COMPARISON OF TURBULENCE MODELS IN SIMULATING KEY ELEMENTS OF OUTDOOR WIND ENVIRONMENT AROUND BUILDING COMPLEXES

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ABSTRACT

CFD (Computational Fluid Dynamics) simulation is the main research method for assessing the wind environment around building complexes. Recent research showed the importance of turbulence models used in simulation and different turbulence models were developed to improve the precision of CFD simulation results. In this paper, a comparison of different turbulence models in simulating wind environment around building complexes is conducted to discuss their precision of simulation in three key elements of engineering application. The recommended turbulence model is determined based on the comparison and the wind environment of a residential district is simulated with the suggestions. Finally, the simulation result is compared against filed measured data, where the results coincide.

INTRODUCTION

The wind environment around a building complex directly affects the ventilation, thermal comfort and the energy consumption of buildings, which are all critical in architectural design. However, the wind environment is always difficult to measure and even more difficult to predict in the design process.

CFD (Computational Fluid Dynamics) simulation methods are employed as the main methods for studying the outdoor wind environment today. The precision of simulation results is influenced by many factors, such as algorithms, boundary conditions and turbulence models. A wealth of research has been conducted on these simulations. For example, AIJ (Architectural Institute of Japan) and COST (European Cooperation in the Field of Scientific and Technical Research) have developed strict guidelines about CFD simulation based on a series of studies. (Tominaga, Y., et al., 2008. Yoshie, R., et al., 2007. Franke, J., et al., 2004.) Researchers agreed on the importance of turbulence models used in simulation and different turbulence models were developed. Tominaga and Stathopoulos, for example, simulated the dispersion of wind speed around an isolated cubic building by different *k*-*ε* models. (Tominaga, Y. and Stathopoulos, T., 2009.) Taifeng also compared different turbulence models in simulating the wind environment of a single building. (Jiang T.F., 2003.) However, previous researchers compared different turbulence models in simulating the wind environment around a single building, and the recommendation of the turbulence model was determined based on the simulation precision of the length of recirculation zone. In engineering applications, there is always more than one building and architects are more interested in other results instead of the length of recirculation zone.

In this paper, a comparison of different turbulence models in simulating wind environment around building complexes is conducted to discuss the precision in simulating three key elements of engineering application, which are wind pressure coefficients on the facades of buildings, the velocity distribution at pedestrian height and the influences of vegetation. The results of simulation in different turbulence models are compared to experimental data and then the recommended turbulence model in engineering application is determined based on the comparison. Finally, wind environment simulation of a residential district is given and the result is compared to the real-time measurement data to verify the conclusion.

TURBULENCE MODELS

In outdoor wind environment simulations, the two-equation model, for example, the Standard *k*-*ε* model (Oomiyasi, H., et al., 1998. Meng, Y. and Hibi, K, 1998.), is the most widely used turbulence model. However, when simulating the air flow around a single building with the Standard *k*-*ε* model, the result of the turbulence kinetic energy k at the top of building is too great. (Jiang T.F., 2003.) Therefore, the MMK model (Tao W.Q., 2001.) and the Durbin model (Gaskell P. and Lau A.K.C., 1988.) have been developed, they make a revision on the calculation of turbulence kinematic viscosity coefficient v_t. The following provides a brief introduction to the three turbulence models and notes their main differences.

Standard *k*-*ε* model

The Standard *k*-*ε* model is the most widely used two-equation model, which has a high rate of accuracy and stability at the same time. By using this model, a lot of improvement were achieved in CFD simulation, especially in the field of engineering application.

A basic equation is used in the Standard *k*-*ε* model to calculate related parameters, including velocity U_i , temperature T, turbulence kinetic energy k and its dissipation rate ε. The equation is:

$$\frac{\partial(\rho\varphi)}{\partial t}+div\left(\rho\bar{U}\varphi\right)=div\left(\Gamma_{\varphi}grad\varphi\right)+S_{\varphi}$$

φ - related parameters, including velocity U_i, temperature T, turbulence kinetic energy k and its dissipation rate ε.

Γ_{ϕ} - general diffusion coefficient, which is changing with parameters.

For U_i: $\Gamma_{\phi}=\mu_{eff}=\mu+\mu_t$

For k: $\Gamma_{\phi}=\mu+\mu_t/\sigma_k$

For ε: $\Gamma_{\phi}=\mu+\mu_t/\sigma_{\varepsilon}$

For T: $\Gamma_{\phi}=\mu/\mathrm{Pr}+\mu_t/\sigma_T$

σ_k - constant for k.

σ_{ε} - constant for ε.

σ_T - constant for T.

S_{φ} - source terms.

For U_i: $S_{\varphi}=\frac{\partial\rho}{\partial x_1}+\frac{\partial}{\partial x_i}\left(\mu_{eff}\frac{\partial U_i}{\partial x_i}\right)$

For k: $S_{\varphi}=\mu_t S^2-\rho\varepsilon$

For ε: $S_{\varphi}=\frac{\varepsilon}{k}\left(c_1\rho G_k-c_2\rho\varepsilon\right)$

μ_t - turbulence viscosity coefficient, $kg(ms)^{-1}$.

$$\mu_t=\rho c_{\mu}k^2/\varepsilon$$

ν_t - turbulence kinematic viscosity coefficient, m^2s^{-1}.

$$\upsilon_t=c_{\mu}k^2/\varepsilon$$

P_k - source term of turbulence kinetic energy.

$$P_k=\upsilon_t S^2$$

S - strain rate scale, s^{-1}.

$$S=\sqrt{\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)^2}$$

MMK model

When simulating the air flow around a building by the Standard *k-ε* model, the result of turbulence kinetic energy *k* at the top of the building is too great. So the MMK model makes a revision in the calculation of the turbulence kinematic viscosity coefficient to solve this problem. Otherwise, the majority of the two turbulence models are the same. The only difference is the turbulence kinematic viscosity coefficient, shown as follows.

In the Standard *k-ε* model,

$$\upsilon_t=c_{\mu}k^2/\varepsilon\ .$$

In the MMK model,

$$\upsilon_t=C_{\mu}k^2/\varepsilon \qquad \text{when } \Omega/S>1$$

$$\upsilon_t=C_{\mu}k^2/\varepsilon\cdot\left(\Omega/S\right) \qquad \text{when } \Omega/S\le 1$$

Durbin model

The Durbin model is also a model with a revision of calculation of the turbulence kinematic viscosity coefficient. Variables are defined as follows.

$-\overline{u_i'u_j'}$ - reynolds stress.

$$-\overline{u_i'u_j'}=\upsilon_t\left(\frac{\partial\langle u_i\rangle}{\partial x_j}+\frac{\partial\langle u_j\rangle}{\partial x_i}\right)-\frac{2}{3}\sigma_{ij}k=2\upsilon_t S_{ij}-\frac{2}{3}\sigma_{ij}k$$

S_{ij} - strain rate

$$S_{ij}=\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)$$

In the Durbin model,

$$\upsilon_t=C_{\mu}\overline{\mu^2}T^*$$

$\overline{\mu^2}$ - strain rate scale

T^* - time scale

$$T^*=\min\left(\frac{k}{\varepsilon},\frac{2k}{3\langle v^2\rangle C_{\mu}}\sqrt{\frac{3}{4S^2}}\right)=\min\left(\frac{k}{\varepsilon},\frac{\alpha}{\sqrt{3}SC_{\mu}}\right)$$

when $0\le\overline{\mu^2}\le 2k$

When α =1.0, named Durbin1Model; when α =0.5, named Durbin2 Model.

EXPERIMENT AND SIMULATION

Comparison of different turbulence models in the simulation of wind environments is conducted. The simulation results of different turbulence models are compared to the data from several wind tunnel experiments given by former researchers, in order to analyse their precision in three key elements of engineering application: wind pressure coefficients on the facades of buildings, the velocity distribution at pedestrian height and vegetation simulation. Here is a brief summary of cited experiment data.

Wind pressure coefficients data

The referenced wind tunnel data of wind pressure coefficients is cited from 2009 ASHRAE Handbook - Fundamentals. (ASHRAE Inc., 2009.) Shown as Figure 1.

Velocity distribution wind tunnel data

The data of velocity distribution at pedestrian height around building blocks is cited from wind tunnel experiment database conducted by AIJ (Architectural Institute of Japan, 2004.) The geometric information of the wind tunnel experiment is shown, as Figure 2. The measurement points are shown as Figure 3.

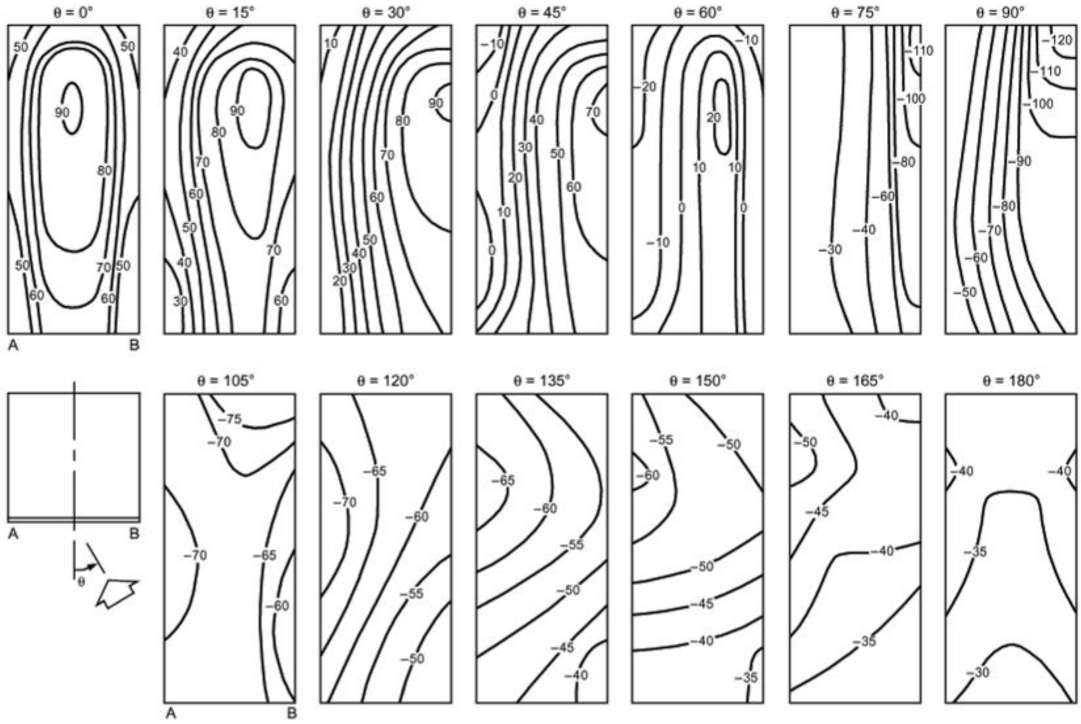


Figure 1 Wind pressure coefficients ($C_p \times 100$) for tall building with varying wind direction

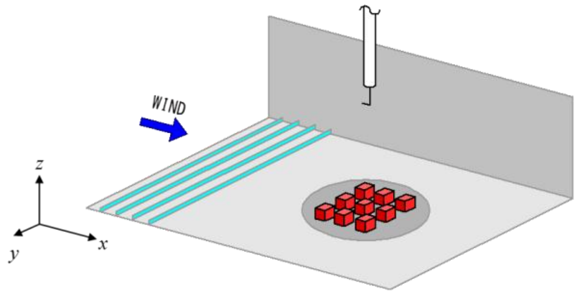


Figure 2 Geometric information of experiment

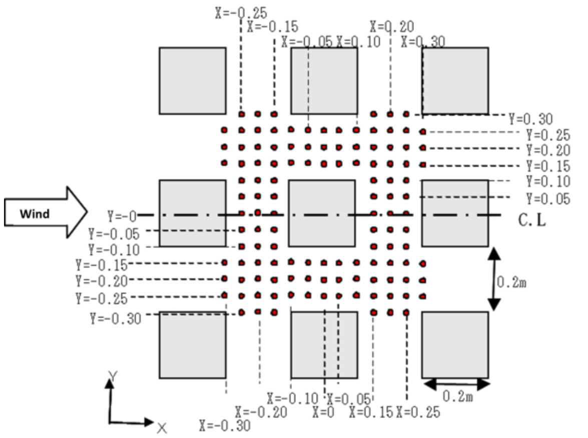


Figure 3 Measurement points

Vegetation wind tunnel data

The wind tunnel experiment involving vegetation is conducted by S.R. Green (Green, S.R., 1992). 700 cone tree models were attached to a rough plate and placed in the wind tunnel with a 0.2m height for each tree, 0.125m height for the crown and 0.04m weight at the bottom of the crown. The length of tree models was 2m in total while the geometric size of the wind tunnel was 1.53m width, 1.07m height and 5m length. The inflow increased with the height in a 1/6 power function law. 13 measurement points were set at the middle of the wind tunnel, from -1m to 3.8m (0.4m distance for each and negative sign means in front of the tree models), at three different heights, 0.05m, 0.15m and 0.25m.. LADs (Leaf Area Distribution) of all 10 levels (0.02m height for each) in the tree models were measured, which is shown as Table 1.

Table 1
LADs of each level in vegetation experiment

LEVEL NO.	LAD($m^2 \cdot m^{-3}$)
1	0.890
2	0.688
3	0.484
4	13.36
5	34.95
6	36.01
7	30.31
8	26.86
9	15.11
10	6.110

Simulation

All of the wind tunnels above are simulated by PHOENICS 3.5 (Ludwig, J. C., 2010), the first commercial CFD software by CHAM in England. In addition, some of the turbulence models were developed by Tsinghua University, as well as the model of vegetation in wind environmental simulation. The inflow, geometry and all other boundary conditions are set according to the wind tunnel experiment. The aerodynamic effects of vegetation are simulated by applying extra terms in flow, momentum and energy equations in the turbulence model. (Lin, B.R., et al., 2008.) Then, different turbulence models are employed in simulation - the Standard k-ε model, the MMK model and the Durbin model. Simulation results are compared to the data from wind tunnel experiments. The Durbin model, as a recommended turbulence model in engineering application, is concluded in this study. Detailed results are shown as follows.

RESULT ANALYSIS

Wind pressure coefficients

The wind pressure coefficients data for a tall building with front wind direction and simulation results of different turbulence models are shown as Figure 4.

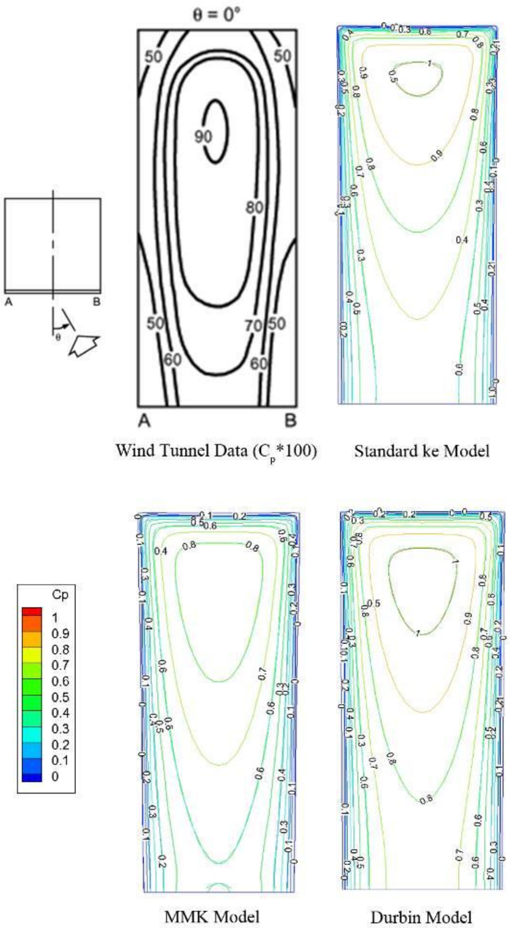


Figure 4 C_p distribution data and simulation results

Compared to the wind pressure coefficients data given by ASHRAE, the wind pressure of the front side of the building in the simulation result of the MMK model is too low. The average C_p in the result of the MMK model is around 0.5 while that of ASHRAE experiment is around 0.7. For simulation results of the other two turbulence models, the average C_p is almost the same. But the wind pressure distribution in the simulation result of the Durbin model is more similar to wind tunnel data. As a conclusion, the Durbin model performs better in simulating the wind pressure coefficients on the facades of buildings.

Velocity distribution

In the wind tunnel data of velocity distribution at pedestrian height, three lines of measurement points (x=0.2, x=0 and x=-0.2) are picked out for comparison. The velocity ratio (velocity value normalized by the inflow velocity at the same height) of measurement and simulation results of different turbulence models are compared and shown as Figure 5.

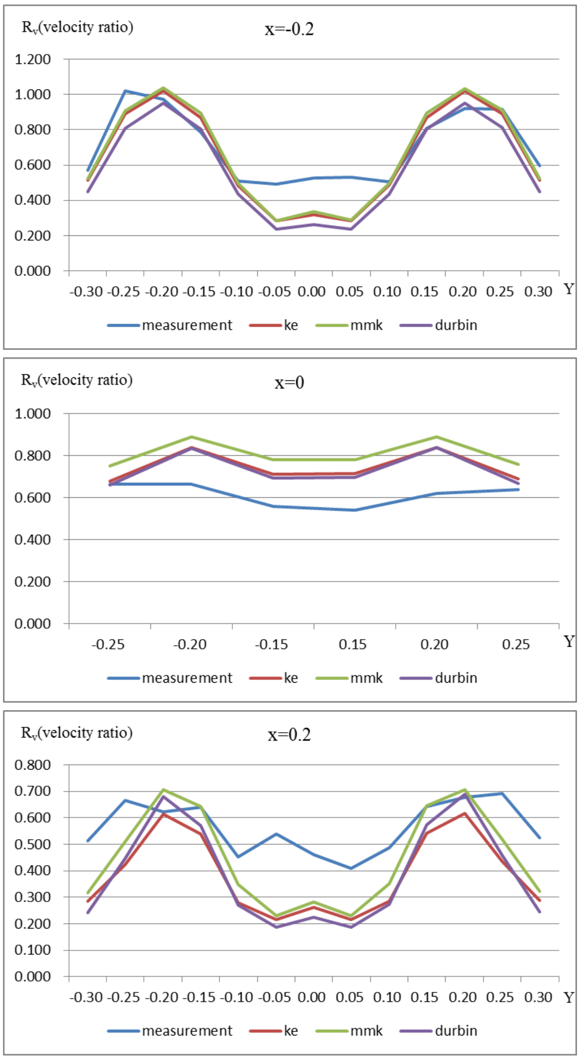
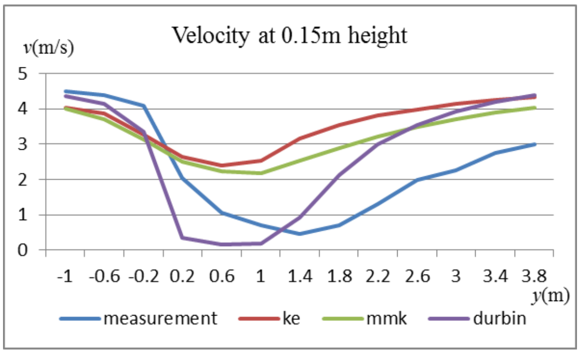


Figure 5 R_v measurement and simulation results

In the wind environment simulation of the building complex, the three turbulence models perform similarly, which means that the turbulence model has little influence on the velocity at pedestrian height.

Vegetation simulation

In the vegetation simulation result, measured velocity v and turbulence kinetic energy k at 0.15m height are compared to simulation results of different turbulence models. Shown as Figure 6.



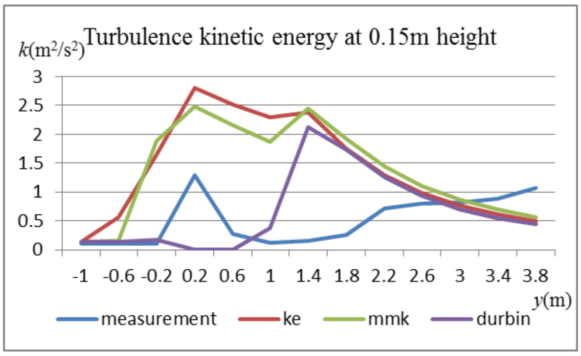


Figure 6 Measurement and simulation of vegetation

In the vegetation simulation result, the Durbin model performs better in velocity simulation. However, in simulation of turbulence kinetic energy, all three turbulence models perform poorly. The reason is that in the wind tunnel experiment, the trees are 700 isolated models, which has greater influence on turbulence strength. While in simulation, the tree models are simplified as 10 levels of porous media to simulate the aerodynamic effects of vegetation. (Lin, B.R., et al., 2008.)

Summary

As a summary of the three simulation comparison, the Durbin model performs better in simulating three key elements of engineering application, which are wind pressure coefficients on the facades of buildings, the velocity distribution at pedestrian height and vegetation simulation. Taking previous research into consideration, the Durbin model is the recommended turbulence model in simulating outdoor wind environments in engineering application.

CASE STUDY

To verify the summary, a case study was conducted. Field measurement of velocity in a residential district was performed. Then the wind environment of the residential district was simulated by PHOENICS with the Standard k-ε model and the Durbin model. Measurement data and simulation results are compared to conclude a recommended turbulence model.

Field measurement

Wind speed and wind direction at a pedestrian height of 8 points in the residential district were automatically recorded by small weather stations. The position of the measurement points is shown as Figure 7. The parameters of the small weather station are shown as Table 2.

Figure 7 Position of measurement points

Table 2
Parameters of small weather station

PARAMETERS	MEASUREMENT RANGE	RESOLUTION	PRECISION
Temperature	-40~80℃	0.1℃	±0.1℃
Humidity	0~100%RH	0.1% RH	±2% RH
Velocity	0~70m/s	0.1m/s	±0.3m/s
Wind Direction	0~360°	1°	±3°

The measurement was taken from 10 a.m. to 4 p.m. on March 28th, 2010. The weather was sunny. According to the record of the weather station at the site, the weather condition of inflow in this area was quite stable that day, especially from 12:30 p.m. to 1:30 p.m. However, the wind velocity and wind direction measured near the ground was much more flexible, so the main wind direction was chosen and the average wind velocity in this direction was calculated, in order to compare with simulation results. As an example of the measurement data, wind frequency rose figure and velocity data at measurement point 1 are shown as Figure 8 and 9. The wind direction of point 1 changed from northwest to northeast, and the average wind speed from the north was around 1.5m/s. However, the wind speed and wind direction were changing all the time. So the main wind direction and average wind speed from that direction between 12:30 p.m. and 1:30 p.m. were used for comparison with simulation results.

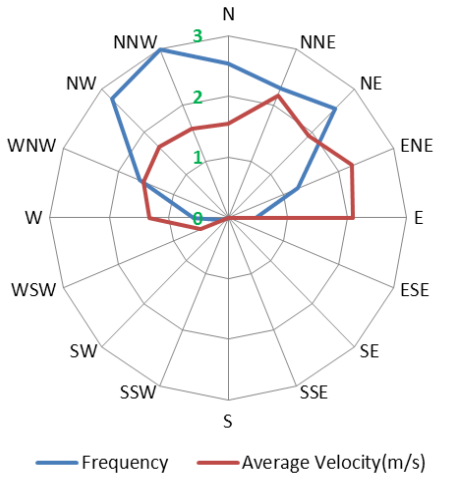


Figure 8 Wind frequency rose of point 1

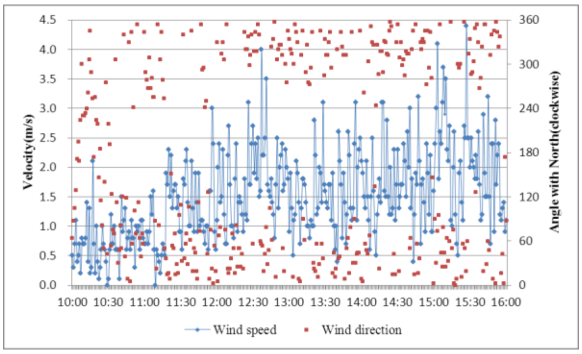


Figure 9 Wind environment data of point 1

Simulation boundary conditions

The boundary conditions include modelling and inflow setting.

When modelling this residential district, the buildings and vegetation were simplified based on CAD plans. The model of vegetation was simplified as porous media to simulate the aerodynamic effects of vegetation. The inlet setting was determined based on a gradient wind model.

The inflow condition was set up according to the measurement data from the small weather station placed on the highest building in this area. According to the record of the weather station at the site, the inflow from 12:30 p.m. to 1:30 p.m. was stable, so the wind environment at 1:00 p.m. was chosen for simulation.

The inlet setting was determined based on a gradient wind model. The vertical distribution of the wind speed and the turbulence strength are described as power law equations:

$$\begin{cases} \dfrac{V}{V_g} = \left(\dfrac{h}{h_g}\right)^a \\ I_u(Z) = I_0 \left(\dfrac{Z}{H}\right)^{-a-0.05} \end{cases}$$

Where V is the average wind speed at height h, and V_g, the average wind speed at hight h_g. In this paper, h_g=20m. The power law index a differs according to the ground condition. In this paper, a=0.238. I_0 is the turbulence strength at height H. When H=30m, I_0=a, the power law index in gradient wind model. In this paper, after calculation, I_u(20)=0.3.

PHOENICS 3.5.1 was used to simulate the wind environment. The gridding is around 2,000,000 in each case. The defferencing scheme is hybrid scheme while the turbulance model differs in different cases.

Simulation result

The wind speed and wind pressure distribution of different turbulence models were simulated. For example, the simulation result of the distribution of wind speed in the simulation result of the Durbin model is shown as Figure 10 and Figure 11. Both of the figures are at pedestrian height, which is also the height of measurement point in field measurement.

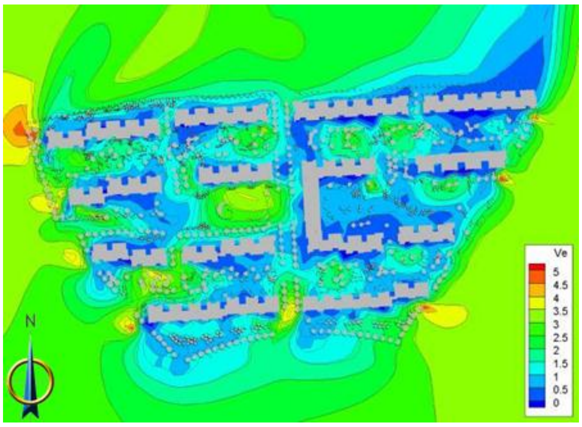


Figure 10 Wind environment at 1:00 p.m. (nephogram)

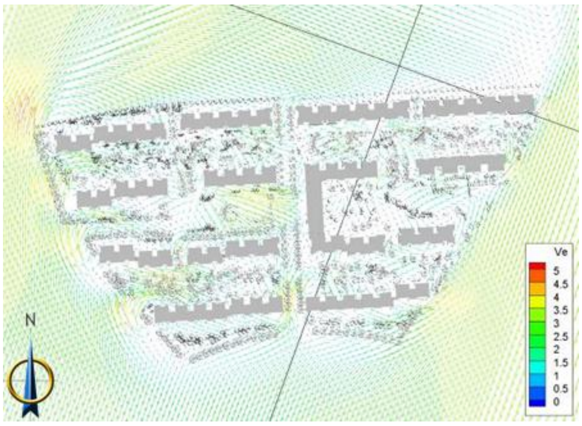


Figure 11 Wind environment at 1:00 p.m. (vectorgraph)

Then the simulation results of wind speed and wind direction were recorded at the measurement points, which are shown in Figure 7.

Comparison

In the wind environment data, the most frequent wind direction and average wind speed from that wind direction from 12:30 p.m. to 1:30 p.m. are compared to the simulated results of two different turbulence models. Shown as Table 3, Table 4 and Figure 12.

Table 3
Comparison of wind speed (m/s) in case study

POINTS NO	MEASUREMENT	STANDARD *K-E* MODEL	DURBIN MODEL
1	2.25	2.72	2.70
2	1.53	1.66	1.66
3	1.07	0.80	0.87
4	1.39	0.97	1.14
5	1.3	0.96	1.13
6	1.42	1.54	1.62
7	1.3	1.26	1.35
8	0.46	0.50	0.54

Table 4
Comparison of wind direction in case study

POINTS NO	MEASUREMENT	STANDARD *K-E* MODEL	DURBIN MODEL
1	NE	E	E
2	N	NE	NE
3	NNE	NE	NE
4	NE	NEE	NEE
5	NEE	E	E
6	N	N	N
7	E	E	E
8	NEE	NNE	NNE

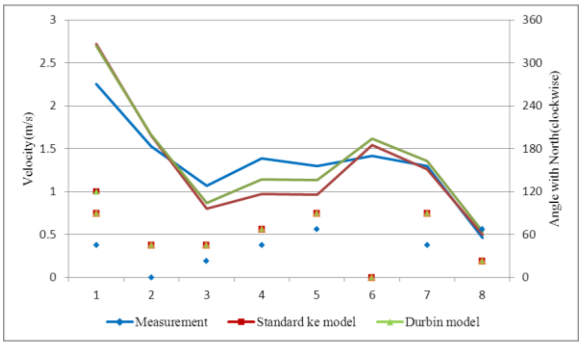


Figure 12 Comparison of measurement data and simulation results

Shown as the comparison, the simulation results of the Standard *k-ε* model and the Durbin model are almost the same. The simulations of wind direction were almost the same in measurement. In velocity simulation, the results of some points in the Durbin model have a smaller relative range of error compared to measured data; while the average relative error of the Durbin model is 2.5% that of the Standard *k-ε* model is 9.2%.

CONCLUSION

Research on the precision of different turbulence models in simulating outdoor wind environments around building complexes was conducted in this paper. Three key elements in engineering application were discussed, which are wind pressure coefficients on the facades of buildings, the velocity distribution at pedestrian height and the influence of vegetation.

Research of the performance of different turbulence models in simulating these three key elements of building complexes was conducted. Wind tunnel data and simulation results were compared in this paper. However, the wind tunnel data was taken before by other researchers and the experiments were not designed for this comparison. This may mean that the wind tunnel data is not so accurate. For example, the wind pressure coefficients on facades given by ASHARE are only figures, which makes them difficult to compare with the simulation results. Also, the precision of measurement data in velocity distribution at pedestrian height is low, which leaves uncertainty regarding the comparison result. Based on the study shown in this paper, conclusions were drawn as follows. In simulating the wind pressure coefficients on the facades of buildings, the Durbin model performs better than the Standard *k-ε* model and the MMK model. In the simulation of velocity distribution at pedestrian height, different turbulence models have a similar precision. In simulating the influences of vegetation, only the results of the Durbin model agree with the wind tunnel data. In conclusion, based on previous research and comparisons drawn in this paper, the Durbin model is recommended when taking all three key elements into consideration together.

What's more, a case study of a wind environment simulation in a residential district is given based on the suggestion above and the simulation result is compared to the real-time measurement data. The simulation result of wind direction was similar to measurement data, while the result of wind velocity of the Standard *k-ε* model had an average relative error of 9.2% and that of the Durbin model had an average relative error of 2.6%. As a conclusion, precision of the Standard *k-ε* model in simulating velocity distribution at pedestrian height is enough for engineering application.

In one sentence, the Standard *k-ε* model has an acceptable precision for engineering application while the Durbin model is recommended for a better precision in research.

NOMENCLATURE

φ - related parameters, including velocity U_i, temperature T, turbulence kinetic energy k and its dissipation rate ε.

Γ_ϕ - general diffusion coefficient.

For U_i: $\Gamma_\phi = \mu_{eff} = \mu + \mu_t$

For k: $\Gamma_\phi = \mu + \mu_t / \sigma_k$

For ε: $\Gamma_\phi = \mu + \mu_t / \sigma_\varepsilon$

For T: $\Gamma_\phi = \mu / \mathrm{Pr} + \mu_t / \sigma_T$

σ_k - constant for k.

σ_ε - constant for ε.

σ_T - constant for T.

S_φ - source terms.

For U_i : $S_\varphi = \frac{\partial \rho}{\partial x_1} + \frac{\partial}{\partial x_i}\left(\mu_{eff}\frac{\partial U_i}{\partial x_i}\right)$

For k : $S_\varphi = \mu_t S^2 - \rho\varepsilon$

For ε : $S_\varphi = \frac{\varepsilon}{k}\left(c_1 \rho G_k - c_2 \rho \varepsilon\right)$

μ_t - turbulence viscosity coefficient, $kg(ms)^{-1}$.

ν_t - turbulence kinematic viscosity coefficient, $m^2 s^{-1}$.

P_k - source term of turbulence kinetic energy.

S - strain rate scale, s^{-1}.

$-\overline{u_i' u_j'}$ - Reynolds stress.

S_{ij} - strain rate

$\overline{\mu^2}$ - strain rate scale

T^* - time scale

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