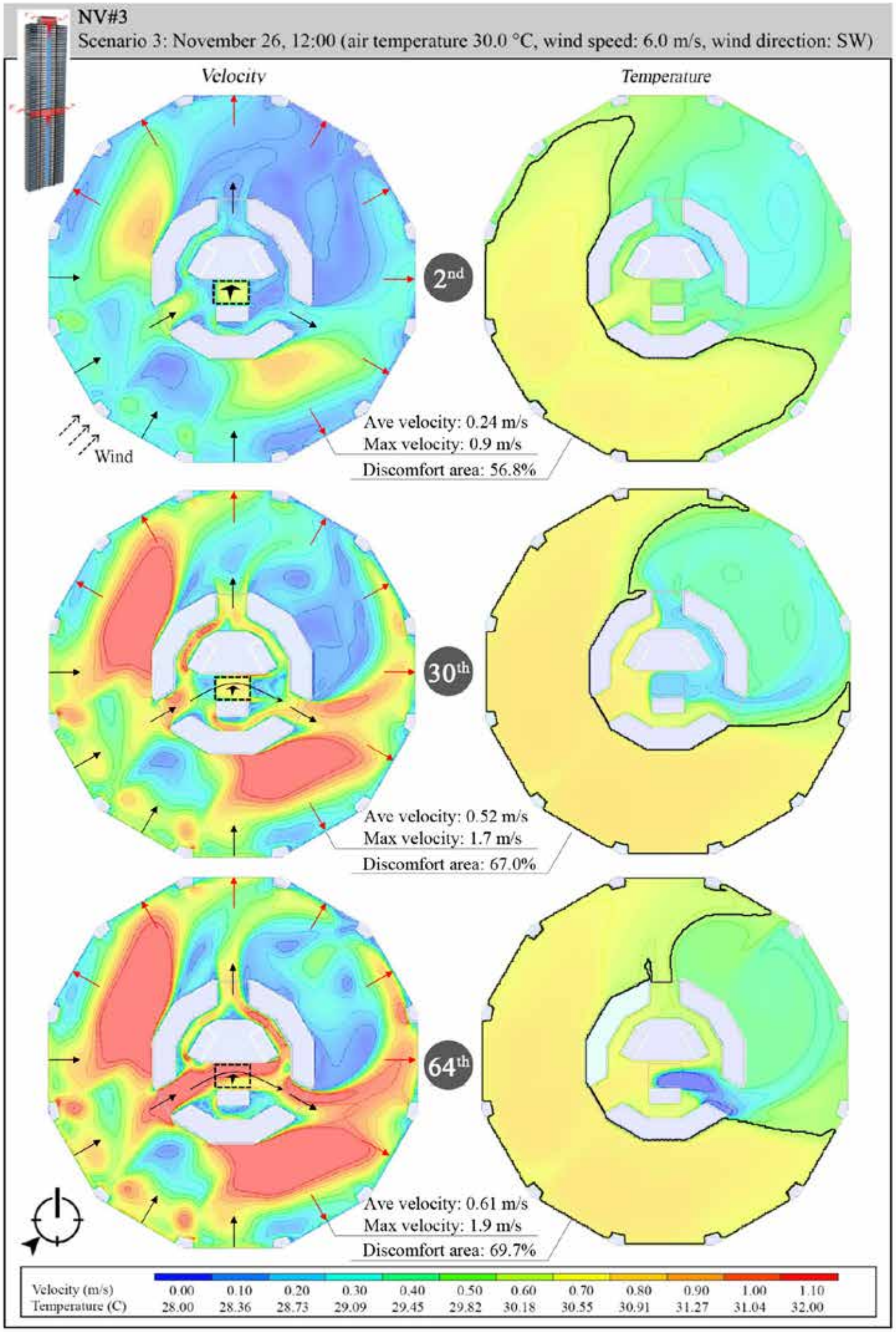
(a) NV#1



NV#2
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Wind
Ave velocity: 0.29 m/s
Max velocity: 0.9 m/s
Discomfort area: 39.8%
30th
Ave velocity: 0.51 m/s
Max velocity: 1.7 m/s
Discomfort area: 60.2%
64th
Ave velocity: 0.66 m/s
Max velocity: 2.2 m/s
Discomfort area: 87.9%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(b) NV#2

TOC


NV#3
Scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed: 6.0 m/s, wind direction: SW)
Velocity
Temperature
2nd
Wind
Ave velocity: 0.24 m/s
Max velocity: 0.9 m/s
Discomfort area: 56.8%
30th
Ave velocity: 0.52 m/s
Max velocity: 1.7 m/s
Discomfort area: 67.0%
64th
Ave velocity: 0.61 m/s
Max velocity: 1.9 m/s
Discomfort area: 69.7%
Velocity (m/s) 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
Temperature (C) 28.00 28.36 28.73 29.09 29.45 29.82 30.18 30.55 30.91 31.27 31.04 32.00

(c) NV#3

TOC

FIGURE 5.25 The magnitude and direction of air flow and air temperature through the plan for different ventilation strategies under wind speed of 6 m/s and outside air temperature of 30.0 °C (November 26, 12:00). Under the temperature header, an enclosed area within the black line represents the discomfort area.

§ 5.9.3 Cooling effect of elevated velocities

The physiological cooling effect of air movement through enhanced evaporation from the human skin is one of the most important passive control techniques in hot and humid climates. In order to calculate the potential cooling effect of elevated velocities, Szokolay's physiological cooling equation (Auliciems & Szokolay, 2007) is implemented.

$$\Delta T = 6\times(v-0.2) - 1.6\times(v-0.2)^2$$

Where ΔT (K) is the cooling effect by elevated air velocity, and v (m/s) is the air velocity at the body surface. This equation gives a numerical approximation of this cooling effect for velocities between 0.2 and 2 m/s. In Figure 5.26, the potential cooling effect of various velocities between 0.2-2 m/s is plotted by using Szokolay's equation. There is no cooling effect for velocities below 0.2 m/s. An increase of indoor air velocity till 2.0 m/s could extend the upper comfort limit by as much as 5.6 K. It is important to note that air velocities beyond 1.5 m/s can cause light objects such as papers to be blown away in the office area and therefore, it may override any desirable cooling effect (Szokolay, 1997). In this study, the maximum cooling effect of NV strategies to reduce thermal discomfort is calculated by taking velocities of up to 2 m/s.

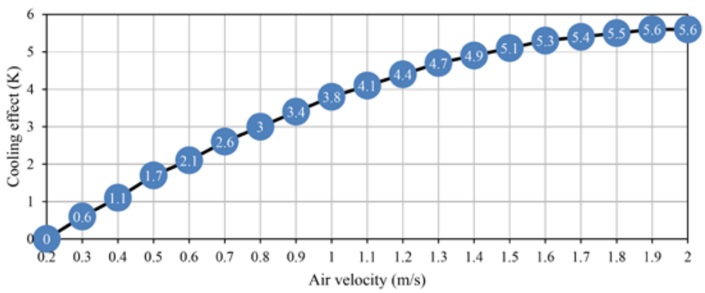


FIGURE 5.26 Cooling effect of elevated air velocity based on the physiological cooling model of Szokolay.

By using the results of Figure 5.26, the increased comfort area in the office zone on the three test floors due to elevated velocities is calculated for all ventilation strategies. The results are presented in Figure 5.27 (a, b, and c) for different weather scenarios. Additionally, in appendix 1 (a, b, and c), the graphical maps on the working planes show the exact locations of discomfort areas for the different NV strategies prior and after taking the physiological cooling effect of elevated velocities into account. The cooling potential of elevated velocities would be very limited when taking the wider comfort temperature range (±3 K). For this reason, for the calculation of the discomfort area, the narrower comfort temperature range (±2 K) was chosen. In case of the reference design with an air-conditioning system, the area of discomfort was calculated on different test floors for when the system is shut off. The indoor air temperatures for the entire office zone at different floors were higher than the adjusted cooling set point temperature (24 °C) under different weather scenarios.

In scenario 1 (Figure 5.27a), the increased area of comfort due to the cooling effect of elevated velocities is in a range between 7.9% and 22.1% depending on the effectiveness of a NV strategy for increasing the air flow on a particular floor. A wind-driven ventilation strategy (NV#1) is able to improve the comfort area on different test floors almost in the same range. The range of comfort area is increased from 39%-48% to 48%-64% when adding the cooling effect of elevated velocities. In case of the buoyancy-driven ventilation, the percentage of comfort area has a direct relationship with the location of the test floors alongside the vertical shaft. The base floor has the largest comfort zone amongst the test floors by around 100% of the floor area in NV#2 and 92% in NV#3. for the higher floors, the area of comfort reduces. The area of comfort is between 10%-20% for those three top floors that are located at close distance from the air outlets of the vertical shaft; 30th and 64th in NV#3 and 64th in NV#2.

In scenario 2 (Figure 5.27b), in the absence of wind, the indoor air velocity is very low. Higher velocities that can provide a cooling effect (higher than 0.2 m/s) only exist in over-pressured areas at the upper-levels of the building in NV#2 and NV#3. Due to ventilation short circuits in over-pressured areas, a small percentage of floor space can take the advantage of higher velocities. The increased comfort area is therefore about 6.8% in NV#2, and 2.7% in NV#3 for the upper floors. When there is no wind, the area of the office zone that has an indoor air temperature within the upper comfort limit of 30 °C is up to 14%, with the exception of lower-levels that have a higher comfort area. On the base floor, between 90%-100% of the total office area has an indoor temperature within the comfort boundaries.

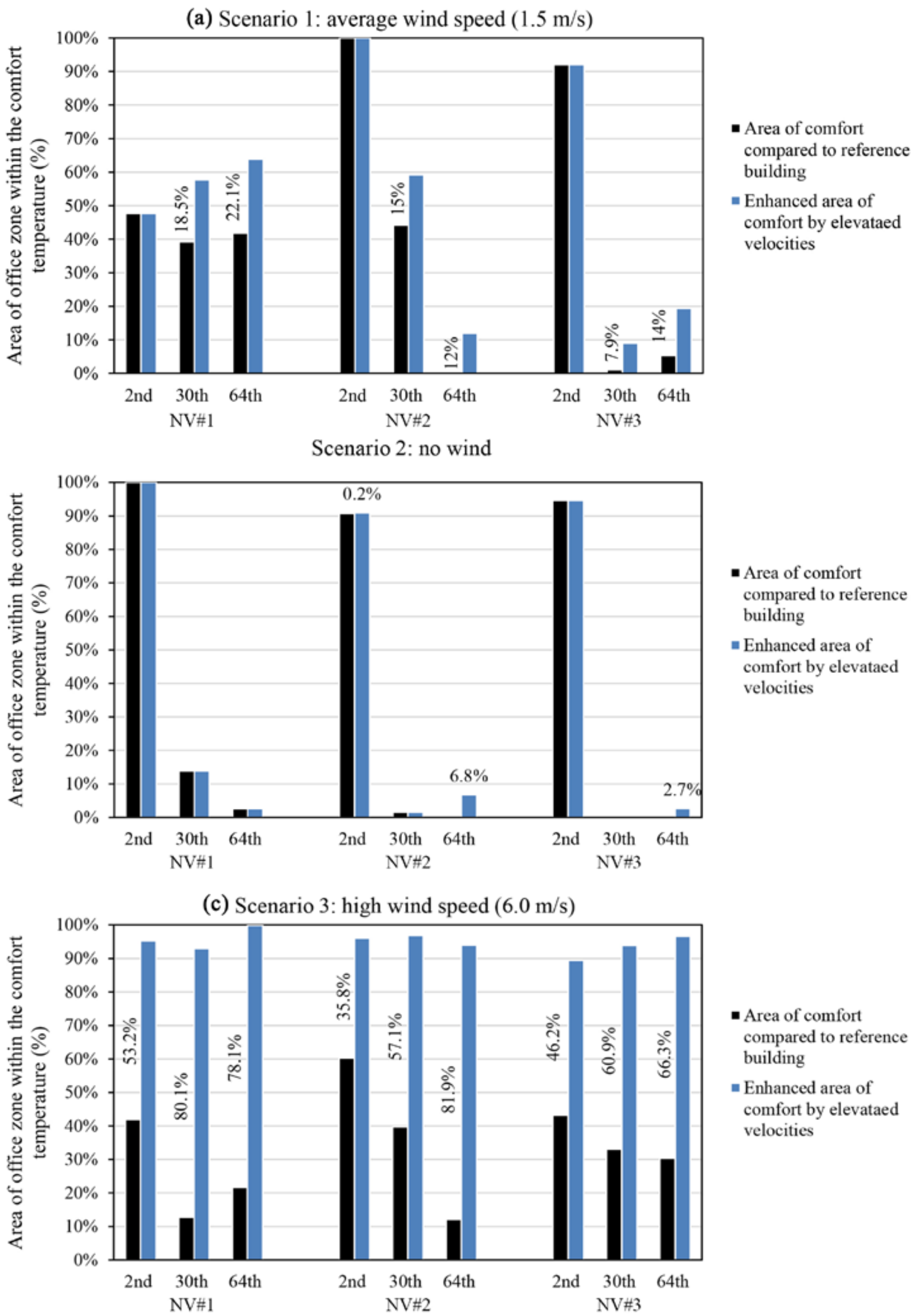


FIGURE 5.27 The increased area of comfort by the application of NV strategies and the enhanced cooling effect due to elevated velocities under three weather scenarios.

In scenario 3 (Figure 5.27c), the range of comfort area is increased from 12%-60% to 89%-100% when adding the cooling effect of elevated velocities by the application of NV strategies. This indicates the importance of elevated velocities for improving thermal comfort conditions in hot and humid climates. However, it should be noted that this high range of comfort is only possible during the rare periods of high wind speed.

§ 5.10 Conclusion

In this chapter the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation was investigated. The KOMTAR tower was selected as a conventional design for tall office buildings in the tropical climate. Three natural ventilation strategies were developed, and EnergyPlus combined with the CFD code in DesignBuilder, was employed for the purpose of investigation. It was found that on average between 96.8%-99.8% of the occupancy hours, natural ventilation strategies can meet the minimum fresh air requirements needed for an office space. However, an assistant mechanical ventilation system might be essential for up to 10% of the occupancy time on certain floors depending on the physical mechanism driving the air flow. Those floors that are in higher demand for mechanical ventilation are the lower floors of a building with a wind-induced ventilation strategy, and the middle floors of a building with a buoyancy-induced ventilation strategy.

Furthermore, the results showed that the application of natural ventilation strategies can considerably reduce the percentage of the occupancy time when air-conditioning is required for space cooling in the reference building: between 80%-88% for the wider comfort boundaries and between 56%-65% for when selecting the narrower comfort boundaries. The following natural ventilation strategies have the highest to lowest number of comfort hours: buoyancy-driven ventilation using a full height atrium (NV#2), buoyancy-driven ventilation using a segmented atrium (NV#3), and wind-driven ventilation (NV#1). However, in practice the demand for mechanical ventilation and cooling can increase to a higher level when considering the influence of other factors such as surrounding buildings, undesirable outdoor conditions (noise, air pollution, high humidity and wind speed) and occupant behaviour on the operation of natural ventilation.

In the next step, CFD simulations were employed to investigate the potential use of ventilation alternatives to extend thermal comfort by using Szokolay's physiological cooling equation. With the application of NV strategies, the average percentage (at different floors under different weather scenarios) of comfort area (based on 90% acceptability limits) increased to 25% in NV#1, 39% in NV#2, and 33% in NV#3. The area of comfort can be extended further when adding the physiological cooling effect of elevated velocities. The results showed that the increased area of comfort due to elevated velocities were 53% in NV#1, 62% in NV#2, and 55% in NV#3.

In this study, the performance of three test floors connected to a ventilation shaft was tested for the situation that the shaft is connected to only three floors. The indoor velocity and temperature might therefore be slightly different from the situation in which the vertical shaft is connected to a large number of floors along the building height. Additionally, for the study of a segmented vertical shaft, the middle floor (30^{th}) might not be a good representative of a mid-level floor for the purpose of comparison with the other two strategies as it is located at close proximity to the air outlets on the wind floor. However, for the reason of keeping the outdoor conditions (e.g. temperature and wind) the same among NV strategies, the location of the proposed test floors was kept unchanged. So, the average comfort level of the three test floors in NV#3 might be underestimated due to a lower performance of the 30^{th} floor.

In tropical climates, wind speeds are low, stack effects are small and outdoor air temperatures are close to the upper comfort temperature limits. All these factors make the implementation of natural ventilation strategies more challenging in this climate. Increasing the indoor velocity is essential for achieving thermal comfort conditions in such a climate. Greater velocities could extend the upper comfort limit by up to 5.6 K due to enhanced evaporation from the human skin. The design of tall buildings (external envelope and internal layout) should be able to facilitate the air flow across the interior spaces. In this regard, curved or funnel-shaped structures can be used to lead the wind in desired directions. Another effective strategy to capture wind from a wide range of directions is through the outward extension of walls (wind wing walls) when site limitations do not allow to orient the building along the prevailing wind axes. Finally, a natural ventilation strategy that employs wind and buoyancy driving forces together can provide greater chances of having higher indoor velocities under different wind conditions.

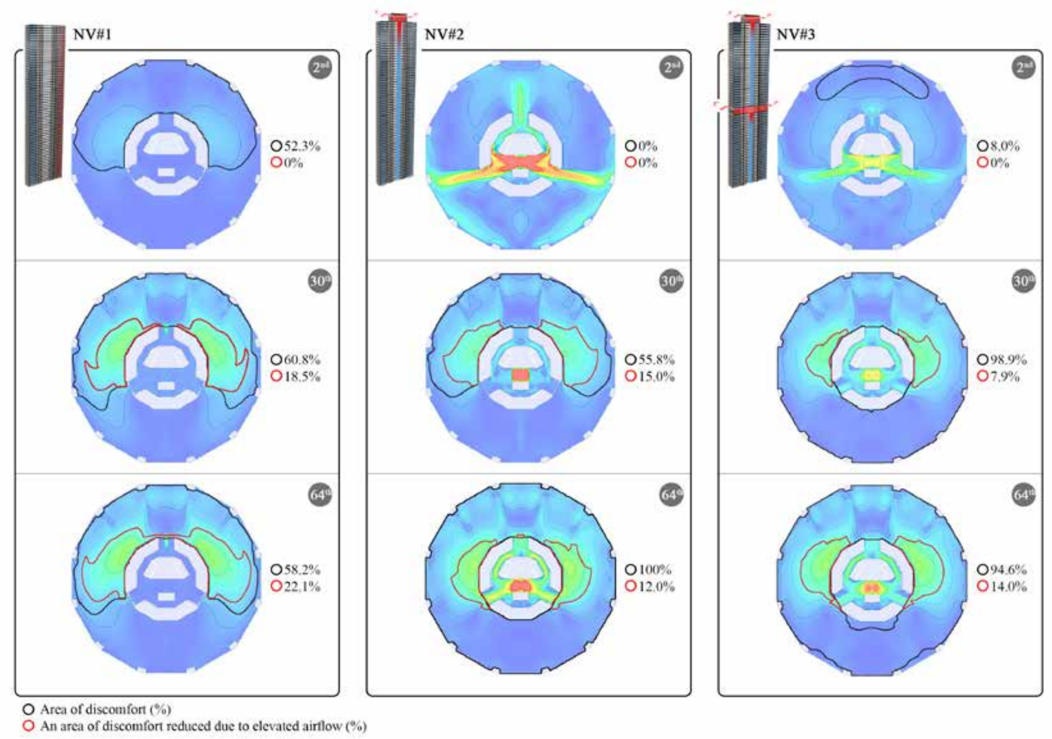


FIGURE 5.28 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 1: June 01, 17:00 (air temperature 29.5 °C, wind speed 1.5 m/s, wind direction: N).

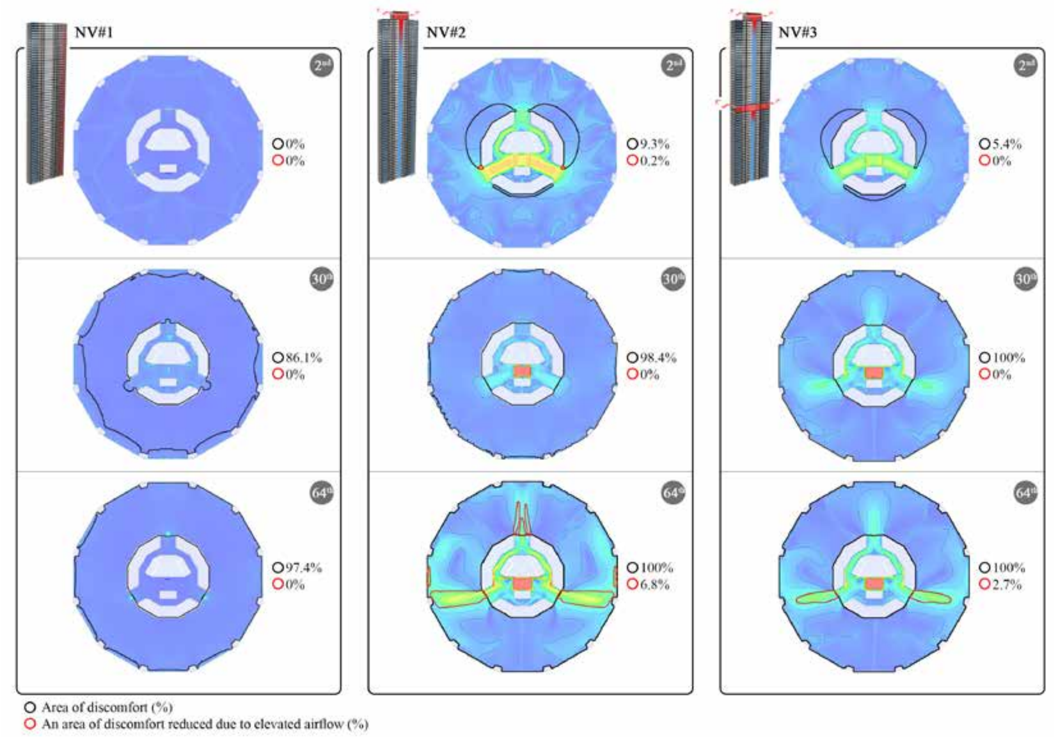


FIGURE 5.29 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 2: May 01, 09:00 (air temperature 29.0 °C, no wind speed).

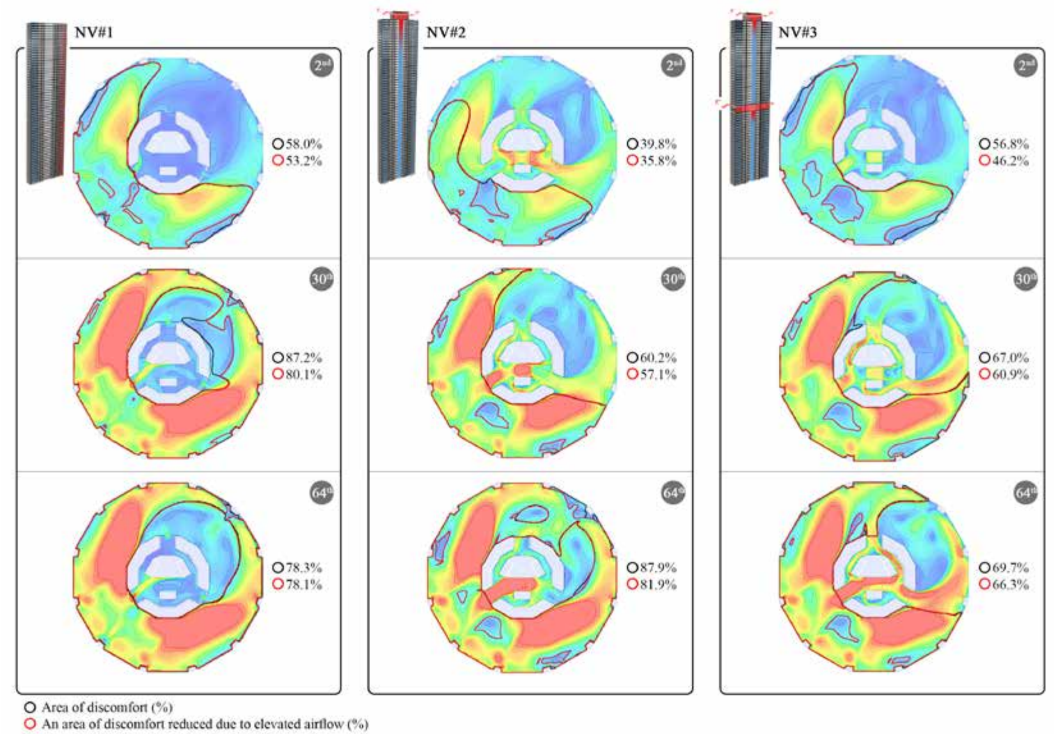


FIGURE 5.30 A comparison of discomfort area for different NV strategies prior and after taking the psychological cooling effect of elevated velocities into account in weather scenario 3: November 26, 12:00 (air temperature 30.0 °C, wind speed 6.0 m/s, wind direction SW).

TOC

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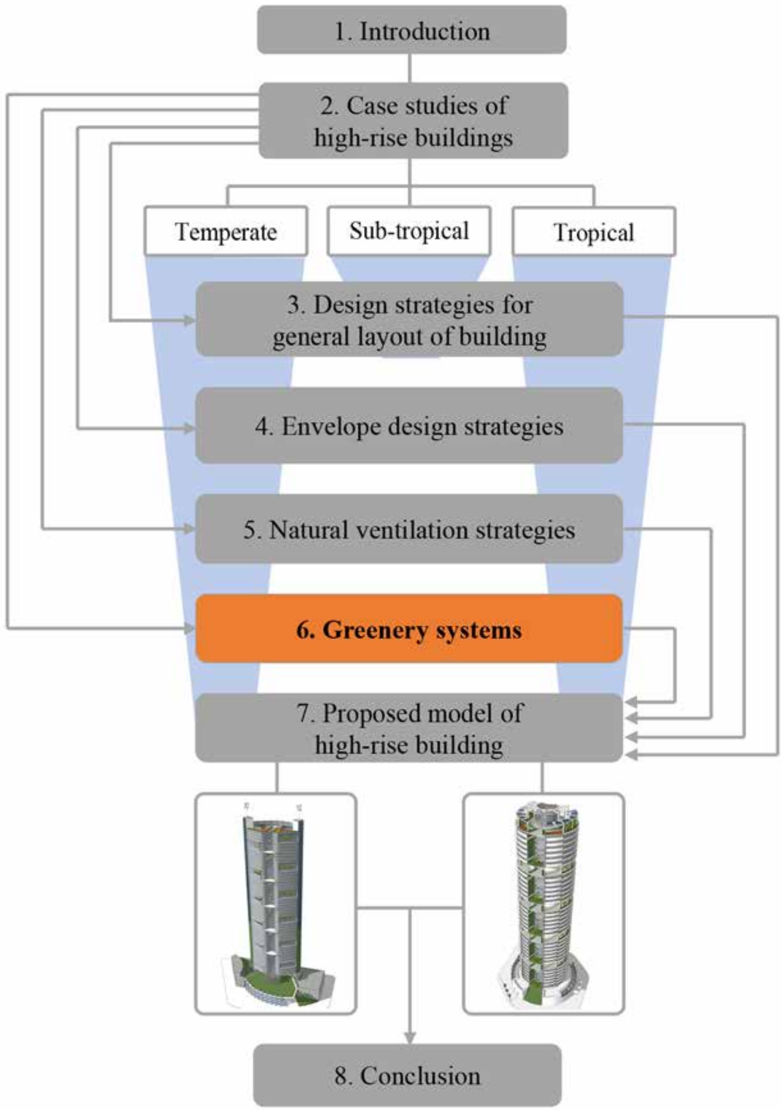
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion