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Original Research Paper

Research on Building Wind Environment Based on the Comparison of Wind Tunnel Experiments and Numerical Simulations

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ABSTRACT

With the continuous development of computer, computer numerical simulation is widely applied. In this paper, a combination of experimental and theoretical analysis, wind tunnel experiments and numerical simulation results are compared. It is anchored to the architectural wind environmental studies, explored the relationship between the environment and the building and the role of the environment on the building development, and the impact of the wind environment on the architectural design and the structural design, in order to restore the positive interactions between the environment and the building, and lay the foundation for the road to the sustainable development of the building.

INTRODUCTION

With the emergence of high-level and high-density buildings in the city, the urban spatial structure is becoming more and more complicated. And wind problems generated by it have already caused the attention of people. Therefore, the research of building's wind environment is very necessary. Because of the complexity of air flow and object geometry, many problems of aerodynamic research can not be simply solved by theories or computational methods. We have to conduct a lot of wind tunnel experiments to find the law or provide data. Wind tunnel experiment can provide reliable assessment to the outdoor wind environment in the human height. It can also be used to investigate the other factors, such as solar radiation, humidity, pollutant diffusion, etc. Before the use of computational method, wind tunnel experiment is the main research method of building's wind environment (Plate 1999). However, with the rapid development of computational method, it has been widely applied in many aspects. This paper combines the experiments with the theoretical analysis, and makes a comparison between wind tunnel experiments and computational simulation results. Meanwhile, based on the research of building's wind environment, it explores the relationship between environment and building, and explores the wind environment's impacts on architectural design and structural design. One most important purpose of this paper is to seek the sustainable development road of future architectural design.

OVERVIEW OF WIND FIELD

Characteristics of wind field: The main characteristic of the wind is its velocity. But the earth's surface will produce the frictional resistance to the horizontal air flow, which can reduce the speed of the air flow. This resistance will be weakened with the height increase. Reaching a certain height, we can ignore the influence of the ground resistance. The air will flow along the isobar in a gradient velocity (Emile 1922). And we call it as the height of atmospheric boundary layer or the boundary layer thickness. We use δ to express the atmosphere which is above the boundary. Meanwhile, we regard the beginning height of the gradient wind velocity as wind gradient velocity height, use Z_G to express it, and use V_{zG} to express the gradient wind velocity.

There are two main types of average wind profiles: (1) logarithmic rotameter, (2) index percent. However, because the difference of them is not obvious, we usually adopt index percent according to the calculation need. The formula is as follows (Zhang 2006):

$$V_{AVERAGE}(z') = v^*_{AVERAGE} \times \ln(z'/z_0)/k$$

k is Karman constant, and we take 0.40 as k; z' is the effective height; $v_{AVERAGE}$ (z') is the average wind velocity in z' height within the atmospheric bottom, $v^*_{AVERAGE}$ is the friction velocity, and Z_o is the length of terrain roughness.

What can be measured in actual record is wind velocity. However, we need to adopt wind pressure to conduct calculation during the process of engineering design. The transformation formula is as follows:

$$w_0 = \frac{1}{2} r v_0^2$$

According to China's specific standard, the definition formula of basic wind load can be concluded as: Basic wind load is the average maximum wind velocity (m/s) at the 10m high.

Standard value of average wind load which is perpendicular to the surfaces of buildings can be calculated with the following formula:

$$w_{cz} = \mu_s \mu_z w_0$$

w_{cz} is the standard value of average wind load; μ_s is the shape coefficient of wind load; μ_z is the height variation coefficient of wind load; w_0 is the basic wind load.

Influence of wind field: Wind can be divided into two types: static wind load and fluctuating wind. The main classification is according to the wind frequency. Usually, compared to the frequency of building structure, the static wind load has a much bigger difference. Therefore, the resonance phenomenon will not appear. Considering the static wind, we regard it as the transverse load which is equally distributed. Because of the fluctuating wind's frequency, it will cause the structural vibration and make people feel uncomfortable.

After long-time research and the accumulation of experience, the wind influence on architectural structure can be concluded as follows:

1. It makes the structure or structural member receive a large wind and become unsteady.
2. It makes the structure or structural components produce excessive deflection or deformation, which can cause the damage of exterior walls and exterior decoration materials.
3. Because of the effect of repeated wind vibration, the structure or structural components become
4. Aeroelastic instability, leading to structures in the wind movement greater aerodynamic.
5. Due to excessive dynamic movement, so that building occupants or personnel without comfort.

BUILDING WIND ENVIRONMENT ASSESSMENT

Building wind environment assessment mainly investigate the factors, such as temperature, solar radiation, humidity, pollutant distribution, etc., which can affect human comfort. It also studies the influence of wind field on the building, and explores building environmental assessment methods.

Pollutant dispersion: Of different wind conditions on city streets intersection, convection-diffusion of contaminants in the law of effect, in the free stream wind speed of 5.37m/s (400mm height) under the conditions of the laser system has been tested. Concentration field line source (traffic sources) emissions pollution material in the proliferation of urban road intersection design will be derived from experimental analysis of digital images to achieve relative quantification of the effect, then the numerical simulation and wind tunnel test results were analysed to achieve the same qualitative results. Near the intersection of the city and to predict the air quality within buildings and how to improve air quality to provide a basis on which to make the intersection does not become a heavily polluted area and the post-improvement work is also the main significance of the study.

Wind resistance: During the actual calculation of building structure, the main consideration is its ability to safe and economical to use in the period, with a complete variety of predetermined functions.

Security and economy are major design goals, and the probability-based structural reliability of the calculations rely on the theory of rationality as a theoretical basis for use at this stage is an important indicator of structural safety analysis by a reliable indicator of B to specifically measure the reliability of the structure. In general, the structure of the limit state refers to the entire structure or a part of the destruction of the structure does not meet the design makes it functional requirements.

Thus, when wind-resistant design of structures, mainly for its bearing capacity, deflection, and fatigue damage were studied in order to ensure a certain degree of reliability, thus ensuring both security and economic structure, and for a reasonable planning and design structure.

According to common sense we can understand that the main component is the horizontal wind component, for tall structures, high-rise structure, the horizontal component is the main object of study, while the vertical component can be ignored, and a great structure for the horizontal projection plane must taking into account the two. The high wind and soft for vertical, horizontal long, thin flexible structure has a decisive role. Generally speaking, are based on a few levels of structural adjustment arrangement, structure and other methods to better play structure, function, and now is the use of vibration control devices to reduce the response approach to the purpose. Under action of the wind, not only to the vibration of the wind, but also produce cross-wind vibration, especially in the cross-wind vortex shedding resonance case, the magnitude of vibration at the same level with the wind, or even more. In addition, people's living standards improvement is not only for buildings with strength, stiffness and stability requirements, but also requires adequate structures comfort requirements.

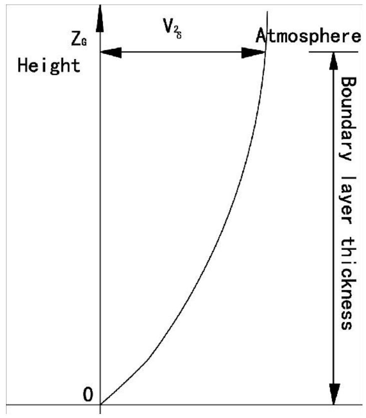


Fig. 1: Atmospheric boundary layer.

SIMULATION METHOD OF THE EXPERIMENTS

What is studied in this paper is as follows: Block A, United Plaza, Shanghai Tongji and B, two high-grade commercial office buildings located at the intersection of the road the wind environment simulation. Two buildings of 22 layers, each about 4 meters, a total of 88 meters, are cylindrical side floor, following the construction of wind tunnel experiments and numerical simulations.

Wind tunnel experiments: Wind tunnel experiments is a specially designed pipe, the use of experimental power plant in the pipeline segment to create the air flow speed which can be adjusted, for all types of aerodynamic experiments. Generally, from the cave tunnel, drive systems and measurement system are composed of three parts. According to the relative liquidity and similarity theory, the experimental model is fixed in the experimental section, and artificially create the ideal airflow through auxiliary means to obtain experimental data. Simply put, wind tunnel that is created artificially in the laboratory a "atmospheric boundary layer."

Atmospheric boundary layer wind tunnel simulation of wind environment in an experimental basis, to ensure that the simulated atmospheric boundary layer and the actual conditions of the atmospheric boundary layer are similar to the mock object. As the surface roughness of different levels of friction, the resulting change in average speed with height and wind speed is slower at closer to the surface. In the boundary layer at the top of the gradient wind speed is usually called. Fig. 2 shows the different average wind speed on rough terrain changes with height (Niu 1993).

Experimental model: Geometric model in wind tunnel experiments to ensure similar conditions, and to choose a good model of reduced scale ratio was used. Reduced scale model wind tunnel test section size must have the air flow not blocked by obstructions to the flow leaving the wind speed

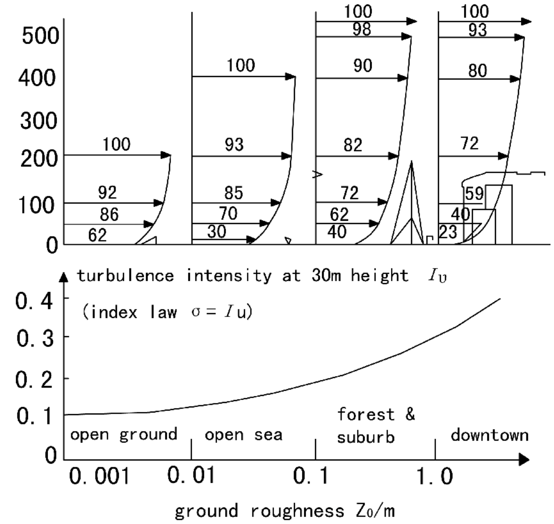


Fig. 2: Change of wind velocity in different heights and terrain roughness.

and wind speed is too large to cause obstruction (Tao 2003). To ensure the geometric model that physical appearance is similar to the flow of solid wall boundary, conditions are similar in Shanghai Tongji Union Square Block B and Block A, and the intersection of the two commercial buildings and the physical model using the ratio of 1:250. Fig. 3 shows the intersection of buildings with high temperature glass production, keeping the wall smooth.

Wind tunnel: DC suction wind tunnel experiments steel form is shown in Fig. 4 with total length of 33m, the test section length 18m, width 2.5m of the structural parameters, wind speed 0.5m/s ~ 20m/s, power of 90 kilowatts of electric fans (SCR power and promise speed) of the operating parameters, the use of speed in homogeneity ≤ ± 1%, maximum speed of 50% to 80% range, dynamic pressure fluctuation ≤ 1%, pitch direction of ≤ ± 0.5°, yaw direction ≤ ± 1°, turbulence intensity ≤1% of the flow quality (Qian 1955). As the wind tunnel test section is longer, you can make the full development of the boundary layer airflow, the study area to meet the airflow requirements.

(1) Turbulent viscosity:

$$h_t = C_m r k^2$$

(2) Continuity equation:

$$\frac{\partial(r u_i)}{\partial x_i} = 0$$

(3) Momentum equation:

$$\frac{\partial(r u_i u_j)}{\partial x_i} = \frac{\partial}{\partial x_i}(h_{off}\frac{\partial u_i}{\partial x_i}) - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}(h_{off}\frac{\partial u_i}{\partial x_j})$$

Fig. 3: Physical models located in the urban road intersection (experiment of university of Shanghai for science and technology).

(4) K equation:

$$\frac{\partial(ru_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}\{(h+\frac{h_t}{s_k})\frac{\partial k}{\partial x_i}\}-re+h_t(\frac{\partial u_i}{\partial x_i}+\frac{\partial u_i}{\partial x_j})\frac{\partial u_j}{\partial x_i}$$

(5) ε equation:

$$\frac{\partial(ru_i e)}{\partial x_i}=\frac{\partial}{\partial x_i}\{(h+\frac{h_t}{s_e})\frac{\partial e}{\partial x_i}\}-c_2\frac{re^2}{k}+\frac{c_1 e h_t}{k}(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j})\frac{\partial u_j}{\partial x_i}$$

***In the situation of along-wind direction, the flexible structure and static and dynamic wind load displacement equation*:** Record shows the wind speed, but also to the addition to the pulse of the average wind speed component (Chen 2007). When the structure is very rigid, the fluctuating wind structures caused by wind-induced inertial force are not obvious, and may be omitted, when a more flexible structure, in addition to static wind loads, it should also consider the wind-induced inertial forces that wind vibration force load, and the total wind load expression of W(z, t) = w(z) wd (z, t)

Where: W(z, t) = with a guaranteed rate of the total wind load (Du 2008); w(z) = z height of the average wind load; wd(z, t) = with a guaranteed rate of vibration of the wind power wind load.

The wind-sensitive one-dimensional flexible structure is a vertical cantilever structure, the structure and stiffness along the vertical distribution of uneven quality, now its abstract one-dimensional cantilever system of limitless freedom. The equations of motion can be expressed as (Kenmal 2008):

$$y_d(z,t)=\sum_{j=1}^{\infty}y_{dj}(z,t)=\sum_{j=1}^{\infty}f_j(z)q_j(t)$$

In this formula: $y_d(z,t)$ = the dynamic displacement of j-th vibration; $f_j(z)$ = the coordinate at z height of j-th vibration; $q_j(t)$ = the generalized coordinate of j-th vibration.

The maximum displacement of the structure at z height can be expressed as:

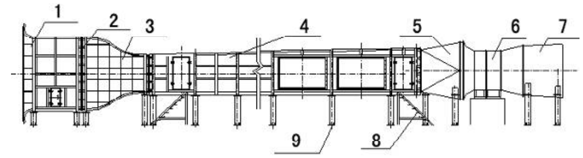


Fig. 4: Structure of the wind tunnel.

Table 1: Coefficient of standard k-ε model.

c_μ	c_1	c_2	σ_κ	σ_ε
0.09	1.44	1.92	1.0	1.3

$$y(z)=gs_y(z)=g\sum_{j=1}^{m}s_{yj}(z)$$

In this formula: $\sum_{j=1}^{m}s_{yj}(z)$ = the displacement response variance of j-th vibration; g = the peak factor, and its formula is :

$$g=2\ln vT+\frac{0.577}{2\ln vT}$$

The usual range of g is from 3.0 to 4.0.

***Wind vibration formula along the wind direction*:** The wind effect on the structure when the structure will produce alternating sides of the vortex behind, and will turn off side to side to form a Karman vortex. Karman vortex is the building pressure on the surface of cyclical changes, and the role of wind direction and the vertical. The role of structure and vertical wind vortex induce vibration. The vibration is accompanied by the emergence of the vortex generated by forced vibration when the vibration enhanced, and there will be control by the vibration of the vortex occurs, the performance from the excited vibration. When the wind speed at a given wind speed range, the vibration will become more significant.

For the vertical cantilever, horizontal wind vortex in the excited force loads, the equations of motion (Yoshie 2007):

$$m(z)y''(z,t)+c(z)y'(z,t)+\frac{2}{z^2}\left[EI(z)y''(z,t)\right]$$

$$=\frac{1}{2}rv^2(z)D(z)m_L\sin w_s t$$

In this formula: $y''(z,t)$ = horizontal acceleration of different particles; $y'(z,t)$ = horizontal velocity of different particles; r = mass density of the air; v = average velocity of coming air flow; $D(z)$ = objects in the plane perpendicular to the average velocity projection on the feature size; m_L = lift coefficient

Setting the boundary conditions: In this study, fluid dynamics CFD software' user-defined functions have been used to realize consistent with the experimental characteristics of the average wind speed and turbulence characteristics such laws.

To the selection of stream surface gradient wind due to surface friction effects, close to the surface wind speed with height in the decreases. Only 300m ~ 500m above the ground where the surface wind speed was not affected, the role of gradients in the atmosphere can freely flow.

Outlet boundary conditions: The use of a fully developed flow boundary condition that any physical quantity along the flow gradient of zero to export laws; fluid domain at the top and sides: free slip wall conditions; building surfaces and ground: no-slip the wall conditions (Liu 1996).

ANALYSIS OF EXPERIMENTAL RESULTS

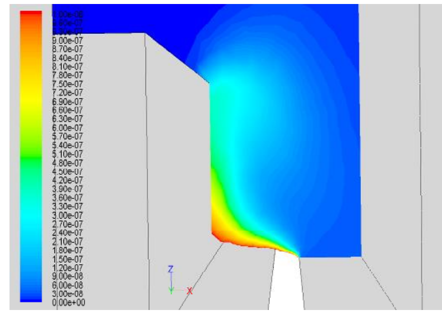
Pollutant diffusion: The wind velocity of free stream is 5 m/s in the experiment, the street width of the road intersection is 0.06m, adopts two different wind directions, one is the vertical direction, and another is the 45-degree wind direction. According to the laser light sheet images of records, each representing different wind direction results in Fig. 5 and 6(a). Then the results of the Matlab software were used to experiment with image after image processing to achieve the distribution of the relative wind quantitative analysis, as shown in Fig. 5 and Fig. 6(b).

In order to quantitatively reflect the relative difference between simulation and experiment, the experimental image processing out a few lines of the gray pixel contrast curve, to a certain extent, and the picture that the laser light can be quantitatively show wind changes.

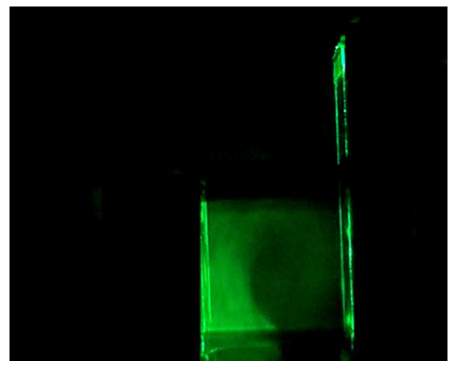
From Figs. 5 and 6, through simulation and experiment can be qualitatively concluded, that with elevations in the street there is a clear clockwise spiral, and the pollutants gathered to leeward, and more pollutants in the vortex into the upper space rarely been brought to the windward side of the vortex. In 45-degree wind conditions, the two show a different side street in the flow of pollution, and results clearly identified one of the streets and experimental simulation results flow field in the same situation.

Wind load: Evaluation criteria in accordance with green building requirements is to select height of a study object from the ground at 1.5 m . Figs. 7 and 8 show the construction of 1.5m high numerical simulation of the summer wind speed and air pressure chart.

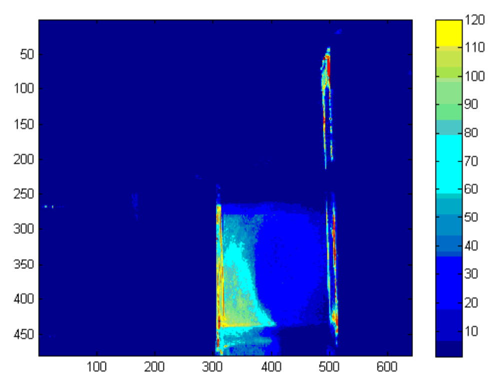
The measured wind speed wind tunnel tests and numerical simulation of wind pressure results were compared (Figs. 9 and 10), which show numerical simulation of wind pressure calculation and give good results.



a. Simulation Results (Experiment of University of Shanghai for Science and Technology).



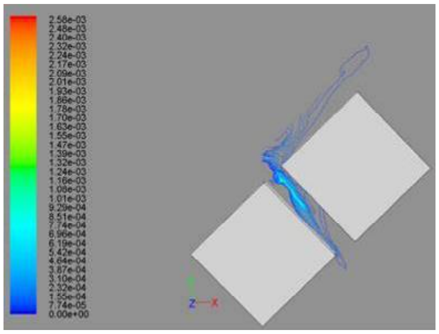
b. Experiment Result of Wind Tunnel (Experiment of University of Shanghai for Science and Technology).



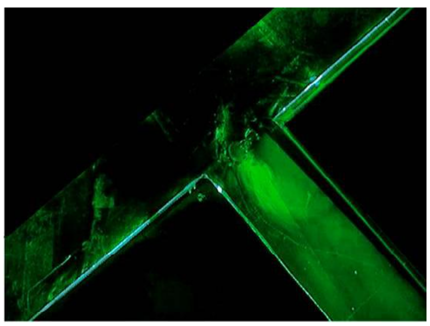
c. Cloud Picture after Processing (Experiment of University of Shanghai for Science and Technology).

Fig. 5: The vertical direction y <0 on the streets from the streets of port 2cm vertical distribution of pollutants in the wind tunnel simulation results and experimental results comparison.

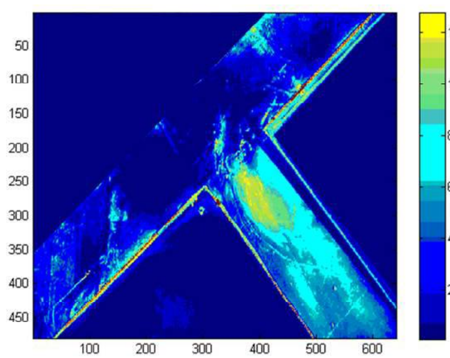
Simulation study was made around building at 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o direction of flow conditions. Numerical simulation results from the overall trend, with relatively consistent wind tunnel experiments, are given in Table 2.



a. Simulation Results (Experiment of University of Shanghai for Science and Technology).



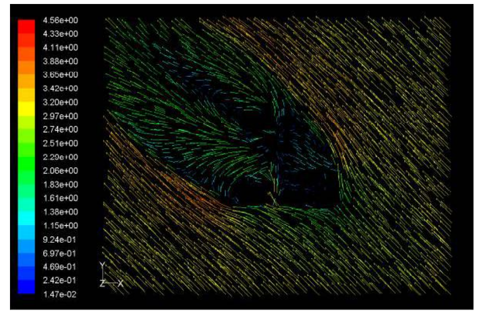
b. Experiment Result of Wind Tunnel (Experiment of University of Shanghai for Science and Technology).



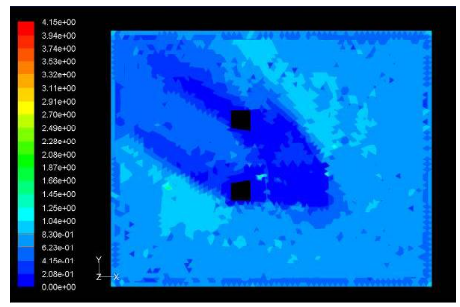
c. Cloud Picture after processing (Experiment of University of Shanghai for Science and Technology).

Fig. 6: 45-degree wind conditions from the ground 0.6cm high level of pollutants in the wind tunnel simulation results and experimental results comparison.

What has been measured in the experiment is that the positive side of the cylinder building is pushed by the wind pressure. The negative side, profile, and top are sucked by the wind pressure. To bluff-body buildings, the center-front pressure on the department is the largest near the bottom on both the sides, and at a smaller pressure, air flow down the surface with the trend, and flow around the sides and top, about in building 2/3 height, the air in front of a stagnation point, flow from the stagnation point spread. The point above,



a. Column Picture of the Wind Velocity



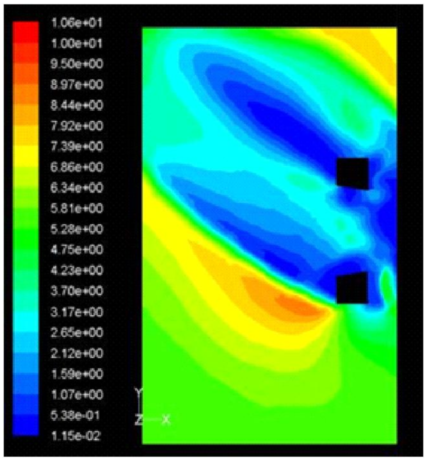
b. Cloud Picture of the Wind Velocity

Fig. 7: Simulation pictures of 1.5 m wind velocity in summer.

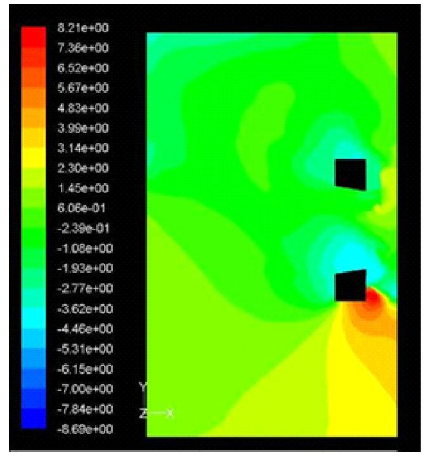
increased flow across the top surface of the building, at which point the following, and the flow of air down the ground in this area, scroll down in the air, in the windward side of the building close to the ground to form a horizontal scrolling, a vortex area. Building on the side of the pressure distribution of air flow separation at the side moldings, off the top 1/3 of the height of segregation within the stable, while the wind speed was significantly lower than the current wind speed, the same height, caused by the vertical vortex mixed mix to the side along the height direction of the flow becomes uniform.

CONCLUSIONS

Wind environment is the air flow's impact on the internal or outside building space. It is a very important part of architectural environmental design. Unreasonable wind environment will cause many problems. And the wind environment has a direct connection with people's daily life. However, wind environment not only relates to the local climate but also relates to the building's body size and layout. We can see from the above-mentioned analysis examples that wind tunnel experiment can get direct and effective measurement results. But restricted to the conditions, it can not be used in a wind range. However, with the development of computer technology, we can make a full use of simulation software, and then it is possible to get accurate data. Only when the



a. Cloud Picture of the pressure (Dynamic Pressure)



b. Cloud Picture of the pressure (Static Pressure)

Fig. 8: Simulation pictures of 1.5m wind pressure in summer.

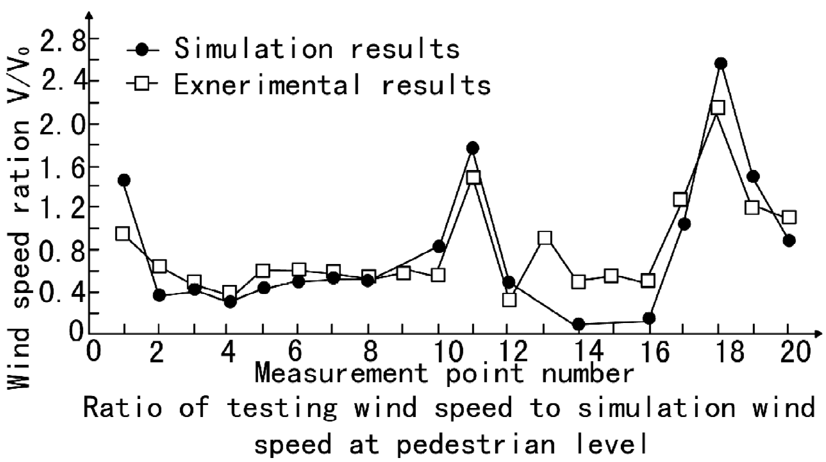
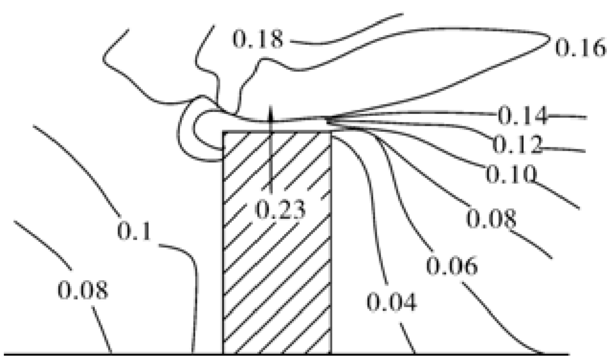
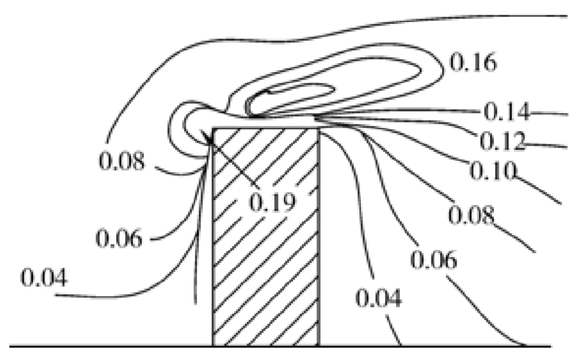


Fig. 9: Comparison between wind tunnel experiment and simulation results.



a. Result of wind tunnel experiment.



b. Simulation results

Fig. 10: Comparison between wind tunnel experiment and simulation result.

Table 2: Average pressure coefficient under the comparison between wind tunnel experiment and simulation result.

Typical Measurement Point	Method	Wind Direction							
		0°	45°	90°	135°	180°	225°	270°	315°
A	Wind Tunnel Simulation	-0.04	-0.20	-0.41	0.80	0.83	0.84	-0.53	-0.43
		-0.02	-0.18	-0.46	0.84	0.85	0.87	-0.57	-0.50
B	Wind Tunnel Simulation	-0.02	-0.15	-0.43	0.83	1.21	0.83	-0.47	-0.43
		-0.03	-0.17	-0.41	0.91	1.20	0.90	-0.51	-0.44
C	Wind Tunnel Simulation	-0.03	-0.16	-0.45	0.09	0.05	-0.09	-0.43	-0.15
		-0.02	-0.18	-0.44	0.07	0.07	-0.12	-0.47	-0.13
D	Wind Tunnel Simulation	-0.47	-0.13	-0.50	0.87	1.03	0.38	-0.50	-0.43
		-0.51	-0.15	-0.52	0.90	1.09	0.42	-0.53	-0.41

simulation results are the same with the simulation conditions, we can examine the results through comparisons. And it is possible for us to use the results to guide the architectural design and urban planning. Therefore, wind environment analysis will greatly improve the architectural design and create a livable internal and outside environment.

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