The numerical analysis of outdoor wind and thermal environment in a residential area in Liaocheng, China

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Abstract. With the improvement of people's living standard, people not only pay attention to the indoor environment, but also the outdoor environment. The paper simulated the outdoor wind environment and thermal environment for the building in its design stage, then suggestions are provided for further design stage using a case study in a residential area in Liaocheng, China. SketchUp is used to establish 3D model and PHOENICS is adopted to simulate wind environment and thermal environment. The evaluation criterion mainly utilized Green Building Evaluation Criteria and Urban Residential Area Thermal Environment Design Criteria and ISO7243. Through the analysis of the wind and thermal environment problems, this paper puts forward measures and suggestions to provide reference for the later planning.

1. Introduction
With the improvement of people's living standard, people not only pay attention to the indoor environment, but also pay attention to the outdoor environment. The increasing of building dense and population density will influence the wind and thermal environment, which will influence the building energy consumption and resident life. Therefore, the outdoor thermal and wind environment are main conditions to determine residential planning. Numerical simulation of outdoor environment will provide high reference value for the construction of the residential area.

There are many studies about outdoor environment, Wang et al [1] studied a residential outdoor thermal environment by CFD simulation and field measurement, and the outdoor thermal environment is compared under the conditions of no wind and gentle breeze. The results showed that thermal environment will be close to outdoor environment under gentle breeze. That is to say the outdoor thermal environment is influenced by wind environment, meanwhile, thermal environment is affected by different factors at different vertical heights. Zhang [2] used CFD simulation to simulate the thermal and wind environment of a residential area, the results showed that the environment did not meet the requirements in the local area. The improvement scheme is put forward for the unreasonable areas, and then the numerical simulation is conducted. Finally, the thermal and wind environment reached the Green Building Evaluation Criteria. Liu et al [3] used CFD simulated the outdoor thermal and thermal environment about a residential area, the results showed that wind speed distribution and temperature field are all reached the Green Building Evaluation Criteria, and they can provide good conditions for indoor natural ventilation. Yang et al. [4] conducted the measurements and explored the
relationship of microclimate environments, park use and human behavioural patterns in urban area of Umeå, Sweden, which is under subarctic climate. This paper takes a residential area as an example to simulate the outdoor thermal and wind environment in summer, and then put forward evaluation based some standards, so as to make recommendations for the later improvement.

2. General situations of residential area
This area is situated in Liaocheng, China. It is located in south of Construction Road, east of Lu Road, and the west of Planning Road. The planned land is about 25129 m², the total construction area is 75000m². The residential area has five high-rise residential buildings with eighteen floors and the height of each floor is three meters, and a 10.8 meters commercial building with three floors. The paper simulates the thermal and wind environment at 14:00 in July 14th of 2017. The average temperature is 31°C and the average wind speed is 2.7m/s, the dominant wind direction is SW. The basic form of residential areas is slab-type building. Figure.1 is the general layout of residential district.

Figure 1. The general layout of residential district.

3. Evaluation criteria of outdoor wind and thermal environment

3.1. The evaluation criteria of outdoor wind environment
In Green Building Evaluation Criteria, evaluation for wind environment is mainly to keep the environment that is beneficial to walking and natural ventilation. The evaluation criteria in summer are as follows:
- People in the activity site does not appear vorticity or breezeless.
- There should have more than 50% openable windows, and the air pressure difference between indoor and outdoor surface is greater than 0.5Pa.
- In summer and transition seasons, the pressure difference of more than 75% buildings should remain about 1.5Pa.

3.2. The evaluation criteria of outdoor thermal environment
In China, there are some evaluations about thermal environment including Green Building Evaluation Criteria and Design Standard of Thermal Environment in Urban Residential Area. ISO7243 international standard for the WBGRT has detailed introduction. Green Building Evaluation Criteria and Design Standard [5] for thermal environment are concentrated in taking measures to reduce heat island intensity. The evaluation criteria in summer is as follows:
- In the outdoor activities, the shading area of trees and buildings should reach 10%.
- More than 70% of the road and roof, the radiation reflection coefficient are less than 0.4.

Design Standard of Thermal Environment in Urban Residential Area [6] for thermal environment mainly uses wet bulb globe temperature and average temperature as design index. The evaluation criteria in summer show as follows:
- The wet bulb globe temperature should not exceed 33°C.
- The average heat island intensity should not greater than 1.5°C.
- The greenbelt and green trees should not less than 30%.
WBGT is an index related to wet bulb globe temperature and black globe temperature, and it is also related to dry-bulb temperature under insolation. The calculation method is in following formula.

Indoor or outdoor without sun exposure: \( \text{WBGT} = 0.7t_{nw} + 0.2tg \)  \hspace{1cm} (1)

Outdoor with sun exposure: \( \text{WBGT} = 0.7t_{nw} + 0.2tg + 0.1t_a \)  \hspace{1cm} (2)

Introductions for the WBGT in ISO7243 [7] international standard are in Table 1:

| Metabolism level | Metabolic rate (W/m²) | Outdoor activity and walking speed | Recommended value of WBGT(°C) |
|------------------|-----------------------|-----------------------------------|-------------------------------|
| 0                | M≤117                 | Rest                              | Comfortable: 33, Uncomfortable: 32 |
| 1                | 117＜M≤234             | ＜0.97m/s                         | Comfortable: 30, Uncomfortable: 29 |
| 2                | 234＜M≤360             | 0.97～1.53 m/s                    | Comfortable: 28, Uncomfortable: 26 |
| 3                | 360＜M≤468             | 1.53～1.94 m/s                    | Feeling for air movement: No, Yes |
| 4                | M＞468                 | ＞1.94 m/s                        | Feeling for air movement: No, Yes |

4. Model establishment

4.1 Physical model

SketchUp was used to establish the 3D model of residential area, and then imported into the PHOENICS for numerical simulation. Figure 2 is the model of residential area.

![Figure 2. The model of residential area (y represents the north).](image)

4.2 Numerical model

PHOENICS is used to simulate the thermal and wind environment, making the following hypotheses to simplify the question.

- Outdoor air is considered as incompressible and unsteady fluid, the control differential equation adopted RANS, the turbulence model used k-ε equation.
- Solar radiation has great influence on the surface temperature of the building, so the solar radiation should be considered in the simulation of thermal environment. The radiation model selected IMMERSOL model in PHOENICS, which considered the various longwave radiation. The simulation results have better accuracy and authenticity.

The equation of IMMERSOL radiation model for the temperature inside the solid is shown as:

\[ c \frac{dT_i}{dt} = \Delta (\lambda \times \text{grad}T_i) + q \]  \hspace{1cm} (3)
Where $T_1$ is the inside temperature of solid, $c$ is specific heat capacity, W/Kg·K, $\lambda$ is thermal conductivity of solid, W/m·K, $q$ is heat flux of per unit volume, W/m$^3$, $T_1$ is absolute temperature in solids, K. The differential equation of air temperature between solid is as follows:

$$\Delta \left[ \frac{1}{0.75 \left( \alpha + \varepsilon + \frac{1}{L} \right)} \times \text{grad} E_3 \right] = (\alpha + s) \times (E_{12} - E_3)$$  \hspace{1cm} (4)

Where $E_3$ is radiation force of air, W/m$^2$, $E_{12}$ is blackbody radiation force between two walls, W/m$^2$, $\alpha$ is absorptivity, $\varepsilon$ is emissivity, $L$ is the distance between two walls, m.

### 4.3. Simulation settings in PHOENICS

The condition of entrance boundary selected the distribution of velocity gradient as the entrance condition [8,9]. The equation is as follows.

$$V_{H} = V_{0} \left( \frac{H}{H_{0}} \right)^{\alpha}$$  \hspace{1cm} (5)

Where $\alpha$ is coefficient of power function, the building in this residential area is mostly flat ground, so the $\alpha$ takes 0.14, $V_H$ is wind speed at $H$ height, $H_0$ is the reference height, take the 10m as the reference height, $V_0$ is the wind speed at $H_0$ height.

The condition of exit boundary selected the pressure boundary, taking ambient atmospheric pressure. The condition of wall boundary is calculated according to smooth wall. In the area of nearing wall region adopted the wall equation of General Log Law, dimensionless distance $\gamma$ within the range of $30 < \gamma < 500$. On both sides and the top of region all adopted symmetric boundary conditions. Other settings are shown in Table 2.

| Classification          | Content                                |
|------------------------|----------------------------------------|
| Computational domain   | Upstream domain                        |
|                        | Downstream domain                      |
|                        | Lateral domain                         |
|                        | Top domain                             |
| Computational grid     | Grid analysis                          |
|                        | Grid number(X×Y×Z)                     |
|                        | Algorithmic Options                    |
|                        | Convergence standard                   |

|                        | 2H from the zone entrance              |
|                        | 3H from the zone exit                  |
|                        | 2H on bilateral domain                 |
|                        | 2H from the top domain                 |
|                        | Hexahedral structured grid             |
|                        | 175×135×55                             |
|                        | QUICK algorithm                        |
|                        | The residual error ratio of inlet and outlet is less than $10^{-4}$ |

### 5. Simulation results

#### 5.1. Wind environment

The paper simulated the wind environment in summer, the dominant wind direction is SW and the average wind speed is 2.7m/s.

**Figure 3.** Velocity distribution at 1.5m.  \hspace{1cm} **Figure 4.** WAMP cloud chart at 1.5m.
From the results of simulation as shown in Figure 3 to Figure 5, in most areas the wind speeds are below 5m/s at the pedestrian height of 1.5 meters, which meets Green Building Evaluation Criteria. Because of the resist of the building, there appeared calm wind area on the leeward side. The region of low pressure is unfavourable for the diffusion of pollutants, as well as the heat dissipation around the buildings that can increase air conditioning load in summer. As shown in the pressure distribution diagram of building surface, only number 5 residential building's pressure is around 1.5Pa between windward and leeward, while the rest buildings' pressure difference is within 1.5Pa–8Pa which cannot meet the criteria. The WAMP is less than 2 in this area that meets Green Building Evaluation Criteria.

5.2. Thermal environment
This paper mainly simulated thermal environment in summer, the highest temperature usually occurs at 14:00, so the simulation mainly studies the situation of 14:00. Because the breathing zone is at the height of 1.5m, so the paper selected the thermal environment at 1.5m as the analysis.

As shown in Figure 6 and 7, there are some high temperature regions around the building at the height of 1.5m. For those high temperature zones, it is mainly due to the resistance of building on wind and the solar radiation. The maximum temperature can reach 48°C, the average temperature of the district is about 36.5°C. Outdoor air conditioning temperature is 34.4°C, so the heat island intensity is 2.1°C which cannot meet the Urban Residential Area Thermal Environment Design Criteria. The highest WBGT was 27.2°C which meet the ISO9273 standard when the metabolic rate is lower than 260 W/m².

From the simulation of wind environment and thermal environment, the wind speed can meet the standard, the pressure difference between windward and leeward is larger so that it cannot meet the criterion. For the thermal environment, there are still some high temperature zones.

6. The optimization scheme of the wind and thermal environment
To improve the thermal environment, some measures are chosen, such as adding planting trees and grasses, that the greening rate can reach 35%. Trees are planted around residential areas mainly, grasslands and shrubs in the residential area. The greening arrangement is shown in Figure 8. The settings about plants is shown in Table 3.
Table 3. Settings about plants in paper

| Types of plants | Size                  | Distance | Coefficients in PHOENICS |
|-----------------|-----------------------|----------|--------------------------|
| Grass           | Height: 20 cm         | —        | Fixed temperature: 28°C  |
| Shrub           | Height × Width: 1.5m×1.5m | 1m       | Emissivity: 0.95         |
| Tree            | Height × Width: 7m×5m | 4m       | Solar absorption: 0.8    |

Figure 8. Greening arrangement in residential area

6.1. Simulation results of wind environment for optimization scheme

Figure 9. Velocity cloud chart at 1.5m

Figure 10. WAMP cloud chart at 1.5m

Figure 11. The pressure distribution on surface of building (a is windward side, b is leeward side)

Figure 12. Temperature cloud chart at 1.5m (°C)

Figure 13. WBGT cloud chart at 1.5m (°C)

In the optimization scheme of wind environment from Figure 9 to Figure 11, there are little static pressure zone. It is also found that greening has less influence on the wind environment. In summary, the improved measures can meet Green Building Evaluation Criteria.
6.2. Simulation results of thermal environment for optimization scheme

From the optimization scheme of thermal environment in Figure 12 and Figure 13, the overall temperature declined in the area, the high temperature areas are reduced obviously. The highest index of WBGT is 23.5°C that is lower than no greening. Therefore, greening has obvious effect on outdoor thermal environment, this scheme can be adopted to improve thermal environment in summer.

7. Conclusions

For the wind environment simulation before improvement, the wind speeds below 5m/s at the pedestrian height of 1.5m, which meets Green Building Evaluation Criteria. Only the pressure difference between windward side and leeward side of building is larger with around 1.5Pa. After the optimization scheme, the pressure difference is still too larger, so the greening cannot improve the wind environment obviously. For the thermal environment simulation before improvement, there are many high temperature regions. Outdoor air conditioning temperature is 34.4°C, so the heat island intensity is 2.1°C which cannot meet the Urban Residential Area Thermal Environment Design Criteria. After the optimization scheme, WBGT is 23.5°C, and the high temperature areas are reduced obviously. Therefore, in this study, greening is suggested to plant grasslands and shrubs around residential areas. The results were found that increasing planting trees and grasses in the designing stage can effectively improving the thermal environment. However, this study also exists some limitations, the paper did not take into account some factors on the thermal and wind environment, such as the different arrangement of greening, layout of residential area building and so on. These aspects can be carried out in the following researches.

Acknowledgement

This study was sponsored by Natural Science Foundation of China (NSFC, No.51608310), Natural Science Foundation of Shandong Province (ZR2016EEB08), Science and Technology Plan Project of University in Shandong Province (J16LG07).

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