Simulation Study on the Influence of Indoor and Outdoor Ventilation on Thermal Comfort in Zero Energy Buildings

Chunxue Gao¹*, Jintong Xiang¹, Songlin Wu¹ and Qiuxin Liu¹,²

¹ Wuhan University of Science and Technology, Wuhan 430065, China
² City College, Wuhan University of Science and Technology, Wuhan 430083, China
Email: 575882723@qq.com

Abstract: Based on the rational utilization of natural wind, it is particularly critical to study the role of natural ventilation convection in zero energy buildings, so as to reduce building energy consumption and lay a good foundation for realizing the goal of zero energy consumption in buildings. The commercial software PHOENICS is used to numerically simulate the outdoor wind environment of the building complex layout and the indoor ventilation of the building itself. After a comparison analysis of simulation models, this paper first points out the main factors that affect the wind environment and indoor natural ventilation of the building complex. Reasonable suggestions were given to the architectural planning and design as well as the living habits of the residents which can save energy to the greatest extent. With these suggestions, the unnecessary energy consumption of air conditioning can be reduced on the premise of ensuring the indoor temperature and humidity environment which is very beneficial to the realization of zero energy consumption of buildings.

1. Introduction

With the accelerated pace of urbanization, more and more large residential areas and even super-large communities have been built in cities. The growing urban buildings not only provide people with sufficient housing needs, but also bring many problems like urban heat island effect, air pollution, light pollution, etc. Due to improper planning and design in the initial stage, many residential areas have poor environment outside the building complex, and the local heat island effect is obvious in summer. The residential areas cannot achieve good ventilation, which further leads to the inability to carry out natural ventilation and cooling within the building during the transitional season, thus causing unnecessary energy consumption. However, in winter, the excessive wind in some roadways affects the comfort of citizens’ travel [1-3]. Therefore, it is extremely critical to rationally distribute buildings in combination with the climate characteristics of the city.

2. Simulation Analysis of Outdoor Wind Environment

2.1. Modeling of Simulated Objects

2.1.1. Mathematical Model. The flow of wind in the community is generally incompressible and low-speed turbulence. The commonly used mathematical models mainly include standard k-ε model, Large Eddy Simulation (LES) model and so on. The standard k-ε model has low calculation cost, small fluctuation and high accuracy in numerical calculation, it is more widely used in low-speed turbulence numbers. So the standard k-ε model is adopted in this paper. All the governing differential
equations include continuity equation, momentum equation, k equation and \( \varepsilon \) equation. The equations can be expressed as in equation (1) to equation (5) (Considering that the fluid is incompressible, it is a simplified with consideration of the steady state) [4-5].

\[
\eta_i = \frac{C_\mu \rho k^2}{\varepsilon} \quad \text{(1)}
\]

Continuity Equation:

\[
\frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad \text{(2)}
\]

Momentum Equation:

\[
\frac{\partial (\rho u_i u_j)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \eta + \frac{\eta_i}{\sigma_i} \right) \frac{\partial u_i}{\partial x_j} \right] - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \eta \frac{\partial u_i}{\partial x_j} \right) \quad \text{(3)}
\]

K Equation:

\[
\frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \eta + \frac{\eta_i}{\sigma_i} \right) \frac{\partial u_i}{\partial x_j} \right] - \rho \varepsilon + \frac{\partial}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} \right) \frac{\partial u_j}{\partial x_i} \quad \text{(4)}
\]

\( \varepsilon \) Equation:

\[
\frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \eta + \frac{\eta_i}{\sigma_i} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_2 \frac{\rho \varepsilon^2}{k} + \frac{C_\varepsilon \eta_i}{k} \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \frac{\partial u_j}{\partial x_i} \quad \text{(5)}
\]

In the above equations, equations (4) and (5) are convection term, diffusion term, generation term and dissipation term from left to right, respectively.

2.1.2. Physical Model. After determining the calculation equation of the model, in order to reduce the calculation nodes, the tiny concave and convex parts of the building are often ignored in the calculation process. So the rectangular building with regular shape is replaced by square. To meet the requirements of calculation accuracy, this study takes a rectangular region along the incoming flow direction and selects the following dimensions as follows: the height of the computational domain is 3 times of the building height, the incoming flow direction is 3 times of the building width, the outgoing flow direction is 10 times of the building width, and the width of the computational domain is 5 times of the building width [5-6].

2.2. Simulation Results and Analysis of Wind Environment of Buildings

Wuhan is located in the central region with an annual average wind speed of 2.5m/s. In order to study the characteristics of the wind environment of buildings under the unfavorable conditions, this paper analyzes the situation where the wind speed is 4 m/s. In this paper, the calculation results are given when the positive angle between the incoming flow and the y-axis is \( \theta = 0^\circ \) and \( \theta = 30^\circ \) respectively. Simulation models are realized using the computational fluid dynamics software PHOENICS. The simulation results are post-processed by Tecplot 360. The horizontal plane at 1.5 m of the ground is selected as the observation surface.

The simulation is performed in two aspects. First, a building model is established by PHOENICS to simulate the situation of wind bypassing a single building. This model is to explore the basic law of outdoor wind environment of a single building. Second, the wind environment characteristic of the building complex is simulated [7].
2.2.1. Simulation Analysis of the Wind Environment of a Single Building. The size of a single building is: length*width*height=100*45*50(m). The size of the computational domain is X*Y*Z=500*600*150(m). The incoming flow direction is in the same direction as the positive direction of the Y-axis, and the wind speed is 4m/s. The simulation results are shown in figures 1 and 2.

![Figure 1](image1.png)  ![Figure 2](image2.png)

Figure 1. Velocity distribution of flow field in a single building on the 1.5m horizontal plane (XOY).

Figure 2. Velocity distribution of flow field in a single building on the ZOY plane.

In figure 1, when the head-on wind speed of a single building is 4m/s, the average wind speed at a height of 1.5 m from the ground is 3.27 m/s, which will not significantly affect people’s movement and comfort. However, at the same time, it can be seen that due to the shielding of the building, the wind speed in front of the building decreases sharply especially in the rear.

When the wind blows vertically towards a single building (θ=0°), the airflow that affected by the obstruction bypasses the edge of the building. As a result, the wind speed drops rapidly on the front and back of the building while the speed increases obviously near the edge of the building (figures 3 and 4). At the same time, the airflow on the rear side of the building forms two symmetrical large vortices with opposite rotation directions. After the airflow bypasses the building, the range of the wake flow increases continuously and eventually tends to be normal.

![Figure 3](image3.png)  ![Figure 4](image4.png)

Figure 3. Local velocity vector diagram of flow field in a single building on the 1.5m horizontal plane (XOY).

Figure 4. Local velocity vector diagram of flow field in a single building on the ZOY plane.

2.2.2. Simulation Analysis of the Wind Environment of Building Complex. The simulation object is a residential area with six residential buildings. The distribution of velocity field and pressure field under different wind directions in the building complex are mainly studied and evaluated. The three-dimensional layout of the complex is shown in figure 5. The size of a single building is still length*width*height=100*45*50(m). The size of the computational domain is X*Y*Z=500*600*150(m). The distance between the front and back of the building is 45 m. The distance between the left and right is 90m. PHOENICS is used to simulate the situation of the building complex when the incoming wind is at an angle of 0° and 30° respectively. The velocity field and pressure field are extracted for analysis.
When the included angle of the incoming wind direction is 0°, the distribution of its velocity field is shown in figures 6 and 7. The flow rate of the air flow is reduced due to the obstruction of the building. The leeward side of the residential area forms a “wind shadow area” and two symmetrically distributed recirculation zones are formed on the leeward side of the rear buildings. Basically, the wind speed in the “wind shadow area” is lower than 1m/s, which is within the reasonable wind speed range. When the air flow flows through the north-south road to form a ventilation lane, the wind speed at the entrance is close to 5m/s. The high wind speed may affect the comfort of pedestrians. The wind speed decreases gradually from the entrance to the exit [8]. The pressure imbalance between the front and rear rows of the buildings will create local vortices which may cause the accumulation of pollutants and hinder the ventilation and heat dissipation of the building complex in summer.

When the incoming wind is at an angle of 30° from the positive direction of Y-axis, the velocity profile and the velocity vector diagram are shown in figures 8 and 9.
Since the incoming flow has an included angle of 60° with the first row of building facades, when the wind blows through the front and rear rows of buildings, it passes through the laneway between the buildings from left to right, and the wind shadow area formed in the laneway is much smaller than that in figure 7. Besides, the vortex formed is also smaller. The wind shadow area of the whole building complex shifts to the northeast and forms a vortex area in the northeast region.

Therefore, the influence of local dominant wind direction on the wind environment of the residential area should be considered in the layout of the building complex [9-10]. According to relevant researches, when the wind angles are 0°, 30°, 45° and 60° respectively, the reduction rate of wind speed in the natural ventilation room and the size of the wind shadow area behind the building are shown in table 1 (where H is the height of the building):

Table 1. Influence of different wind angles on natural ventilation.

| Wind angle | Reduction rate of indoor wind speed (%) | Length of wind shadow area on the leeward side of building |
|------------|----------------------------------------|----------------------------------------------------------|
| 0°         | 0                                      | 3.75H                                                    |
| 30°        | 13                                     | 3.0H                                                     |
| 45°        | 30                                     | 1.5H                                                     |
| 60°        | 50                                     | 1.5H                                                     |

From table 1, it can be seen that the influence of the city’s dominant wind direction on natural ventilation is very obvious. On the one hand, we consider the condition of ensuring the wind speed in the natural ventilation room. The wind shadow area on the leeward side of the building will increase, thus the distance between the front and rear buildings must be increased. On the contrary, in order to save building land and reduce the spacing between buildings, the corresponding wind angle needs to be increased. This will lead to a sharp decrease in the wind speed in the natural ventilation room. In the transitional season, natural wind cannot be fully utilized to realize indoor cooling by ventilation, thus the building energy consumption will increase.

In order to understand the wind speed at a specific point, seven representative monitoring points have been set up during the simulation process to monitor the wind speed and pressure at the corresponding positions as shown in figure 10 and figure 11. The monitoring height is 1.5m, and the monitoring values are shown in table 2.

![Figure 10. Layout plan of the monitoring points (1.5m from the ground).](image1)

![Figure 11. Statistics of the wind speed at each monitoring point.](image2)
Table 2. Comparison of wind speed and pressure values at different monitoring points (1.5 m from the ground).

| Number of monitoring points | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|
| Wind speed (m·s⁻¹)          | 0.659 | 1.722 | 1.565 | 4.789 | 0.651 | 1.726 | 1.508 |
| Angle of 0°                 | 1.763 | 3.777 | 3.924 | 1.848 | 2.087 | 3.465 | 3.058 |
| Pressure(Pa)                | 11.071 | -2.506 | -0.386 | -3.278 | 11.096 | -2.527 | -0.422 |
| Angle of 0°                 | 9.657 | -2.083 | -3.094 | 0.96 | 9.201 | -3.95 | -2.181 |

From the comparison of wind speed in table 2, it can be found that when the incoming wind is perpendicular to the building facade (i.e. at an angle of 0°), the fluctuation of wind speed between different monitoring points is much larger than that of wind speed at an angle of 30° between the incoming wind and the building facade. It can be concluded that when the incoming wind avoids being perpendicular to the building facade, the wind speed field is more uniform. Also, the wind speed in the ventilation lane is low and thus excessive local wind speed can be avoided.

(2) Analysis of pressure field in the wind environment of building complex

The pressure distribution on the outer surface of the building determines whether it can effectively use natural wind to ventilate and cool the room in summer. The buildings’ capacity to resist wind vibration and wind pressure also needs to be considered from the structural point of view. As shown in figure 12, under the condition of incoming wind speed at two different angles, the pressure distribution on the outer surface of the building complex is less different. The common feature is that the surface pressure of the first row of buildings located at the incoming flow position is significantly higher than that of other rows of buildings due to the direct contact with the incoming flow. Due to the shielding of the first row of buildings, the incoming wind has little influence on the pressure distribution on the outer surfaces of other rows of buildings, and even there is almost no pressure difference between the front and rear walls of these buildings.

Figure 12. Statistic of pressure values at each monitoring point.

Figure 13. Pressure profile of the building complex (At an included angle of 0°).

Figure 14. Pressure profile of the building complex (At an included angle of 30°).
Through the simulation analysis of a single building and the whole building complex (figure 13 and figure 14), the following conclusions can be drawn under the condition of comparing different wind angles of incoming flow:

1. When the incoming flow direction is perpendicular to the building (i.e. at an angle of 0°), the vortices may be formed between the front and rear buildings, resulting in dead corners of vortices, which is very unfavorable to the ventilation and heat dissipation of building complex in summer and may form local heat island effect. Therefore, even if the window is open during the transitional season, there is not enough wind speed to enter the room, which cannot achieve the goal of lowering the indoor temperature. Therefore, this situation should be avoided as much as possible.

2. When the incoming flow direction is perpendicular to the building (i.e. at an angle of 0°), the roadway wind is easy to be formed in the walkway between two rows of buildings. Excessive wind speed will cause discomfort to pedestrians on the street, dust and paper scraps flying in the sky, doors and windows being blown out and damaged, etc. At the same time, ventilation and cooling during the transitional season will cause discomfort of indoor personnel and increase indoor wind speed excessively.

3. When the inflow direction changes, the wind speed increases in the gap area between buildings, and the wind speed distribution is more uniform in the whole residential area. There is a more obvious wind speed distribution between the residential buildings in the front row which avoids the former dead corners of vortices. Meanwhile, a good wind environment can ensure that buildings have sufficient ventilation capacity to discharge the indoor waste heat in time and reduce the air-conditioning energy consumption in sultry summer.

3. Simulation Analysis of Indoor Natural Ventilation

3.1. Establishment of Natural Ventilation Model

A room model of the laboratory is established by using the computational fluid dynamics simulation software PHOENICS. The size of the room is determined according to the existing laboratory: length*width*height = 9 m*3.9 m*2.8 m. There is a window on the north and south sides of the room respectively. The size of the south-to-outside window is 3200 mm (width) *1800 mm (height). The size of the north-to-outside door is 950 mm (width)*2000 mm (height) and the windowsill is 800 mm from the ground. The size of the north-to-outside window is 1000 mm (width)*1800 mm (height). The room is equipped with a seated person and a table. The wall temperature is set at 30.4 °C. The temperature of the outer window is set at 37 °C and the temperature of the outer door is set at 31 °C. The model building is shown in figure 15.

![Figure 15. Physical model of natural ventilation.](image)

3.2. Analysis of Thermal Comfort with Doors and Windows Closed in Transition Season

This simulation focuses on the distribution of indoor temperature and PMV index in Wuhan area when doors and windows are closed in the transition season. According to the results of computer simulation, indoor temperature distribution and PMV index are analyzed respectively.

Firstly, the indoor temperature distribution, PMV index distribution and wind speed distribution...
cloud are analyzed in XOZ coordinates when the doors and windows are closed, as shown in figures 16 to 18. As the indoor heat cannot be smoothly discharged to the outdoor, obvious temperature stratification appears in the vertical direction after stabilization (figure 16). The temperature near the ground is relatively low, mostly within the range of 30 °C; However, the temperature gradually rises with the increase of height and reaches about 33 °C at the ceiling position. The temperature difference between the upper and lower reaches 3 °C. The reason for stratification is the accumulation of indoor heat. Hot air will accumulate in the upper part of the room due to its relatively small density. Cold air will sink to the lower part of the room after stabilization due to its high density. Meanwhile, the average temperature of the whole room reaches 32.05 °C.

Figure 16. Temperature distribution cloud on XOZ (Y=1.1 m) plane with window closed.

Figure 17. Wind speed distribution cloud on XOZ (Y=1.1 m) plane with window closed.

Figure 18. PMV index distribution cloud on XOZ (Y=1.1 m) plane with window closed.

Then, the artwork of wind speed in XOZ coordinates is analyzed (figure 17). Since there is no ventilation process, no obvious airflow disturbance in the whole room is observed and the wind speed is basically below 0.06 m/s.

Finally, the vertical space is analyzed from the perspective of PMV index (figure 18). Similar to the temperature distribution cloud, the PMV value is between 1.1 and 1.2 on the ground with lower temperature which is in the range of slight warmth. However, with the increase of space height, the indoor temperature rises, the PMV value also increases correspondingly and reaches about 1.4 at the ceiling. The average PMV value of the whole room is about 1.32. According to the quantitative relationship between the PMV index and the PPD, about more than 40% of the population expressed dissatisfaction in this environment. Therefore, in the transitional season, closing doors and windows
will make people feel more sultry.

Figures 19-21 show the distribution clouds of three parameters at a height of 1.2 meters on the XOY plane. Compared with the above clouds on the XOZ plane, it can be seen that the indoor temperature distribution is very uniform on the same horizontal plane. However, due to the existence of window gaps on both sides, the indoor wind speed near the window will be higher than that at other positions. At the same time, because the window surface temperature is higher than the wall temperature, the PMV value near the window is also higher than that of other places. The mean PMV index of the whole 1.2 m high plane working area reaches 1.33 and the thermal comfort of the room is still poor [11].

3.3. Analysis of Thermal Comfort with Window Open for Ventilation in Transition Season

In this section, the window is set to be half open from the closed state. Meanwhile, the inlet wind speed is set to 2.5 m/s and the inlet air temperature is set to 27 °C. The value of this wind speed refers to the annual average wind speed of 2.3 m/s in summer in Wuhan area in *Design Code for Heating Ventilation and Air Conditioning of Civil Buildings* (GB50736). Due to the increase of natural ventilation, the number of computation iterations is increased from 3,000 to 5,000 to ensure the convergence of the simulation results. Figure 22 shows the interface where PHOENICS is performing iterative computations.

![Figure 19. Temperature distribution cloud on XOY (Z=1.2 m) plane with window closed.](image1)

![Figure 20. Wind speed distribution cloud on XOY (Z=1.2 m) plane with window closed.](image2)

![Figure 21. PMV index distribution cloud on XOY (Z=1.2 m) plane with window closed.](image3)
After more than one hour of calculation, the calculation result meets the requirements of convergence, and then it is post-processed as shown in figures 23 to 28. The first three figures are clouds of indoor temperature, indoor wind speed and PMV index values in XOZ coordinates while the last three are the corresponding clouds in XOY coordinate plane.

In figure 23, when the room is well ventilated in the transitional season, the indoor heat can be effectively discharged in time so that the indoor temperature is quickly balanced with the outdoor temperature. The average room temperature of the whole room is about 27.36 °C, which is obviously lower than the wall temperature of 30.4 °C and basically equal to the ventilation temperature. At the same time, comparing figure 23 with the previous simulation figure 16 without natural ventilation, it can be seen that natural ventilation not only reduces the indoor temperature but also makes the temperature distribution more uniform in the vertical space.

Figure 23. Temperature distribution cloud on XOZ (Y=1.1 m) plane with window open (v=2.5 m/s).

Figure 24 shows the indoor wind speed distribution under natural ventilation. At a wind speed of 2.5 m/s with ventilation, the wind speed near the window opening position is obviously higher than that in other area. However, as the wind blows into the room, the wind speed decreases continuously. Finally, it is discharged from the window on the right side and takes away the indoor waste heat at the same time. The average wind speed of the whole room is 1.5 m/s. This is very useful for timely discharging indoor waste heat and decreasing room temperature in transition season because it can reduce indoor temperature and humidity in a short time.

Figure 24. Interface of the computer’s iterative computation process.
Figure 24. Wind speed distribution cloud on XOZ (Y=1.1 m) plane with window open (v=2.5 m/s).

Figure 25 shows the PMV index of the whole room under natural ventilation. By comparing and analyzing it with figure 18, it can be found that due to the effect of natural ventilation, the PMV index of the whole room ranges between -1 and +1, and even approaches the value of 0. PMV value in this range is more appropriate, indicating that the indoor thermal comfort is better and can satisfy most people’s feelings [12].

Figure 25. PMV index distribution cloud on XOZ (Y=1.1 m) plane with window open (v=2.5 m/s).

Figures 26-28 show the distributions of temperature, wind speed and PMV index of the whole room at a height of 1.2m on the XOY plane. The conclusion after analysis is basically consistent with the previous one. The indoor temperature near the window is closer to the ventilation temperature. The wind speed is higher. Due to good ventilation, the temperature of the whole room is close to the outdoor temperature. And the PMV index value is 0.29, which is closer to 0 by comparing with the average value of 1.33 in figure 21. When PMV index value is about 0.29, only no more than 10% of the population expressed dissatisfaction with the environment. This indicates that the thermal comfort is better with windows open for natural ventilation in transition season.

Figure 26. Temperature distribution cloud on XOY (Z=1.2 m) plane with window open (v=2.5 m/s).
For the same indoor parameters in the same room, the distribution of indoor temperature, wind speed and PMV index are simulated under the two modes: closing doors and windows or opening windows for ventilation. It can be found that keeping the windows open for ventilation is a very effective way to reduce the indoor temperature in a transition season like summer. With effective ventilation, the indoor temperature can be reduced to close to the outdoor temperature. The indoor thermal comfort can be enhanced and the indoor sultry environment can be improved by making full use of the fresh air with lower outdoor temperature to improve the indoor air quality. This not only achieves the goal of cooling down in summer, but also avoids additional energy consumption. Therefore, as for the zero energy buildings, we should pay attention to natural ventilation in transition seasons which will effectively reduce the air conditioning load and reduce the annual load demand of buildings to the point where other renewable energy sources can be used for supply [13].

In the meantime, the effect of natural ventilation often depends entirely on the external wind speed and direction. Therefore, a reasonable building layout can ensure a good outdoor wind environment of the building complex and make better use of the natural wind as well. Since the wind speed is set at 2.5 m/s in this case, the indoor temperature can be rapidly reduced to a temperature similar to the outdoor temperature. However, most of the time, the wind speed entering the room may not reach the average value of 2.5 m/s because of the wind direction and wind speed. Considering the above factors, the wind speed with window open is 0.5 m/s is simulated by computer. The clouds of indoor temperature distribution, wind speed distribution and PMV index value are shown in figures 29 to 34. By comparing the cloud at the wind speed of 2.5 m/s (with window open) with the cloud at the wind speed of 0.5 m/s (with window open), it can be seen that opening windows for ventilation can effectively reduce the indoor temperature even if the wind speed is very low. A better indoor thermal environment can be achieved since the average indoor temperature is reduced to 27.6 °C. At the same time, its PMV index also reaches about 0.54 which can still provide an indoor thermal environment that most people are satisfied with.
**Figure 29.** Temperature distribution cloud on XOZ (Y=1.1 m) plane with window open (v=0.5 m/s).

**Figure 30.** Wind speed distribution cloud on XOZ (Y=1.1 m) plane with window open (v=0.5 m/s).

**Figure 31.** PMV index distribution cloud on XOZ (Y=1.1 m) plane with window open (v=0.5 m/s).

**Figure 32.** Temperature distribution cloud on XOY (Z=1.2 m) plane with window open (v=0.5 m/s).

**Figure 33.** Wind speed distribution cloud on XOY (Z=1.2 m) Plane with window open (v=0.5 m/s).
Figure 34. PMV index distribution cloud on XOY (Z=1.2 m) plane with window open (v=0.5 m/s).

4. Conclusion
In this paper, PHOENICS is used to simulate and analyze the outdoor wind environment of building complex and the indoor natural ventilation of the building in the transition season. According to the simulation results, the following conclusions can be drawn:

1) According to the dominant wind direction of the city, the reasonable layout of building complex can not only effectively avoids excessive wind speed in the local area in winter, but also improves the phenomenon of local ventilation difficulties in summer, strengthens the air circulation and alleviates the local heat island effect. In the transition season, fresh outdoor air can be introduced into the room to improve the sultry indoor environment.

2) In the transition season, since the outdoor temperature is often lower than the indoor temperature, natural ventilation by opening windows can timely discharges the indoor waste heat, improves indoor thermal comfort and further reduces air conditioning energy consumption. According to the research results, it can be seen that even if the wind speed is small, it can still effectively decreases the indoor temperature, reduces the temperature difference between indoor and outdoor, and increases the indoor thermal comfort [14]. Therefore, the utilization of natural ventilation in the transition season is also very critical in zero energy buildings. Residents are required to develop a good awareness of energy conservation and attach importance to the use of natural fresh air to improve the indoor thermal environment.

References
[1] China Building Energy Conservation Association 2014 China Building Energy Conservation Status and Development Report (2013-2014) (Beijing: China Building Industry Press) 12 20-24.
[2] Moldovan M D, Visa I, Neagoe M and Burduhos B G 2014 Solar heating & cooling energy mixes to transform low energy buildings in nearly zero energy buildings Energy Procedia 48 924-937.
[3] Xu X L and Li B Z 2005 The influence of indoor thermal environment on human thermal comfort Journal of Chongqing University (Natural Science Edition) 04 102-105.
[4] Tao W Q 2003 Numerical Heat Transfer Xi’an: Xi’an Jiaotong University Press 332-380.
[5] Wang F and Xiao Y Q 2005 Using PHOENICS software to simulate and evaluate the wind environment of buildings Journal of Shandong Institute of Civil Engineering 20(5) 39-42.
[6] Zhang B Y, Sang J G and Wu G C 2004 The characteristics and simulation of the environmental wind field of the building complex Mechanics and Practice 2(3) 1-9.
[7] Duan Z Z, Fang H H, Li J J and Wang S X 2019 Comparative analysis of outdoor wind environment measurement and PHOENICS simulation——Taking Xuzhou high-rise residential area as an example Building Techniques 09 124-126.
[8] Li P Y 2017 Research on the Parametric Generation Method of Building Morphology Based on Wind Environment Dalian University of Technology.
[9] Li S G 2017 Study on the Influence of Planning Elements on Outdoor Wind Environment in Residential Areas University of Nanhua.
[10] Zhou M L 2016 The Impact of High-Rise Residential Building Openings and Inter-Building...
Openings on Wind Environment Zhejiang University.

[11] Li Y M 2019 Research on Optimization Strategy of Thermal Comfort of Small-Scale Public Space in Cold City during Transition Season Harbin Institute of Technology.

[12] Chen Z L, Xin J J and Liu P Y 2020 Air quality and thermal comfort analysis of kitchen environment with CFD simulation and experimental calibration Building and Environment 172.

[13] Park B, Ryu S R and Cheong C H 2020 Thermal comfort analysis of combined radiation-convection floor heating system Energies 13(6).

[14] Verma P K and Netam N 2020 A case study on thermal comfort analysis of school building Materials Today: Proceedings 28(4) 2501-04.