SIMULATION RESEARCH OF WIND AND THERMAL ENVIRONMENT IN RESIDENTIAL DISTRICT

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ABSTRACT

A good wind and thermal environment of residential districts can speed up the outdoor heat and pollutant dissipation, as well as ensure the comfort and health of residents. The thermal environment in residential districts is affected mainly by layout form, building shape, underlying surface characteristics, etc. In this paper, a residential area located in Qingdao is studied. Numerical simulations of the wind field and thermal environment of the residential district in summer are adopted to evaluate the rationality of the original design. Then, an improved design is proposed to meet the relevant provisions of evaluation mark of the green building on residential wind and thermal environment through appropriate adjustments of the building layout and the underlying surface characteristics. From the contrast between the simulation results of original and improved designs, it can be concluded that: 1) Setting ventilation aisles in the residential area by adjusting building layout can improve the comfort level of wind environment. 2) Changing the thermal performance of underlying surface materials (such as tree, artificial lake, lawn, etc.) for increasing the reflectivity of the ground material could reduce the ground surface temperature and the sendible temperature in summer to improve thermal comfort of the residential district.

INTRODUCTION

Residential building layout and vegetation planning design have become a prime concern of residents, which have a tremendous impact on residential wind and thermal environment. Reasonable planning and residential green space design will improve the utilization of land and the beautification level of residential quarters, promote the quality of residential thermal environment, and reduce the energy use.

Application of CFD (computational fluid dynamics) in the wind and thermal environment and numerical simulation in the residential area planning and design have been studied by a number of researchers, which helps to rationalize the layout of buildings in the district to create the most suitable residential area's microclimate for human habitation and living. Omar (2010) investigated the effect of different building grouping patterns on the resulting wind environment in the outdoor spaces and the resulting ventilation potential of these buildings using CFD. Some rational configurations were recommended for better wind-driven ventilations, where the main design objective is passive cooling. Takahashi (2004) established a new simulation code, using CFD for coupled numerical simulation with combination of the unsteady heat conduction of building walls and grounds, radiation heat exchange between them as well as airflow to predict effectively the real air temperature, humidity, wind velocity, and boundary layer heat flux of the urban area for comparison with the measured results. Li et al. (2005) proposed a method combining CFD simulation of airflow and energy balance calculation of surfaces to simulate the outdoor thermal environ-ment around buildings. In every computing time step using this method, the outdoor air distribution is calculated as quasi-steady condition, and the surface temperatures of buildings and ground are simplified as “shadow zone temperature” and “sunshine zone tem-perature” to reduce the calculation time and memory space. Chen et al. (2008) built an optimal design method using genetic algorithm (GA) for investigating the outdoor thermal environment, and carried out simulations and experiments on different building pattern arrangements and different forms of vegetation to verify the effectiveness of this method. The results have shown that the GA applied in the residential optimal design is valid.

In this paper, a residential area located in Qingdao is chosen as the research object. Numerical simulation software (i.e., CFD) is applied to simulate the wind environment and the heat environment of the residential area in winter and summer. Unreasonable wind environment in the residential area can be found by analysis of the wind speed profile of the environment, the wind velocity vector, the dynamic pressure and the static pressure profile in summer and winter. Then, two improved programs are proposed and simulated to meet the relevant provisions of evaluation mark of the green building on residential wind environment by making appropriate adjustments of the buildings in the residential area. CFD is also used to simulate the temperature field at different times on one typical summer calculated day. The intensities of the heat island effect of the original design program and the improved design program are assessed. Finally, four different greening forms with arbors, trees, artificial lakes and lawns on the basic design are specified and simulated.

METHODOLOGY

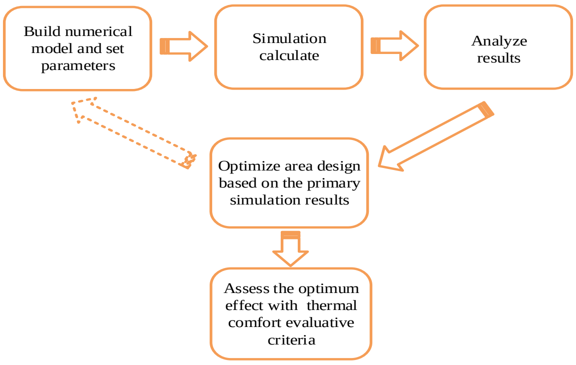


Figure 1 Schematic diagram of the optimal design with CFD simulation for the residential area

In Figure 1, the optimum design for residential district with CFD simulation is composed of these following steps: First, the study method and numerical model are determined, including model parameters with the primary design for analysis. Second, the simulation is performed by using the CFD software. The model simplification is a significant step, which has a great impact on the accuracy of simulation results and the computing time. Third, through comparing model simulation results and the primary design, the current thermal and wind environment are investigated. Finally, the optimum solution are carried out based on the primary results. In particular, some evaluation criteria are selected to assess the effectiveness of the optimum design for creating a resident's thermal comfortable environment, and some suggestions are proposed to designers such as the adjustment of the building layout and vegetation.

In the simulation stage, the CFD software Fluent 14.5 was adopted as the numerical simulation tool, and the standard k-ε model is employed by applying extra terms in the flow, momentum, and energy equations for the aerodynamic effect. In general, analysis of the simultaneous effect of air heat transfer and airflow around the buildings on thermal and wind environment using CFD should consider not only the airflow, but also the solar radiation, long-wave radiation, heat convection as well as comprehensive effects of heat conduction and thermal storage in building materials.

CASE STUDY

Case description

The residential area is located in Qingdao, a coastal city in north China, with highways and an industrial park to the west, another similar residential district to north and east, as well as an urban green park to south. There are totally 22 residential buildings scattered in the area, dominated by high-rise residential buildings. Figure 2 shows the map of the residential area. From the wind rose diagram in the Figure 3, the winter prevailing wind direction in Qingdao is northwest and the average wind speed is 5.3m/s, while the prevailing wind direction in summer is south with a mean wind speed of 4.9m/s. The detailed meteorological data of Qingdao area is illustrated in the Table 1.

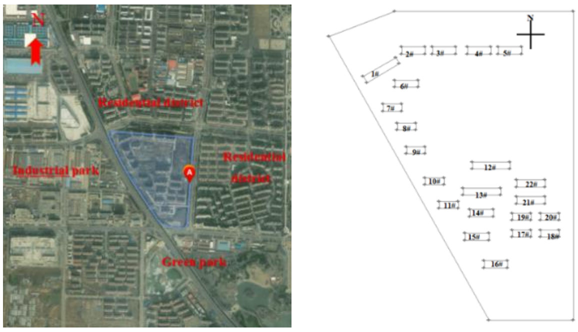


Figure 2 Location layout of the residential area

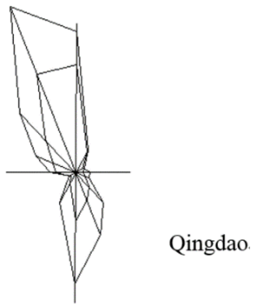


Figure 3 Wind rose diagram of Qingdao

Domain size and grid discretization

Architectural shapes of the buildings in the residential district are made a reasonable simplification due to the little significant impact of complex shapes on the area thermal and wind distribution, which ensure not only the reliability of simulations but also the convergence of the calculation. As the AIJ (2008) recommended, for the size of computational domain, the blockage ration should be below 3% based on the knowledge of wind tunnel tests. The height of the computational domain is determined as 3H (H is the height of the tallest building among the residential area). The inlet and outlet height of the domain are respectively set as 5H and 15H from the actual front and back edge of the

Table 1 Detailed meteorological data of Qingdao

	Prevailing wind direction	**Average wind speed**	**Average air temperature**	**Solar radiation intensity**

Winter	northwest	5.3m/s	/	/
Summer	southeast	4.9m/s	25 ℃	950W/m^2

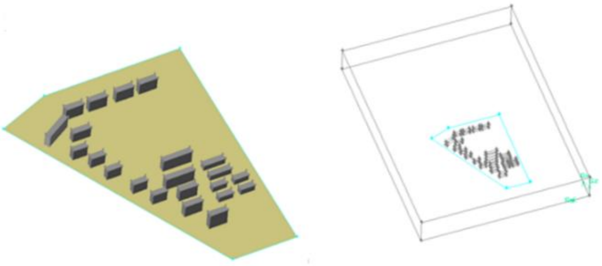


Figure 4 Geometric model and computational domain of the residential area

residential district. The two sides of the domain are both set as 5H from the district outer edge. Then a 1650m×1250m×250m domain is set in this study. The geometric model and computational model are shown in Figure 4.

According to AIJ (2008), the minimum grid resolution should be set to be about 1/10 of the building scale (about 0.5-5.0m) within the region, including the evaluation points around the target building. Then, an unstructured grid system with approximately 1.5 million cells is utilized for numerical silmulation (see Figure 5).

A grid-independence test is conducted by comparing grid systems with different number cells. The number of fine meshes should be at least 1.5 times the number of the coarse meshes in each dimension. Three grid system models with 1.5 million, 3 million and 6

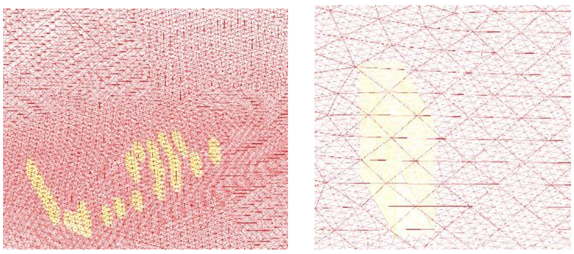


Figure 5 Grid system of the numerical model

million cells were carried out for grid-independence test simulation. Meanwhile, the wind velocity and air temperature at 1.5m high surface above ground of monitoring points (see Figure 6) were compared. The distribution results are shown in Figure 6.

From an overall perspective, the numerical simulation results have not produced significant fluctuations in the tested three grid systems with different numbers of cells. In Figure 6, the distribution trends of wind velocity and air temperature for the same monitoring points achieve a general consensus. Incorporating the condition of calculation speed and accuracy, the present grid system with 1.5 million cells is reliable and can satisfy the grid-independence requirement for the further simulation.

Model parameters and boundary conditions

The coming cross-flow is the atmospheric boundary layer wind, and the average wind speed changes with the height, known as the wind tangent or the wind speed profile. The wind speed profile (v_z) can be expressed using exponential distribution:

$$v_Z = v_0 \left(\frac{Z}{Z_0} \right)^{\alpha} \quad (1)$$

where v_0 is the velocity at the reference height, the reference height is Z_0 =10m, and α is the power-law exponent determined by terrain category. According to the Chinese load code for the design of building structures and the ground surface characteristics of the residential area, α is set as 0.16.

In the simulation, the thermo-physical properties of underlying surface materials as well as the radiant interaction with residential building surface and the underlying surface have a significant influence on the temperature distributions in the area. Given building features in the model, the thermo-physical parameters of building surface material and the underlying surface are set as shown in Table 2.

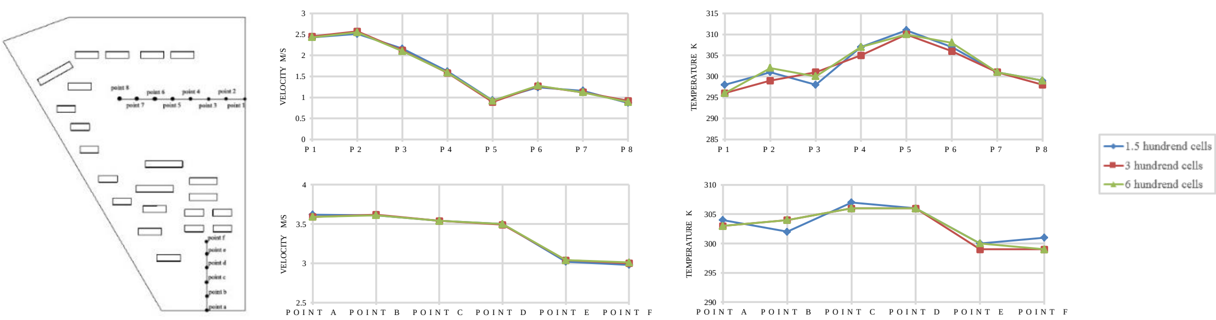


Figure 6 Monitoring points arrangement and the velocity and temperature distribution of monitoring points

Table 2 Thermo-physical parameters of building wall surface and ground surface

	Short-wave reflectivity	**Long-wave emissivity**	**Heat conductivity**	**Density (kgm^{-3})**	**C_p (kJm^{-3}K^{-1})**

			coefficient ($Wm^{-2}K^{-1}$)		
Building wall surface	0.245	0.95	1.16	2150	1600
Ground surface	0.2	0.95	1.16	2000	1600

Table 3 Boundary conditions of the numerical model

BOUNDARY	TYPE	PARAMETER
Inlet	velocity-inlet	k=0.25 ε=0.0067
Outlet	outflow	/
Top surface of the computational domain	wall	radiation heat flux: 950W/m^2
Underlying	wall	thermos-physical parameter of ground surface
Building surface	wall	thermos-physical parameter of building wall surface
Side face of the computational domain	symmetry	/

In the calculation model, considering the influence of the interaction between the solar radiation, residential buildings and ground surface on the thermal environment, the DO radiation model is used and the radiation heat transfer between surfaces is simplified to be the steady-state process. For the feasibility of calculation, the top boundary of calculation field is regarded as the solar radiation emission source. The intensity is set as 950W/m^2 for 12 mid-day summer solar radiation intensity in Qingdao.

Detailed boundary settings of the simulation model are shown in the Table 3.

Results and discussion

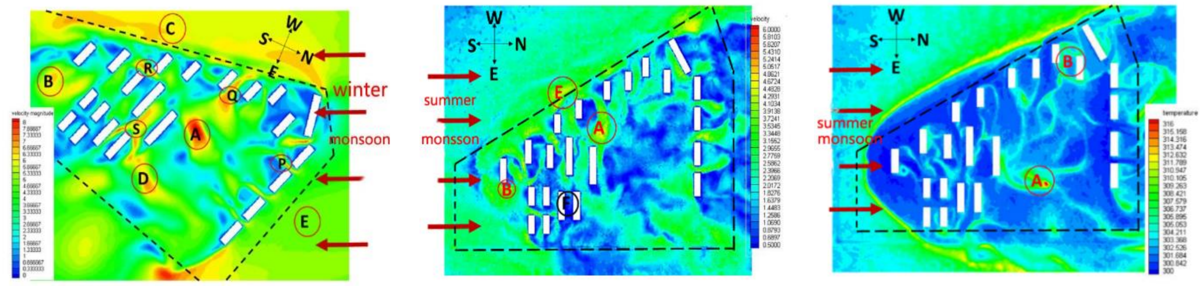
A horizontal plane with a height of 1.5m from the ground is selected as the studied plane for analyzing the temperature and velocity field.

From Figure 7(a,b), it could be concluded that for the original planning and design of residential layout, the average wind speed in winter within the residential quarter in the plane of 1.5m is about 5.1m/s, slightly higher than the comfort level, which may produce obvious sense of cold wind blowing.

The following reasons are concluded. 1) The building layout around C side is easy to form a wind aisle, causing prevailing winter cold air intruding into the community quarter smoothly. 2) There are not any wind settings in peripheral areas of the community along the winter prevailing wind direction (i.e., C and E side) and in an open area of the community (i.e., A, B, and D area). The wind speed is very high, with a maximum sustained value of 7m/s. Comprehensive analyses of residential area wind speed distribution show that a greater wind speed region occurs because these open areas cause larger negative pressure zones integrated by wind with multiple directions crossing around buildings. In addition, in P, Q, R and S areas, the wind speed is very high, which are formed mainly by the building layout and building interval. Usually, high wind speeds are formed with narrow channel when air crossing the area.

Impacted by the summer prevailing wind, the average wind speed of the whole residential area is 4.3m/s. According to the district design, A, B and E areas are the main wind flow channel, and these regional air velocities are slightly higher, but the ventilation effect is good for a uniform air distribution. As can be seen in Figure 5, for F area, the layout of building 21# and 22# cut off the coming wind tunnel, forming wind shadow area where the wind speed in the region fell sharply to a calm state. Surrounding F area, ventilation of buildings is very poor in summer, resulting in poor pollutant dilutions which could have a direct negative impact on outdoor air quality.

In Figure 7(c), the temperature distribution in the residential area is quite uniform, and the average temperature is about 33-37℃. Compared with the summer wind distribution, the temperature distribution is greatly affected by the wind distribution. The main entrance is also the main channel of airflow into the residential area. The wind speed in these areas is frequently high in summer, thus the regional average temperature is usually lower than others, which is close to the inlet air temperature. For A area, a nearly windless area forms by the blocking of buildings. In this windless zone, the corresponding temperature is higher than others due to bad air liquidity, which may result in the reduction of lapsed solar radiant heating by air. In B area, because of the terminals of the summer monsoon, the blocking of front buildings and the undersized building intervals, the temperature is higher than the average.



(a) *(b)* *(c)*

Figure 7 Thermal and wind distribution of the residential district
(a) wind speed distribution of the residential district in winter; (b) wind speed distribution of the residential district in summer; (c) temperature distribution of the residential district in summer

OPTIMUM DESIGN OF RESIDENTIAL DISTRICT

Considering the influence of the wind and thermal distribution on the residents' thermal comfort and air quality under the existing planning, adjustment and optimization solutions are proposed based on the building layout, vegetation greening planning and surrounding environment. As mentioned above, by optimizing the adjustments of the residential area, the simulations of wind and temperature field distribution are performed and the effects of such adjustments are evaluated.

Optimum design of the residential district

- Building layout of residential district

To optimize the summer and winter wind distribution and summer temperature distribution, adjusting the layout of building 21# and 22#, scattering these two and increasing the space between the two buildings are direct and efficient approaches to form a valid coming wind tune into the residential area for the following buildings. Adjusting the position of building 6# and increasing the space between building 1# and 2# are also indispensable and feasible to create a more sound ventilated environment.

- Vegetation

Trees' resistance to the winter prevailing wind and their weakening effect of wind speed on the building channel are taken into account when designing the vegetation solution. Residential district underlying is set mainly with lawns, which can weaken the radiant heating effect of underlying on the air. On the north and west side, planting staggered high trees and low shrubs is acceptable for isolating noise from the adjacent highways and for protection from the winter wind. In addition, planting trees on the regional main entrance and building aisle has a positive effect to improve the local wind environment. Besides, in order to reduce the radiant heating effect, a lake is set in the open area. The optimum design of the residential area is shown in Figure 8.

Model establishment and parameter settings

The improved effects of vegetation on the residential area thermal environment mainly come from the trees' transpiration and its shading effect. The effects on wind environment present in the canopy of trees' blocking flow and reducing wind infiltration. The tree models in the CFD simulation are usually simplified during different computing processes for various tree shapes. Through the simplified simulation of trees by Lin (2004), the results illustrated that the canopy can be simplified to be rectangular models, which has a great advantage for either models or convergence in the simulation. Therefore in this study, the canopy is simplified to be a rectangular model in the simulation, as shown in Figure 9.

The transportation of radiation in the optimized model with vegetation includes solar radiation (short-wave) and long-wave radiation among vegetation canopy and around surfaces. The short-wave (solar radiation) and long-wave radiant fluxes incident to the plant canopy are calculated through a decay exponential function respectively as: $\Phi = \exp(-lka)$, where k is the absorption coefficient for long-wave and short-wave, and l is the length by which radiant flux passes through the plant canopy. The evapo-transpiration, the process by which plants suck up groundwater and evaporate it into the atmosphere, may absorb much heat from the environment in order to reduce the air temperature and increase the air humidity around these vegetation. The heat dissipating capacity from the function of vege-tation transpiration is calculated using Equation (2), where $\varphi_{trans,p\text{-}a}$ is the heat exchange of leaves' transspi-

$$\varphi_{trans,p-a} = 2LAI\frac{0.625\Lambda\rho}{c_p p(r_a + r_i)}\Delta p_{p-a} = 2LAI\alpha_w(d_{a,p} - d_a) \qquad (2)$$

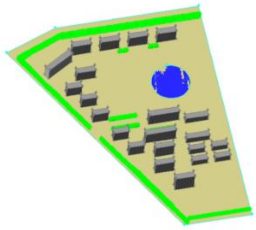


Figure 8 Layout of optimum design

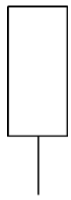


Figure 9 Simplified model of tree

Table 4 Green vegetation parameters in model

	Long-wave dissipation coefficient	Short-wave dissipation coefficient	Long-wave reflection	Short-wave reflection	Transpiration heat release ($kJm^{-2}d^{-1}$)
Lawn	0.85	0.63	0.95	0.15	3018.72
Trees	0.8	0.6	0.95	0.2	6279.25
Artificial lake	0.8	0.6	0.9	0.15	5285.65

ration [W/m^2], LAI is the leaf area index, Λ is the latent heat of vaporization of water [J/kg], ρ is radiation absorptivity, c_p is the air heat capacity at a constant pressure [J/(kg·K)], p is atmosphere transmittance, (r_a+r_i) is total resistance in transpiration [m/s], α_w is the convective coefficients for mass exchange, and d_a is the humidity ratio of air [kg/kg].

During the simulation, the evapo-transpitration of the plants and lake is simplified as a cooling source in the thermal model by using CFD. The thermo-physical parameters of vegetation are set as shown in Table 4. Besides, other parameters and boundary conditions are identical to the original designed models.

Comparative analysis of wind environment results

Select $R = (V_{optimum} - V_{original}) / V_{optimum}$ (V is the wind velocity of the resident district) as the criteria to evaluate the vegetation, and the simulation data are compared for the wind environment at pedestrian level, as shown in Table 5.

In Table 5, it can be concluded that after optimization of vegetation in the residential district, under the identical simulated boundary conditions, the winter and summer wind velocities both decrease. The ration of the maximum wind of the whole residential area with a decreased wind velocity was 36.8% and 34.7% in winter and summer, respectively. Besides, due to the wind-induced effect of vegetation, the average wind velocity of the whole region at pedestrian level decreases obviously.

After adjustment of layout, the simulation results of wind environment in winter and summer are shown in Figure 10 (a,b). Based on the analysis of the summer and winter wind distribution through the adjustment and optimization of residential building layout, the winter wind in the whole area is weakened signifi-cantly with a maximum value less than 4m/s, which means that the drying sense of residents to cold wind could be effectively alleviated. Besides, the vegetation in open areas of the residential area can reduce airflow collection and weaken air swirls. By adjusting the position of building 21# and 22# and increasing space between the two buildings, the summer wind aisle increases the air circulation surrounding the two buildings, which is conducive to the heat diffusion and the pollutant dilution. In conclusion, we can improve the wind environment of the community to increase the thermal comfort of community residents through regional measures, such as adjusting the building layout and increasing plantings.

Results of the residential thermal environment by adjusting building layout and changing the types of underlying are shown in Figure 10(c). It can be seen that the overall temperature is about 26-30 ℃, which is 4-5 ℃ lower than the original design case. In the area near building 1#, 6# and 7#, the average tempera-ture drops significantly due to the layout change of building 6# and the extension of building interval. Therefore, increasing the green vegetation around residential buildings and setting an artificial lake are positive solutions to improve thermal environment, enhance people's comfort, as well as reduce the air conditioning load to some extent.

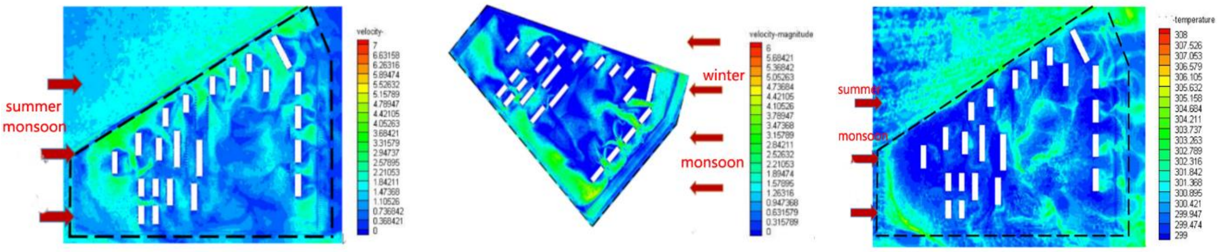
CONCLUSIONS

CFD techniques can simulate and predict the wind speed and temperature distribution formed by airflow around residential buildings. It can obtain the results with direct flow field visualization for observation and judgement, which are conducive for designers and managers to fully consider the microclimate around residential buildings to reduce the negative impacts of

Table 5 Comparison between simulation data with and without vegetation

	Winter		Summer	
	Maximum wind	**Average wind**	**Maximum wind**	**Average wind**

	velocity of region (m/s)	velocity of region (m/s)	velocity of region (m/s)	velocity of region (m/s)
Original model	6.92	5.1	6.31	4.50
Optimum model	4.37	3.15	4.12	3.01
R	36.8%	38.3%	34.7%	33.1%



(a) *(b)* *(c)*

Figure 10 Thermal and wind distribution of the optimum design

(a) wind speed distribution of the optimum design in summer; (b) wind speed distribution of the optimum design in winter; (c) temperature distribution of the optimum design in summer

building layout and underlying types on the thermal environment.

Through comparison of simulation results before and after the vegetation optimization, the outdoor thermal and wind environment is well improved. It illustrates that changing the thermal performance of underlying surface materials (such as trees, artificial lakes, lawns, etc.) to increase the reflectivity of the ground material can reduce the temperature of the ground surface and the sendible temperature in summer.

In addition, building layout should be considered seriously for the regional wind field affected by the air blocking and streaming around buildings. In the case study, through setting ventilation aisles in the residen-tial area by adjusting the building layout in the original design, the optimum solution can meet the general requirement that the wind speed is less than 5m/s at the plane of 1.5m from the ground.

REFERENCES

ASHRAE. 2001. Physiological principles and thermal comfort. In: Handbook of fundamentals, Atlanta; 8.1-8.20.

Chen H., Ooka R., Kato S. 2008. Study on optimum design method for pleasant outdoor thermal environment using genetic algorithms (GA) and coupled simulation of convection, radiation and conduction. Building and Environment. 43(1): 18-30.

China GB. Assessment standard for green building (GB/T 50378-2014) [in Chinese].

Erell E., Pearlmutter D., Williamson T. 2011. Urban microclimate: designing the spaces between buildings. 1st ed. London: Earthscan;

Lin B.R. 2004. Studies of greening's effects on outdoor thermal environment. Doctoral dissertation, Tsinghua University [in Chinese].

Li X., Yu Z. Zhao B. et al. 2005. Numerical analysis of outdoor thermal environment around buildings. Building and Environment. 40(6): 853-866.

Omar S.A. 2010. Prediction of wind environment in different grouping patterns of housing blocks. Energy and Buildings. 42(11): 2061-2069.

Takahashi K. 2004. Measurement of thermal environment in Kyoto city and its prediction by CFD simulation. Energy and Buildings. (36): 771-779.

Tominaga Y., Mochida A., Yoshie R., Kataoka H., Nozu T., Yoshikawa M., Shirasawa T. 2008. AIJ guidelines for practical application of CFD to pedestrian wind environment around buildings. Journal of Wind Engineering and Industrial Aerodynamics. 96: 1749-1761.

Watkiss P. 2011. The ClimateCost Project. Final Report. Volume 1: Europe. Published by the Stockholm Environment Institute, Sweden, 2011[R]. ISBN 978-91-86125-35-6.

Xu P., Huang Y.J., Miller N., Schlegel N., Shen P. 2012. Impacts of climate change on building heating and cooling energy patterns in California. Energy. 44: 792-804.