Research on outdoor wind environment of building groups based on computer simulation

Qian Yi[1]*, Shang Tao[1], Qingming Zhan[1, 2], Liming Bo[1], Jie Yin[1, 2]

[1]*School of urban design, Wuhan University, No.8, South Dong Hu Road Wuhan, Hubei, China*

[2]*Research Center for Digital City, Wuhan University, No.8, South Dong Hu Road Wuhan, Hubei, China*

Received 28 June 2014, www.cmnt.lv

Abstract

Building outdoor wind environment is closely related to indoor air quality and thermal comfort of human, directly affecting the health and quality of life of people living and the building energy consumption at the same time. Enhancing natural ventilation in summer also helps reduce air-conditioning equipment uptime, reducing air conditioning energy consumption and green building should be particularly emphasized natural ventilation. However, in the irrational layout of the buildings or the too high buildings and other factors, outdoor wind will bring no comfort of pedestrians, but also easily lead to loss of energy and increase heating energy consumption, especially in the winter. In this paper, with the careful study of local wind data, wind environment simulation and evaluation and optimized design are conducted about two cases including teaching buildings of Faculty of Engineering in Wuhan University, as well as the modern trade mart layout in Rizhao city of china by using computational fluid dynamics (CFD) technique. Research shows that: 1) Teaching buildings of Faculty of Engineering in Wuhan University have bad ventilation in summer, which cannot meet the green building standards in China. It will bring discomfort to pedestrians on the days of large wind speed in winter and need for windproof design. 2) Through wind environment simulations of modern trade mart plan in Rizhao city, planning of program two is more reasonable than program one in the ventilation by adjusting the building pattern. Using the technique of CFD simulation can guide the existing buildings renovation and architectural planning and design optimization.

Keywords: wind environment, natural ventilation, building environment, computer simulation, CFD

1 Introduction

Wind environment is the status of airflow into and out of buildings and its impact on them [1]. Wind can be a friend of a building because it can naturally ventilate the building, providing a comfortable and healthy indoor environment, as well as saving energy [2]. Natural ventilation can be used for cooling in the spring and autumn for a moderate climate; the spring for a hot and dry climate; the summer for a cold climate; and the spring and summer for a mild climate. Natural ventilation can also be used to cool environments in a hot and humid climate during some of the year [3]. What's more, natural ventilation also has an important significance in the hot summer and cold winter area, especially in the middle of China along the Yangtze River area, take Wuhan city of China as an example. In this area through the summer natural ventilation can take away the heat inside the building group.

On the other hand in the area of hot summer and cold winter wind can be an enemy to a building mostly in winter when it causes discomfort to pedestrians-usually as a result of high wind speed around the building. Table 1 summarizes the effects of wind on people [4]. Beaufort number classifies wind as 0 (calm) to 12 (hurricane). The wind speed is normally referred to as the speed of wind at 10m above an open terrain. The wind speed at pedestrian level (about 1.5m high) is roughly 70% of the tabulated values. Visser [5] proposed comfort criteria with different activities versus the frequency of wind speed higher than 5 m/s, as shown in Table 2. For example, in an area where the number of day with an averaged wind speed higher than 5 m/s is 200 days per year (or the frequency of wind with a speed higher than 5 m/s is 200 days/365 days x 100 = 55%), people who walk fast would feel unpleasant. Clearly, wind speeds greater than 5 m/s are considered uncomfortable for most pedestrians. Therefore, it is very essential to reduce the wind speed around buildings.

In addition, hot in summer and cold in winter climate, it is very important to keep cold temperatures out during the winter by reducing wind speed and promote natural ventilation enhancing thermal comfort during the summer by increasing wind speed around buildings.

This paper takes the teaching buildings of Faculty of Engineering in Wuhan University and the modern trade mart plan in Rizhao, China as research objects and employs Computational Fluid Dynamics (CFD) technology to perform a digital analysis of the wind environment.

***Corresponding author** e-mail: qianyiwhu@gmail.com

TABLE 1 Wind effect on people

Beaufort no.	Description	Wind speed(m/s)	Wind effect
2	Light breeze	1.6-3.3	Wind felt on face
3	Gentle breeze	3.4-5.4	Hair disturbed; clothing flaps; newspaper difficult to read
4	Moderate breeze	5.5-7.9	Raises dust and loose paper; hair disarranged
5	Fresh breeze	8.0-10.7	Wind force felt by body; possible stumbling when entering a windy zoon.
6	Strong breeze	10.8-13.8	Umbrellas used with difficulty; hair blown straight; difficult in walking steadily; wind noise on ears unpleasant
7	Near gale	13.9-17.1	Inconvenience felt when walking
8	Gale	17.2-20.7	Generally impedes progress; great difficulty with balance in gusts
9	Strong gale	20.8-24.4	People blown over

TABLE 2 Coal property parameters and experiment ignition temperature

Activities	Acceptable (%)	Unpleasant (%)	Intolerable (%)
Walking fast: car-park, sidewalk, road, cycle-track	35	35-75	75
Strolling : park, shop centre, footpath building entrance, bus station	5	5-35	35
Sitting/standing short: shop centre, square, playground	0.1	0.1-5	5
Sitting/standing long: terrace, swimming pool, open theatre	0	0-0.1	0.1

2 Methods of analysing the wind environment

There are three methods of studying the wind environment around buildings: field measurements, wind tunnel testing, and Computational Fluid Dynamics (CFD) simulation [6].

2.1 FIELD MEASUREMENTS

The Field measurements are a method using spot investigation and first-hand information collection. But it has difficulties in precisely measuring factors of the wind environment and the long-term accumulation of observation in a large range. Yafeng Gao [7] presents a study on the effects of wind induced airflows through urban built form using statistical analysis. The data employed in the analysis are from the year-long simultaneous field measurements conducted at the University of Reading campus in the United Kingdom. Factor analysis of the measured data identified meteorological and architectural layout factors as key factors. The derivation of these factors and their variation with the studied built forms are presented in detail. Figure 1 shows a field weather measurement at the experimental site.

2.2 WIND TUNNEL TESTING

Wind tunnel testing is a method with a high degree of dependability. Gandemer [8] has simulated several aerodynamic effects that may occur around buildings depending on wind tunnel tests. Such effects can be descriptively used to interpret airflow behaviour in urban environments. For example, Ventura effect can be observed when a narrow distance between two buildings exists. In this case, airflow passing in this distance, known as Ventura nick, is restricted by buildings' walls. This increases its velocity until it leaves this narrow area, where airflow slows down. Another effect is the corner effect. Airflow becomes extremely turbulent at building corners, where the zones of positive and negative pressure interact within a radius equal to building width. Kubota et al. [9] investigated the relationship between the average wind speed at pedestrian-level and building density of actual residential neighbourhoods depending on several wind tunnel tests. These residential neighbourhoods were selected to represent different building coverage ratios and different building heights. The study produced detailed data that emphasize the strong relationship between the coverage ratio and the mean wind velocity ratio, where increasing this ratio decreased wind speed on site. This helped in proposing some planning guidelines regarding the suitability of using detached houses or apartment buildings to achieve acceptable wind environment considering the climatic conditions of Japan. Figure 2 shows a site model placed in a wind tunnel.

2.3 COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION

The numerical simulation of fluid flow, discretely analyses air flow by computer, following hydrodynamic equations. The results are expressed visually by computer graphics. Such numerical simulation technology is called Computational Fluid Dynamics (CFD). This technology has been widely used in manufacturing industries since 1974. And in recent years researchers have applied CFD to the simulation of building environments. Cheung JOP [10] explores the effects of building interference on natural ventilation using computational fluid dynamics (CFD) techniques. Building disposition is therefore one of the feasible solutions to improve the natural ventilation performance in our crowded environment. Sun Z [11] presents a CFD-based virtual test method for control and optimization of indoor environment by combining a ventilated room with a ventilation control system. Figure 3 shows CFD simulation figures. In this paper, CFD analysis was conducted by using PHOENICS software. PHOENICS [12] uses the standard k–ε model [13], staggered grid distribution [14], and simple algorithm. It can be used to simulate flow and heat transfer with PHOENICS calculations. It is the world's first set of computing and computational fluid heat transfer commercial software. Wind speed and wind pressure around buildings are calculated in this research.

FIGURE 1 Field weather measurement

FIGURE 2 Building model in a wind tunnel

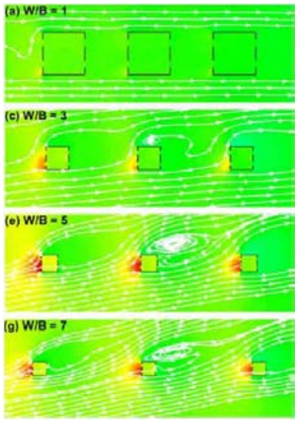

FIGURE 3 CFD simulation figures

3 Simulation analysis of Outdoor wind environment of building groups

Outdoor wind environment design will be illustrated by two application examples. The first example concerns the teaching buildings of Faculty of Engineering in Wuhan University, and the second is modern trade mart plan in Rizhao city of china.

3.1 TEACHING BUILDINGS OF FACULTY OF ENGINEERING IN WUHAN UNIVERSITY

Wuhan is located in the middle and low latitudes, which has a subtropical monsoon climate, four distinct seasons, abundant sunshine, hot in summer and cold in winter, frost-free period long. The annual average temperature of Wuhan is 16.2-16.7 degree, mostly northeasterly wind in winter and southeasterly wind in summer. According to Wuhan meteorological data, the annual average wind speed is 2.5-2.9 m/s, with an average wind speed up to 3 m/s or more in thirty percent days in whole year and average maximum wind speed of 14-19 m/s. The main monthly wind direction and frequency of Wuhan with many years' observations is shown in Table 3.

TABLE 3 The main monthly wind direction and frequency of Wuhan

Month	1	2	3	4	5	6	7	8	9	10	11	12	Whole year
Wind direction	NE	NE	NE	NE	NE	SE	WE	NE	NE	NE	NE	NE	NNE
Wind frequency(%)	18	19	16	12	10	9	10	14	18	17	20	20	14

The dominant wind direction in summer and winter can be obtained from the wind rose figure of Wuhan as Figure 4 shows. The typical working conditions of southeast winds in summer and northeast winds in winter were simulated by PHOENICS so that the Teaching buildings of Faculty of Engineering in Wuhan University could be analysed at a technical level. Figure 5 shows the CFD simulation wind direction layout.

Figure 6 shows a model of teaching buildings of Faculty of Engineering in Wuhan University designed by Jingtang He (Chinese Academy of Engineering). Since this campus building has windy surroundings and uncomfortable wind speed affect based on investigation of many students in campus, the outdoor wind comfort in the area is concerned. At one time the main building is too high (about height of 65 meters) which affect the landscape axis of Wuhan University. The University wanted to remove half floors of the main building. Since understanding possibility impact of wind environment on the area after removing half floors, the University initiated a study of the wind distribution around the teaching buildings of Faculty of Engineering in Wuhan University.

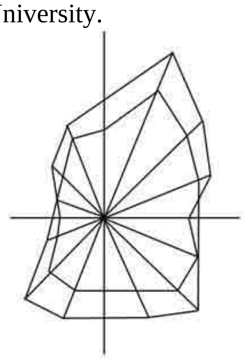

FIGURE 4 Wind rose figure in Wuhan

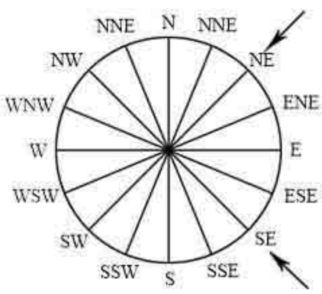

FIGURE 5 CFD simulation wind direction layout

FIGURE 6 Main teaching building (left) and its surrounding (right)

The models of the teaching buildings of Faculty of Engineering in Wuhan University can be established by AutoCAD. (In Figure 7, there is the original state on the left and the completion of removing half floors of the main teaching building on the right.) Figure 7 is the CFD simplified model of the teaching buildings and the main object is the wind environment in the teaching buildings. The boundary of the model is 1200m × 1200m × 200m; the model scaling is 1:1; the foundation is at the height of 0m.

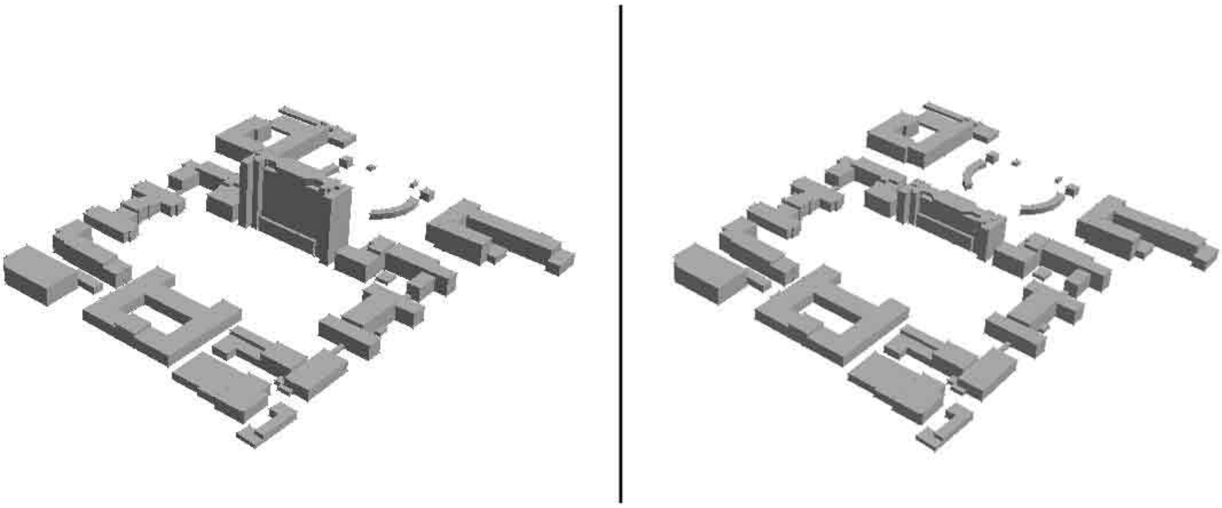

FIGURE 7 The simplified model made by AutoCAD

The reasonable boundary condition must be determined right after the confirmation of mathematical models and the governing equations so that the simulation will be as close to the real situation as possible. To analyse the wind velocity and wind direction in the teaching buildings of Faculty of Engineering in Wuhan University, the wind velocity and wind direction frequency graph mentioned above should be used to confirm the wind velocity and direction which are the input used for simulating the region. The inlet is defined as PHOENICS velocity-inlet boundary condition which is calculated under the typical working conditions in summer (southeast winds, 3m/s) and winter (northeast winds, 2.8m/s). The outlet is defined as the free outflow boundary condition.

Figures 8 to 11 are the wind velocity distribution of teaching buildings of Faculty of Engineering and after removing half floors of the main building in the summer and the winter at the height of 1.5m (pedestrians' height). As can be seen from the comparison between Figure 8 and Figure 10, the main building is too high that lead to bad ventilation in summer in the whole teaching buildings area. Wind speed around teaching buildings behind the main teaching building declines sharply and wind shaded area becomes larger which is not beneficial to ventilation. The average wind speed of the whole area is larger after removing half floors (about 30 meters). Therefore, removing half floors of the main building is necessary that not only promote the teaching buildings' outdoor natural ventilation to improve comfort, but also can reduce the use of air conditioning in summer and save energy under the hot summer environment in Wuhan. In addition, with the comparison between Figure 9 and Figure 11, wind speed of the road area next to the main teaching building where students often need go through is very large especially in the days of large wind speed of outdoor atmosphere. Wind speed ratio (Index of wind environment evaluation) around the main teaching building is almost up to two, which means wind in this area is too large causing discomfort of students in winter. Therefore, removing half floors of the main teaching building is beneficial for ventilation in summer and windproof in winter.

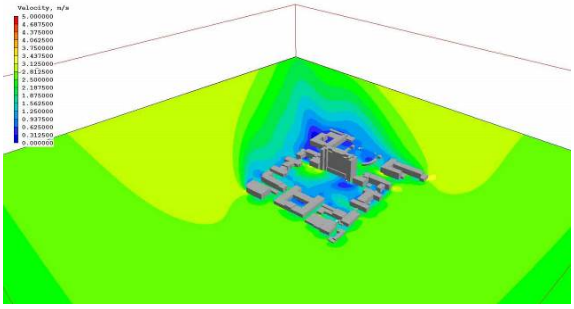

FIGURE 8 Wind velocity distribution of teaching buildings of Faculty of Engineering in summer at the height of 1.5m

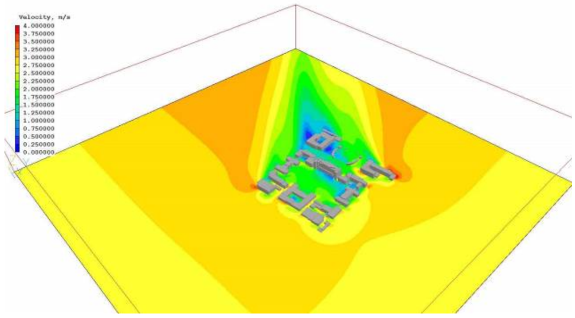

FIGURE 10 Wind velocity distribution of teaching buildings of Faculty of Engineering in summer at the height of 1.5m (after removing half floors)

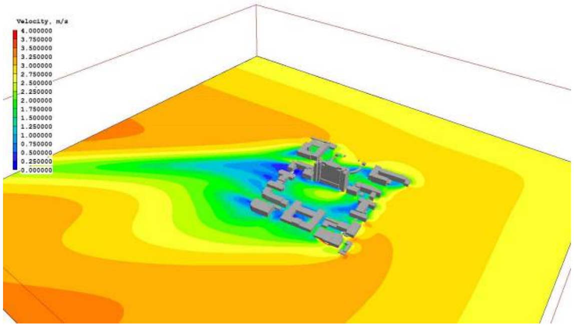

FIGURE 9 Wind velocity distribution of teaching buildings of Faculty of Engineering in winter at the height of 1.5m

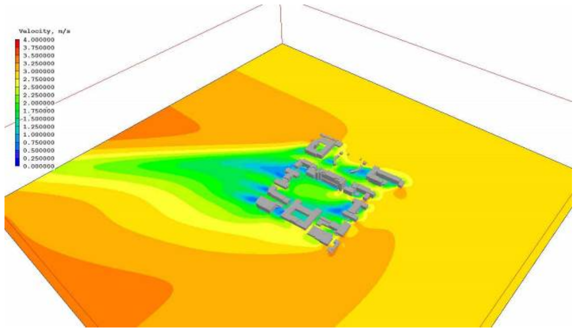

FIGURE 11 Wind velocity distribution of teaching buildings of Faculty of Engineering in winter at the height of 1.5m (after removing half floors)

3.2 MODERN TRADE MART PLAN IN RIZHAO CITY OF CHINA

The project of modern trade mart plan is a building bidding project in Rizhao city of china designed by the author and his design team. The project is a design of commercial complex, including hotel, commercial, office, residential. In order to obtain an excellent design scheme, two design schemes are created. Since both of the two design schemes can meet the design requirements in building function and form, the author wants to conduct wind environment simulations using CFD to judge which scheme is better. Figure 12 shows the final design rendering of general lay out plan and three-dimensional bird's-eye view.

FIGURE 12 General lay out plan (left) and three-dimensional bird's-eye view (right)

The models of modern trade mart plan one and two established by AutoCAD are seen in Figure 13. As can be seen from Figure 13, there are some differences between plan one and plan two in building form. Area of (A) of plan two cancels the shops along the street which makes area of (A) more open. Areas of (B, C, and D) of plan two remove the bottom two floors of the buildings which make the walking streets connectivity from south to north. Area of (E) slows down the polyline angle of commercial streets and the smaller angle of the building form is better to natural ventilation.

The inlet is defined as PHOENICS velocity-inlet boundary condition which is calculated under the typical working conditions in summer (southeast winds, 3.7m/s) and winter (north winds, 5m/s) based on wind rose figure of Rizhao city.

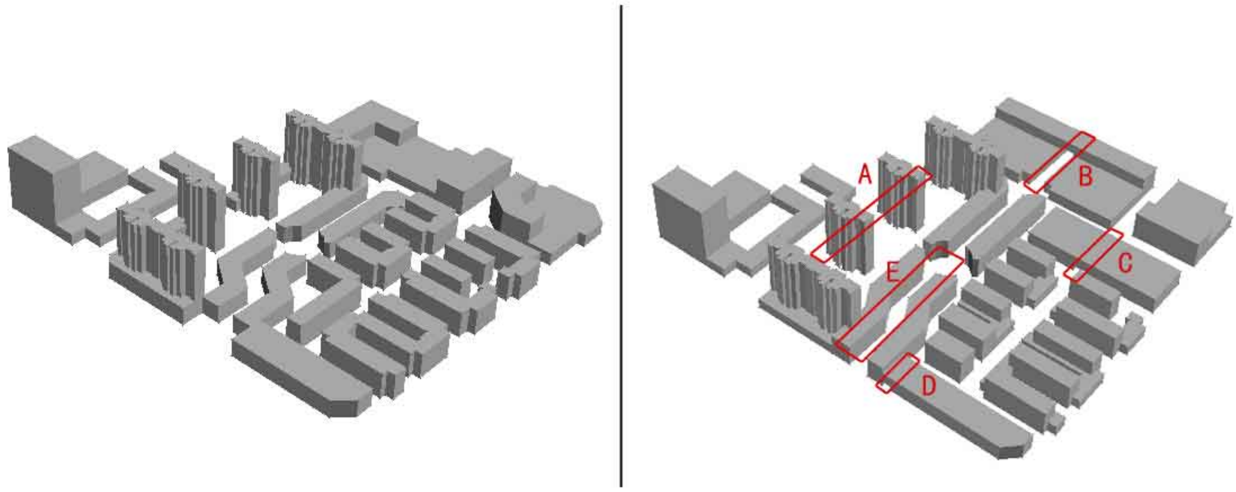

FIGURE 13 Models of modern trade mart plan one (left) and plan two (right)

Figures 14 to 17 are the wind velocity distribution of modern trade mart plan one and two in the summer and the winter at the height of 1.5m (pedestrians' height). As can be seen from the comparison between Figure 14 and Figure 16, the average wind speed of plan two is higher than plan one which means plan two has better ventilation than plan one in summer. In addition, the region of low wind speed of plan one is much more than plan two that will cause discomfort for customers or residents. Wind speed of region of (A) in plan two is bigger than plan one. Wind speed of region of (B, C, and D) and streets' wind speed in plan two are significantly increased. Therefore, by changing the buildings' form can promote the building's natural ventilation and improve comfort of people in summer. With the comparison between Figure 15 and Figure 17, wind velocity distribution of plan two in the region of (A, B, C, and D) and other regions is more uniform and better than plan one. Wind speed ratio (Index of wind environment evaluation) around the modern trade mart is less than two, which means wind in this region is reasonable and comfortable for customers or residents in winter. Therefore, changing buildings' form is beneficial for ventilation in summer and winter.

The wind environment distribution, the influence of the main teaching building and changing buildings' form on the nearby wind environment, and the space changing rule of an atmospheric flow field can be visually observed through simulating and analysing two cases in summer and winter. As a result, we can draw three conclusions:

1) Including the use of PHOENICS should become standard in the planning and construction of building groups. Because the wind environment affects energy use and wind comfort, the layout and positioning of buildings in architectural complexes should promote natural ventilation and increased air circulation.

2) There are a diverse range of wind zones in the leeward side of high-rise buildings, and on the windward side, there are high-velocity areas that have serious effects on the surrounding environment.

3) Changing layout and form of buildings' group have beneficial to wind environment that can reduce wind shaded area and make the wind velocity distribution of whole building groups uniform and reasonable.

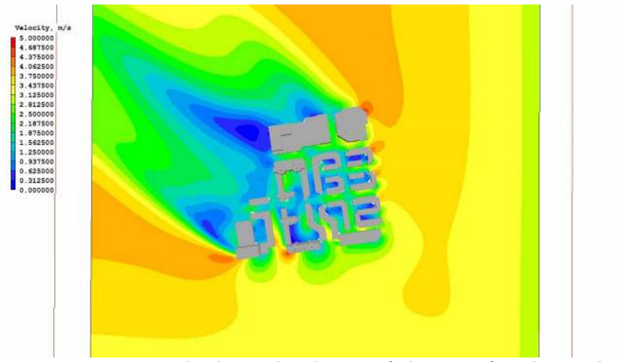

FIGURE 14 Wind velocity distribution of plan one of modern trade mart in summer at the height of 1.5m

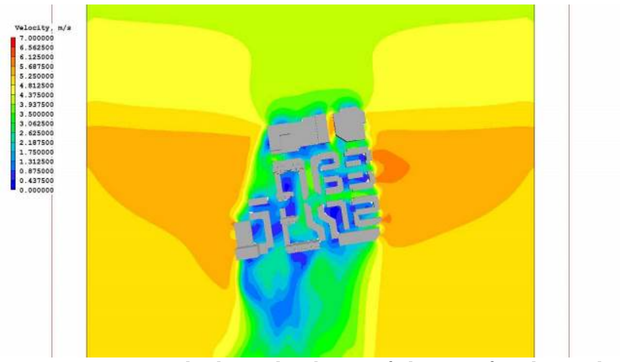

FIGURE 15 Wind velocity distribution of plan one of modern trade mart in winter at the height of 1.5m

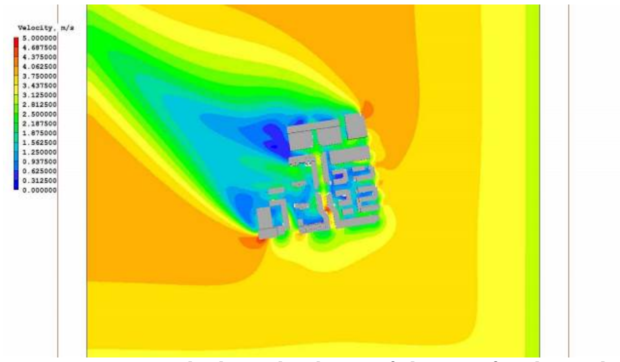

FIGURE 16 Wind velocity distribution of plan two of modern trade mart in summer at the height of 1.5m

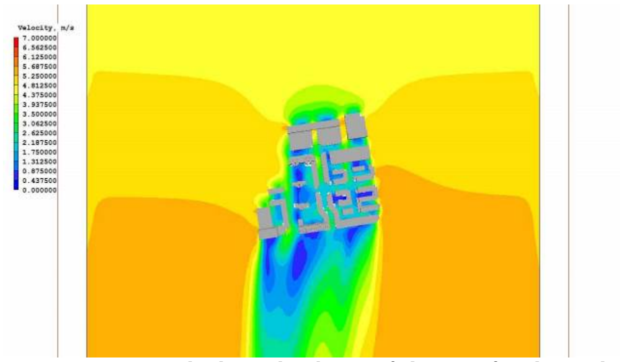

FIGURE 17 Wind velocity distribution of plan two of modern trade mart in winter at the height of 1.5m

4 Conclusions

This paper discusses the available methods for designing a building to take advantage of the wind, such as field measurement, wind tunnel testing, and computational fluid dynamics (CFD). CFD can provide detailed and useful information and is becoming an attractive and popular design tool. Simulation analysis of Outdoor wind environment of building groups illustrate how to collect wind information, develop different strategies for outdoor environment design, and use a CFD software PHOENICS to conduct the design. The outdoor wind design aims at developing pedestrian thermal comfort by varying building form.

In the environment, wind directly affects the lives of people. The wind environment is important not only to climate, but also to architecture's volume, layout, orientation, etc. Architects should factor the wind environment into their designs. They can do this easily by computer simulations of the wind environment that use CFD software. Furthermore, the wind environment and its contributions to natural heating, cooling, and good air quality should be considered as part of the approval process of residential districts by city planning and city construction departments of local governments. Such considerations can lead to improvements in the quality of life for local residents.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (Project No. 51378399). The author wishes to thank all teachers who help me for their contributions at college of urban design in Wuhan University.

References

[1] Boulard T, Haxaire R, Lamrani M A 1999 Characterization and modeling of the fluxes induced by natural ventilation in a greenhouse *Journal of Agricultural Engineering Research* **74** 135-44

[2] Chen Qingyan (Yan) 2004 Using computational tools to factor wind into architectural environment design *Energy and buildings* **36** 1197-209

[3] Lechner N 2009 *Heating, Cooling, Lighting: Design Methods for Architects* 2nd ed., John Wiley & Sons, Inc **28**(7) 695-701

[4] Bottema M 1980 Wind climate and urban geometry *Ph.D. Thesis, Eindhoven University of Technology Eindhoven The Netherlands*

[5] Visser G Th 1980 Windhindercriteria: een litertuuronderzoek naar envoorstellen voor het hanteren van unforme TNO-windhindercriteria (in Dutch) *Report 80-02746 IMET-TNO Apeldoorn The Netherlands*

[6] Li Y 2010 Computational fluid dynamics technology and its application in wind environment analysis *Journal of Urban Technology* **17** 67-81

[7] Gao Y, Yao R, Li B, Turkbeyler E, Luo Q, Short A 2012 Field studies on the effect of built forms on urban wind environments *Renewable Energy* **46** 148-54

[8] Gandemer J 1975 Wind environment around buildings: aerodynamic concepts *in: Proceedings of the Fourth International Conference on Wind Effects on Buildings and Structures Cambridge University Press Cambridge* 423–32

[9] Kubota T, Miura M, Tominaga Y, Mochida A 2008 Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: development of guidelines for realizing acceptable wind environment in residential neighborhoods Build *Environ* **43** 1699–708

[10] Cheung JOP Liu C-H 2011 CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings *Energy and Buildings* **43** 1149-58

[11] Sun Z, Wang S 2010 A CFD-based test method for control of indoor environment and space ventilation *Building and Environment* **45** 1441-7

[12] CHAM PHOENICS Version 3.3 CHAM Ltd., London UK 2000

[13] Launder B E, Spalding D B 1974 The numerical computation of turbulent flows *Computer Methods in Applied Mechanics and Energy* **3** 269-89

[14] Patankar S V 1980 Numerical heat transfer and fluid flow *Taylor&Francis*

Authors

Yi Qian, born in December, 1986, Jiujiang City, Jiangxi Province, P.R. China

Current position, grades: the PhD candidate of School of urban design, Wuhan University, China.
University studies: his B.Sc. in Industrial Design from Northwest A&F University, M.Sc. from Wuhan University in China.
Scientific interest: architectural design, green building, and digital architecture.
Publications: 5 papers.
Experience: completed 3 scientific research projects.

Tao Shang, born in May, 1956, Xinyang City, Henan Province, P.R. China

Current position, grades: the professor of School of urban design, Wuhan University, China.
University studies: M.Sc. from Jilin University, PhD from Wuhan University in China.
Scientific interest: computer applications; heritage conservation.
Publications: 30 papers.
Experience: teaching experience of 30 years, 5 scientific research projects.

Qingming Zhan, born in September, 1964, Yongan City, Fujian Province, P.R. China

Current position, grades: the professor of School of urban design, Wuhan University, China.
University studies: M.Sc. from Wuhan University in China, PhD from Wageningen University in the Netherlands.
Scientific interest: new technology of urban planning, planning support system, urban environmental analysis and duct ventilation plan.
Publications: 50 papers.
Experience: teaching experience of 25 years, 10 scientific research projects.

Liming Bo, born in October, 1982, Qingdao City, Shandong Province, P.R. China

Current position, grades: the PhD candidate of School of urban design, Wuhan University, China.
University studies: B.Sc. in Urban Planning from Wuhan University, M.Sc. from Wuhan University in China.
Scientific interest: eco-city, green building, and green city planning.
Publications: 5 papers.
Experience: teaching experience of 3 years, 3 scientific research projects.

Jie Yin, born in September, 1987, Songzi City, Hubei Province, P.R. China

Current position, grades: the PhD candidate of School of urban design, Wuhan University, China.
University studies: B.Sc. in Urban Planning from Donghu University of Wuhan, M.Sc. from Wuhan University in China.
Scientific interest: urban sustainability, urban planning.
Publications: 5 papers.
Experience: 4 scientific research projects.