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Numerical Model of Flow Field in Urban Canopy Layer

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Abstract: A numerical model of flow field in urban canopy layer based on k- ϵ closure method is developed in this paper, in which a porous medium is used to present the buildings in the urban area and the form drag is used to represent the drag to the flow by the buildings. The results obtained from the model have been compared with the data observed from the Beijing 325m meteorological tower. It shows that during the strong wind, the wind velocity profile obtained from the model accords well with that observed from the tower.

Keywords: Urban Canopy Layer, the effective air volume ratio, form drag

1. INTRODUCTION

Urban Canopy Layer, first named by Oke[1987], is the layer between the land surface and the roof of building. The atmosphere in this layer is most influenced by mankind activity. Urban development has effects on the flow field in the urban area. With the rapid urban development, the buildings in urban area have increased more and more, which results in large surface roughness length, and decreases the surface wind velocity.

We developed a 10^2 — 10^3 m scale model of flow field in urban canopy layer, which can be used for single or few resident area. In this model, all the buildings in the area are not presented by an irregular coarse underlying surface, but the space distributions of buildings are considered entirely without considering geometric shape of single building. The model results can obtain rational

suggestion for the design of construction, and distribution of residential area.

2. NUMERICAL MODEL OF THE FLOW FIELD

In urban canopy layer, the influences on urban climate by buildings include dynamical and thermal effect. The thermal effect includes the influences of buildings on the radiation transport, sensible heat and latent heat, and artificial heat source in city. The dynamical effect mainly is the drag to flow by the buildings. In the paper, the influence on the flow field structure by buildings drag is mainly simulated. The thermal effects are not included.

A porous medium is used to present the buildings in the urban area and the form drag to the flow by the buildings is presented by parameterization.

Here, $G(x, y, z)$ is introduced as the effective

air volume ratio:

$$G(x, y, z) = \frac{V_0(x, y, z) - V_a(x, y, z)}{V_0(x, y, z)} \quad (1)$$

in which, $V_0(x, y, z)$ is the grid volume when the center is located at (x, y, z) , $V_0(x, y, z) = \Delta x \Delta y \Delta z$, $V_a(x, y, z)$ is the volume of the buildings in the grid.

The atmosphere equations are as follows:

$$\frac{1}{G} \frac{\partial(Gu_j)}{\partial x_j} = 0, \quad j=1,2,3 \quad (2)$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{G} \frac{\partial(Gu_i u_j)}{\partial x_j} = -\theta \frac{\pi}{\partial x_i} + \frac{1}{G} \frac{\partial}{\partial x_j} (K_j \frac{\partial G u_i}{\partial x_j}) - ac_j u_i(u) \quad (3)$$

$$\frac{\partial \pi}{\partial z} = -\frac{g}{\theta} \quad (4)$$

$$\frac{\partial \theta}{\partial t} + \frac{1}{G} \frac{\partial(Gu_j \theta)}{\partial x_j} = \frac{1}{G} \frac{\partial}{\partial x_j} (K_j \frac{\partial G \theta}{\partial x_j}) \quad (5)$$

In which, turbulence diffuse coefficient is:

$$K_j = C_\mu k^2 / \varepsilon \quad (6)$$

k and ε is turbulence kinetic energy and its dissipation ratio separately, which are presented by corresponding k - ε equation:

$$\begin{aligned} \frac{\partial k}{\partial t} = & \frac{1}{G} \frac{\partial}{\partial x_j} \left(\alpha \frac{K}{\sigma_k G} \frac{\partial G k}{\partial x_j} \right) + K \left(\frac{1}{G} \frac{\partial G u_2}{\partial x_j} \right)^2 + \left(\frac{1}{G} \frac{\partial G v_2}{\partial x_j} \right)^2 - \\ & \frac{g}{T} \frac{K}{\sigma_\theta G} \frac{\partial G \theta}{\partial x_j} - \varepsilon \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{\partial \varepsilon}{\partial t} = & \frac{1}{G} \frac{\partial}{\partial x_j} \left(\alpha \frac{K}{\sigma_\varepsilon G} \frac{\partial G \varepsilon}{\partial x_j} \right) + c_1 \frac{\varepsilon}{k} \left(K \left(\frac{1}{G} \frac{\partial G u_2}{\partial x_j} \right)^2 + \left(\frac{1}{G} \frac{\partial G v_2}{\partial x_j} \right)^2 \right) - \\ & \frac{g}{T} \frac{K}{\sigma_\theta G} \frac{\partial G \theta}{\partial x_j} - c_2 \frac{\varepsilon^2}{k} \end{aligned} \quad (8)$$

In which, $c_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$, $c_1=1.44$, $c_2=1.92$, $\sigma_\theta=0.74$ [5].

$$C_f = 1 - G(x, y, z) = V_a(x, y, z) / V_0(x, y, z)$$

, α is a semi-empire constant.

3. THE EFFECTIVE AIR VOLUME RATIO

The model area (700m × 700m) is located near the crossroad of Tucheng Road and Badaling Highway, where the Beijing 325m meteorological Tower is located at the east-south corner. Figure 1 shows the distribution of buildings in this area in 1999. The highest building is about 75m in the area. (The building information is got from the GIS data of Beijing City)

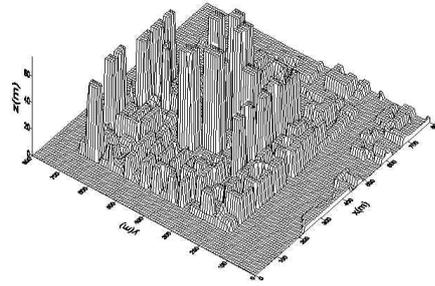


Figure 1. The distribution of buildings in the simulated area. (From the west south, the Tower is located at (800,0))

4. THE BEIJING 325M METEOROLOGICAL TOWER

The Beijing 325m meteorological tower is located at (39°58'N, 116°22'E), 49m above sea level, with 15 observational platforms, which are located at 8、15、32、47、63、80、100、120、140、160、180、200、240、280、320m. The observational elements include wind velocity, wind direction, temperature and humidity. The sample frequency is one per 20 seconds. The average time of each run in this paper is 30 minutes.

5. Computation Domain

The Computation domain includes 41×41×36 grids with the interval of 20m in the horizontal and 10m in the vertical. The simulated area is 800m×800m in the horizontal and 350m in the

vertical.

Table 1. The parameters in the model in each case

item	Case 1	Case 2	Case 3	Case 4
Date	07/11 09:29	07/11 20:29	13/11 19:29	17/11 09:59
Wind velocity	gale	gale	breeze	breeze
Wind direction	303.75	315	303.75	303.75
z_r (m)	10	10	10	10
u_r (m/s)	7.58	8.34	4.09	4.47
P	0.08	0.14	0.08	0.08
θ_0 (K)	285.70	285.92	279.22	280.55
Γ (K/m)	-0.01	0.00	0.005	-0.01
stability	Unstable	neutral	stable	unstable

The initial flow field is set as:

$$u(z) = u_r (z / z_r)^p$$

Where u_r is the wind velocity at the reference

height ($z = z_r$), and p is empire constant.

The initial potential temperature is assumed as:

$$\theta(z) = \theta_0 + \Gamma z$$

Where, $\Gamma = \frac{d\theta}{dz}$ is the lapse rate of potential temperature.

The parameters in Four cases are showed in Table 1, according to the observational data by Beijing 325m Tower at Nov, 1999.

6. RESULTS AND DISCUSSION

(1) The wind velocity profile

Table 2 and Figure 2-5 show the wind velocity profile of the initial flow, observation and simulated results separately.

Table 2. the wind velocity profile

Item	The initial flow	The fitting profiler with Observation data	Simulatd results	Average relatively error(%)
Cas e 1	$7.58(z/10)^{0.08}$	$2.96(z/10)^{0.34}$ ₇	$2.74(z/10)^{0.36}$ ₃	-4.03
Cas e 2	$8.34(z/10)^{0.14}$	$1.95(z/10)^{0.55}$ ₂	$1.99(z/10)^{0.54}$ ₄	-0.69
Cas e 3	$4.09(z/10)^{0.08}$	$1.50(z/10)^{0.31}$ ₉	$1.72(z/10)^{0.57}$ ₇	-12.27
Cas e 4	$4.47(z/10)^{0.08}$	$1.49(z/10)^{0.37}$ ₆	$0.61(z/10)^{0.65}$ ₃	-23.84

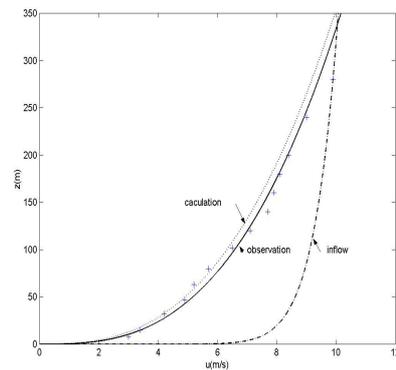


Figure 2. The wind velocity Profile. (case1)

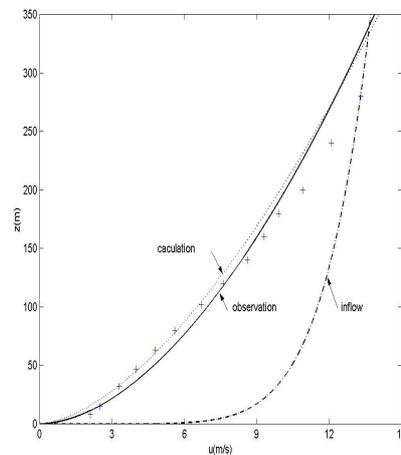


Figure 3. The same as in figure 2 but for case2

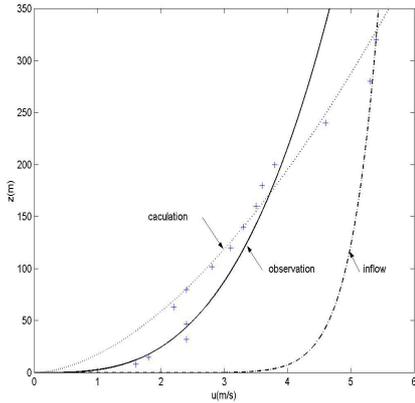


Figure 4. The same as in figure 2 but for case3

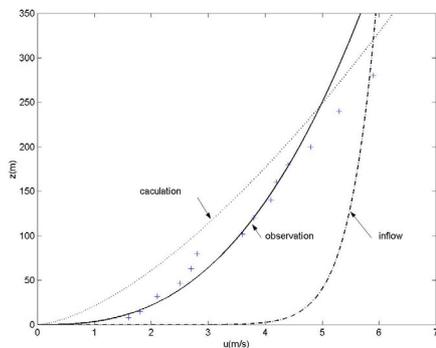


Figure 5. The same as in figure 2 but for case 4

From the simulated results, it can be concluded that the simulation profile and observation data are very similar during the gale, while it is not ideal during breeze especially in stable condition. That may have relation with not including the thermal factors in urban canopy layer.

On the other hand, as shows in Figure 4 during breeze and stable condition, the fitting wind profiles with observation data have large discrete with observation values. It shows that simple power exponent wind profile is not fit for this case. The simulation results above 50m are close to observation values. This can show the complexity of the flow field in urban canopy layer [6].

(2) Character of the flow field

Figure 6 and 7 show the flow field at 10m simulated in case 2 and case 4. We can found

that the minimum wind velocity occurs at the largest density building district. Since the drag of buildings, leeward wind speed cannot resume during area scale.

In Figure 8, the horizontal wind speed on the vertical profile of $y=400\text{m}$ shows that such a area with highest building of 75m can influence the wind speed at about 150m height.

In Figure 9, vertical velocity at $y=400\text{m}$ shows that the complexity of buildings results in the complexity of vertical motion. Basically, updraft airflow lies on the windward of buildings, while downdraft airflow lies leeward at speed of 2m/s. There are two large density buildings near (400m,400m). Updraft and downdraft motion can be obviously seen in the front of building and at the back separately in Figure 9.

(3) The distributing of vertical diffuse coefficient

Figure 10 shows the vertical profile of Km at $y=400\text{m}$. It indicates that Km in lower layer is bigger than in high layer in Urban canopy layer. Large Km value appears near large density building. Otherwise, Km in condition of gale is bigger than that in breeze, which is accordant with the results obtained by Stull [7]. This shows $k-\epsilon$ method is comparatively rational to calculate Km .

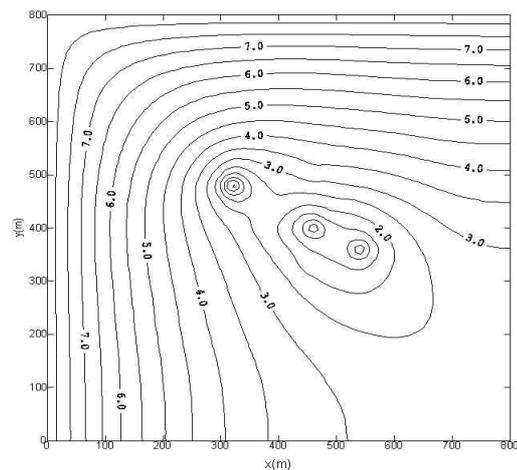


Figure 6. The distributing of horizontal wind speed at 10m (units: m/s) in Case 2

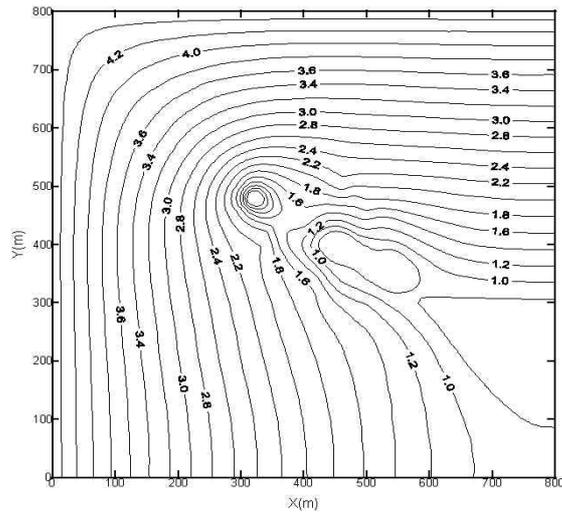


Figure 7. The same as in figure 6 but for Case 4

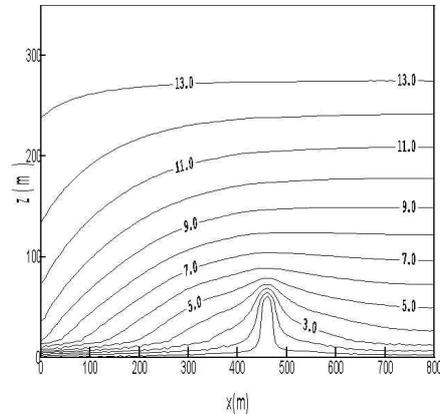


Figure 8. The distributing of horizontal wind speed (units: m/s, at y=400m) for Case 2

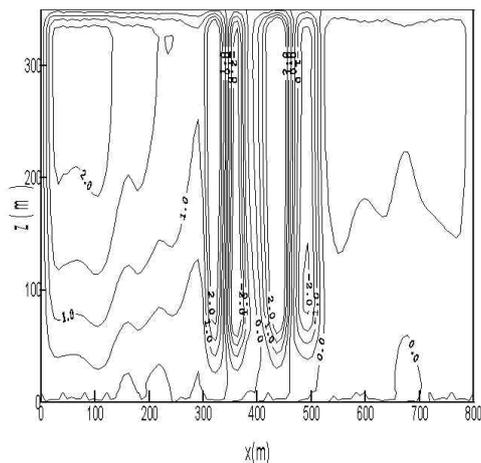


Figure 9. The distributing of vertical wind velocity (units: m/s, at y=400m) for Case 2

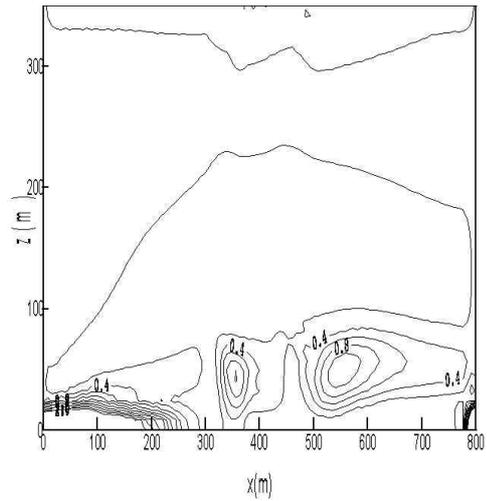


Figure 10. The distributing of vertical diffuse coefficient (units: m/s, at y=400m) for Case 2.

7. BRIEF SUMMARY

A numerical model of flow field in urban canopy layer based on k- ϵ closure method is developed in this paper, in which a porous medium is used to present the buildings in the urban area and the form drag is used to represent the drag to the flow by the buildings. The results obtained from the model have been compared with the data observed from the Beijing 325m meteorological tower. It shows that during the strong wind, the wind velocity profile obtained from the model accords well with that observed from the tower. The simulation on breeze condition is not ideal for not including the thermal factor. It is what we should do next.

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