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模拟街道峡谷内的流场和污染物浓度的格子玻尔兹曼方法

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摘　要：构造了模拟街道内的流场及污染物扩散的格子玻尔兹曼模型，并且用这个模型来模拟了不同高宽比的街道峡谷流场和污染物扩散情况。模拟结果表明，地面附近的污染物浓度随着街道高宽比的增加而递增，这一结果和以往的研究结果有很好的一致性。

关键词：格子玻尔兹曼方法；空气污染
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Lattice Boltzmann method for simulation of air flow and pollutant dispersion in street canyon

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Abstract: A new lattice Boltzmann method model was constituted to simulating the flow patterns and pollutant dispersion in street canyons, and it was applied to simulating the flow patterns and pollutant dispersion of different street canyon aspect ratio (*AR*=*H*/*W*). The results show that it makes more difficult to disperse the pollutants and more concentration near the ground level with increasing the aspect ratio. The numerical results are found to be in better agreement with those of previous studies.

Key words: Lattice Boltzmann method; air pollution

1　Introduction

Much attention has been focused on the flow patterns and air pollution in street canyons, because of increasing urban pollutants and their adverse impacts on human health. With rapid development in computer hardware and numerical algorithms, computational fluid dynamics (CFD) techniques are widely utilized to study the flow patterns and pollutant distributions in street canyons, and have achieved great success[1].

The lattice Boltzmann method, as a relatively new numerical approach, has achieved considerable successes in simulating fluid flows over the past decades[2-9]. Nevertheless, there has been few publications on lattice Boltzmann method to simulate pollutant dispersion in street canyons.

In this paper, we construct an appropriate lattice Boltzmann method model to simulate the flow patterns and pollutant distributions in street canyons. It provides a new feasible way to simulate the flow patterns and pollutant dispersion in street canyons.

2　Mathematical Formulation

The air within the street canyons can be regarded as an incompressible inert flow, and the air and pollutant densities are assumed to be constant. For the two-dimensional isolated street canyon problem, as shown in Fig.1.

The partial differential equations governing the motion of airflow are the continuity and the averaged Navier-Stokes equations, which are given as,

Continuity equation

$$\nabla \cdot u = 0 \tag{1a}$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\nabla p + v\nabla^2 u \tag{1b}$$

Here, *u* and *p* represent fluid mean velocity and pressure, and *v* is kinematic viscosity. Pollutant concentration is calculated with the convective-diffusion

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equation for atmosphere

$$\frac{\partial u}{\partial t}+u\cdot\nabla C=K\cdot\nabla^2 C \qquad (1c)$$

K denotes diffusivity coefficient; *C* denotes the pollutant concentration.

3 Numerical Method

For the pollution concentration lattice Boltzmann method model, we first use the LBM model described in Ref. [8] for the velocity field.

$$f_i(x+e_i\Delta x,t+\Delta t)-f_i(x,t)=-\frac{1}{\tau_u}(fi(x,t)-f^{eq}{}_i(x,t)) \qquad (2)$$

Where τ_u is the dimensionless relaxation time, the discrete velocity directions e_i are defined by

$$e_i=\begin{cases}(0,0) & i=0\\ (\cos(i-1)\pi/2,\sin(i-1)\pi/2) & i=1,2,3,4\\ \sqrt{2}(\cos[(i-5)\pi/2+\pi/4],\sin[(i-5)\pi/2+\pi/4]) & i=5,6,7,8\end{cases}$$

$c=\Delta x/\Delta t$ is the particle speed satisfying incompressible limitation $|u|\leqslant c$, $f_i(x,t)$, is the distribution function, and $f_i(x,t)$ is the equilibrium defined by

$$f_i^{eq}=\lambda_i p+s_i(u) \qquad (3)$$

where $\lambda_0=-4\sigma/c^2$ $\lambda_i=-\lambda/c^2(i=1,2,3,4)$ and $\lambda_i=-\gamma/c^2(i=5,6,7,8)$

with parameters σ, λ and γ satisfying

$\lambda+\gamma=\sigma$

$\lambda+2\gamma=1/2$

and $s_i(u)=\omega_i\left[3\frac{(e_i\cdot u)}{c}+4.5\frac{(e_i\cdot u)^2}{c^2}-1.5\frac{|u|^2}{c^2}\right]$ with the weights, $\omega_0=4/9$, $\omega_i=1/9(i=1,2,3,4)$ and $\omega_i=1/36(i=5,6,7,8)$.

The flow velocity, pressure and kinetic viscosity are given by

$$u=\sum_{i=1}^{8}ce_i f_i，p=\frac{c^2}{4\sigma}[\sum_{i=1}^{8}f_i+s_0(u)]，\upsilon=\frac{(2\tau_u-1)}{6}\frac{(\Delta x)^2}{\Delta t} \qquad (4)$$

The evolution equations for pollutant concentration C reads

$$C_i(x+e_i\Delta x,t+\Delta t)-C_i(x,t)=-\frac{1}{\tau_C}(C_i(x,t)-C_i^{eq}(x,t)) \qquad (5)$$

Where e_i are the discrete velocity directions defined by

$e_i=(\cos[(i-1)\pi/2],\sin[(i-1)\pi/2])$ for i=1,2,3,4 and the equilibrium distribution function C_i^{eq} are defined by

$$C_i^{eq}=\frac{C}{4}\left[1+2\frac{e_i\cdot u}{c}\right]$$

i=1,2,3,4, and τ_C the dimensionless relaxation time. The macroscopic pollutant concentration are given by

$$C=\sum_{i=1}^{4}C_i,K=\frac{(2\tau_C-1)}{4}\frac{(\Delta x)^2}{\Delta t} \qquad (6)$$

Through multi-scaling expansion, Eqs.(1a) and (1b) can be derived from Eq.(2) with Eq.(4) to the order of $O(\Delta t^2)$, while Eq.(1c) can be derived from Eq.(5) with Eq.(6) to the same order if the Mach number $M=\Delta t$.Thus a coupled pollutant dispersion lattice Boltzmann model is obtained for the problem (1).

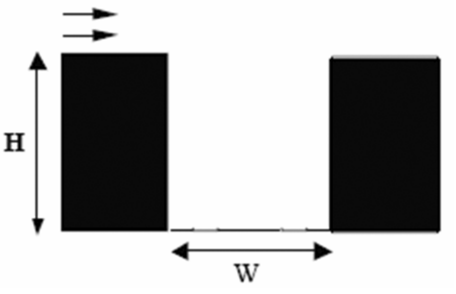

Figure 1 Geometry of research domain

The boundary conditions in this investigation were specified by non-extrapolation rule for velocity and press boundary conditions[10-11], which is of second order, simple form, and exhibits much better numerical stability. In this study we use this scheme for velocity boundary, which is given by

$$f_i(x_b,t)=\overline{f}_i^{(eq)}(x_b,t)+(f_i(x_f,t)-f_i^{(eq)}(x_f,t)) \qquad (7)$$

where $\overline{f}_i^{(0)}(x_b,t)=\lambda_i p(x_f,t)+s_i(u(x_b,t)),x_b$ is a node on the boundary, and x_f is its nearest-neighbour fluid node. Similarly, for the pollution concentration boundary condition, we use

$$C_i(x_b,t)=\begin{cases}C_i^{(eq)}(x_b,t)+(C_i(x_f,t)-C_i^{(eq)}(x_f,t))\\ \quad if\ \ C(x_b,t)\ \text{ is known,}\\ \frac{C(x_f,t)}{4}\left[1+2\frac{e_i\cdot u(x_b,t)}{c}\right]+\\ ((C_i(x_f,t)-C_i^{(eq)}(x_f,t)))\ \text{ otherwise,}\end{cases} \qquad (8)$$

It can be easily shown that the boundary conditions Eq. (8) for problem (1) are both of second order.

4 Numerical Results and Discussions

Numerical simulations were carried out using the model presented above for the air flow and pollutant dispersion in street canyons. The computational domain embodies two parallel buildings and a street canyon. The street canyon considered is of height H and width W (*AR*=*H*/*W*). Between two parallel buildings, in the street canyon of width S a line source is placed on the center of the street floor, where *S*=*W*/2. And the dimensionless concentration is 15. The wind on the roof is orthogonal to the direction of street and inflow velocity is 1.5 m/s. The simulations were carried out on a 100×100 lattice, the value of the Reynolds is 500.

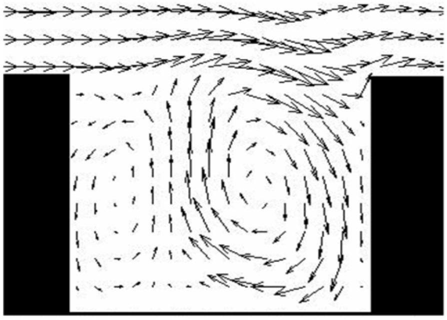

Figure 2-a Wind flow in a street canyon for *AR*=0.5

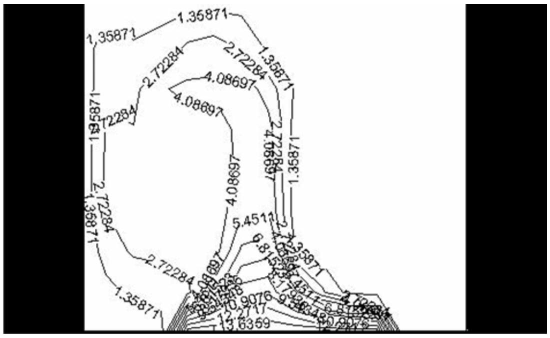

Figure 2-b Pollutant dispersion in a street canyon for *AR*=0.5

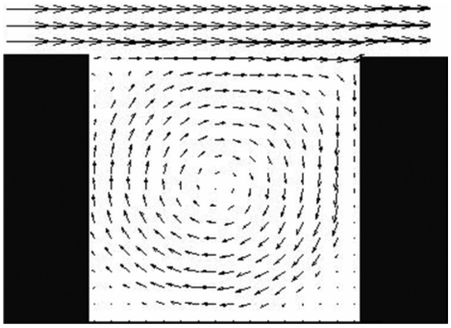

Figure 3-a Wind flow in a street canyon for *AR*=1

The three styles of building employed are as illustrated here (Fig.2-Fig.4). The results show that different canyon aspect ratio has different pollutant distributing characters. For wide canyons (*AR*=0.5), when the wind is blown from left to right, two co-rotative vortices circulation are generated. Pollutant concentration at the leeward of the upstream building is higher than the windward of the downstream building. In case of regular canyons (*AR*=1), the bulk of the synoptic flow skims over the canyon producing the skimming flow, which is characterized by the formation of a single vortex within the canyon, pollutant concentration at the leeward of the upstream building is more higher.

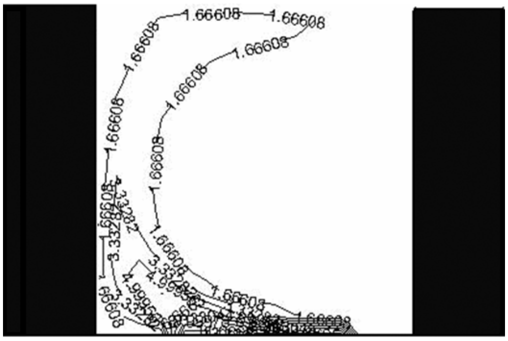

Figure 3-b Pollutant dispersion in a street canyon for *AR*=1

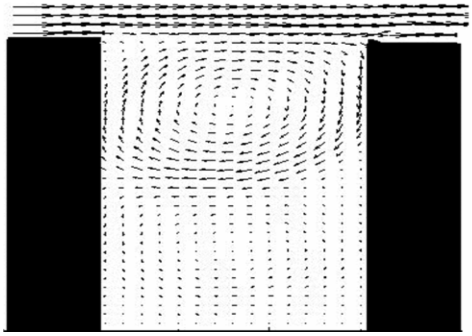

Figure 4- a Wind flow in a street canyon for *AR*=2

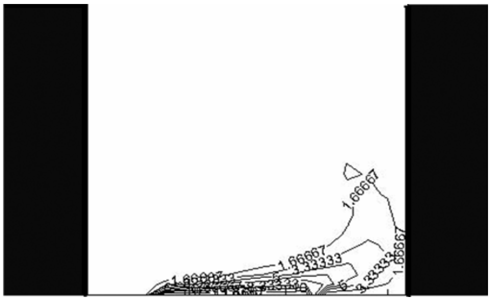

Figure 4-b Pollutant dispersion in a street canyon for *AR*=2

As the aspect ratio increases (*AR*=2), a weak counter-rotating secondary vortex is formed in the bottom of the street canyon, which results in higher pollutant concentration at the windward of the downstream building and lower pollutant concentration at the leeward of the upstream building. When the street between the buildings is widened, the blowing wind approaches the street floor and removes the pollutant more easily from the line source of the street canyon. The calculated and measured data show that the wider street canyon can promote air ventilation within street canyon, hence, less pollutant is accumulated. The numerical results are found to be in good agreement with those of Refs[10-12].

5 Conclusions

In conclusion, we have developed a new lattice Boltzmann method model for simulating the pollution dispersion in street canyons. The simulation results indicate the capability of the present lattice Boltzmann method in simulating flow patterns and pollutant dispersion in street canyons. The close agreement with computational data of previous studies shows the good performance of the model. This method may be a viable tool to simulate some patterns of pollution in street canyons, and the prospect of applying lattice Boltzmann method to study atmospheric environment is very well.

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