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Influence of Meteorological Conditions on Pollutant Dispersion in Street Canyon

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Abstract

Vehicle exhaust pollutants has become a major source of urban air pollution and it is of great significance to study its diffusion law. This paper analyzes the factors that affect the diffusion of motor vehicle emissions in the street canyon and determines the research method of pollutant dispersion. This paper mainly simulates the influence of different wind speed and wind direction on the flow field and pollutant dispersion in the street canyon. Results show that the wind speed and wind direction has a great impact on the air flow and pollutant dispersion in the canyon. Vertical and inclined to the wind, the leeward side of the street canyons pollutant concentrations is much higher than the windward side of the concentration of pollutants, leeward pollutant concentration and the pollutant concentration of the windward side of is almost the same. The results of this paper can provide scientific basis for the control, monitoring and evaluation of urban motor vehicle emissions, and reasonable layout and planning of urban streets.

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Keywords: *Urban Street Canyons，Diffusion of vehicle emissions， PM2.5, Meteorological conditions, Numerical simulation*

1. Introduction

With the rapid urbanization in-depth and industrialization, the number of motor vehicles in China has recently increased remarkably. The vehicle emissions have become a major source of urban air pollution. For reducing the consumption of land resource in the development of cities, high-rise buildings have become the main choice in urban construction. More and more high-rise buildings and their different layout will have different effects on the environment in cities. Especially to the canyon type street, the exhaust of motor vehicles accumulates in the street

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canyon, which do harm to the travelers who directly exposed in the atmosphere. Nowadays traffic emission is considered as the main air pollution source m the urban environment, and it has many adverse effects on the indoor air quality of the buildings along the street. Therefore, it is very necessary to investigate thoroughly the characteristics of the traffic-related air pollution in the urban street and the relationship between the indoor air quality and the outdoor air pollution for the buildings along the street.

To meet the needs of urban environmental management and planning of urban roads, people need understand the diffusion law and concentration distribution of motor vehicles emission pollutants in urban street canyon deeply, study the flow of the air in the city streets and the diffusion regularity of motor vehicle emissions, and apply the law to the urban construction planning. When planning the city streets, considering the angle of streets with local dominant wind direction, street width and the height of the buildings, the structure of the distribution on both sides of street and block shape and taking into account the sunshine conditions and urban traffic characteristics, this will help reduce street canyon pollutant accumulation to control the content of the pollutant within street canyon.

1.1 Progress of Numerical Simulation

The flow characteristics of street canyons and pollutant dispersion problems began the numerical simulation method in the 1990s. The core of the fluid motion description is the Navier-Stokes equations, and all sorts of numerical simulations are based on the equation. We can do different simplified for different subjects to obtain a mathematical model under different circumstances. In street canyons diffusion model, due to the lower fluid velocity, it is considered incompressible fluid. Johnson [1] studied the street canyon flow movement in 1991, his studies have verified the results of several wind tunnel tests, including the vortex flow when the top of wind direction is perpendicular to the axis of the canyon. Leitl and Meroney [2] used the standard K- ε model and RNGK-8 model to simulate the pollutant concentration distribution in the urban street canyon in 1997. Schorling using the Lagrange method to analyze the pollutant dispersion process and noted that atmospheric turbulence models are the primary factors that influence the final result (Wenquan T. [3]. Although the research in this aspect in China starts late, there are also many scholars carried out a certain research and obtained many valuable results .Huang Yuandong et al. [4] based on the standard k- ε equation turbulence model, simulated numerical simulation of the air flow field in the streets of the different buildings. Wu Zhijun et al [5] simulated the law of vehicle emission dispersion in the urban street with band pedestrian arcades. Wang limin et al.[6] simulated the air flow of non-isolated street canyons and pollutants diffusion in the atmosphere. Xie Haiying, Chen Kangmin [7] studied the effects of wind on the spread of pollutants in the street canyon.

1.2 The Main Research Content of this Article

This paper mainly simulates the influence of different wind speed and wind direction on the flow field and pollutant dispersion in the street canyon. Research results presented in this paper for motor vehicle emission pollutants in urban street canyon area control, the control of traffic flow, the rational distribution of urban streets and city planning and street construction , as well as the urban air pollution monitoring and evaluation to provide scientific basis.

2. Methods

2.1 Air Pollution Diffusion Theory

Atmospheric boundary layer, also known as friction layer, belongs to the troposphere. From the perspective of fluid mechanics, atmospheric boundary layer air flow has great randomness, basically turbulent flow, and air flow turbulence intensity up to 20%. Wind speed increases with height increases, wind speed on the ground surface is equal to zero, in the outer edge of the atmospheric boundary the geostrophic wind speed is constant, and the variation rules of the mathematical expression adopt index law and logarithm law two empirical formula to represent. The expression of the exponential law is shown as follows $U_l = U_\infty \cdot \left(\frac{z_l}{z_\infty} \right)^\alpha$. In this formula, α is the ground roughness coefficient, Z_∞

means the height of wind speed achieving uniform flow in the atmospheric boundary layer, U_∞ stands for the wind speed at the height of Z_∞, Z_l represents for the arbitrary height below the height of Z_∞, U_l indicates the wind velocity at the height of Z_l.

2.2 Numerical Simulation of Turbulence Problem

Most flow phenomenon in nature and engineering application is turbulent. The most common method of the street canyon pollutant diffusion at home and abroad is the k- ε two equation model in the Reynolds averaged N-S (RANS). The time averaged equation follows:

$$\bar{\rho}\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_j}\bar{\rho}\cdot\bar{u}_i k=-\bar{\rho}\overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j}-\frac{\partial}{\partial x_j}(\frac{1}{2}\overline{\rho u_i'}\,\overline{u_i' u_j'}-\mu\frac{\partial k}{\partial x_j}+\overline{P' u_j'})+\mu(\frac{\partial u_i'}{\partial x_j}) \tag{1}$$

Substitute it into the turbulent transport equation, the steady flow of turbulent kinetic energy transport equation can be simplified as:

$$\frac{\partial}{\partial x_j}\bar{\rho}\cdot\bar{u}_j k=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_k}\cdot\frac{\partial k}{\partial x_j}\right)-\bar{\rho}\cdot\overline{u_i' u_j'}\cdot\frac{\partial \bar{u}_i}{\partial x_j}-\bar{\rho}\varepsilon \tag{2}$$

The loss of turbulent kinetic energy dissipation rate ε equation of unit mass flow in unit time, and substitute it into the turbulent dissipation rate, sorting by:

$$\bar{\rho}\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial x_j}\bar{\rho}\varepsilon\bar{u}_j=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{\sigma_s}\cdot\frac{\partial \varepsilon}{\partial x_j}\right)+\bar{\rho}\frac{\varepsilon}{k}\left(C_{1\varepsilon}G-C_{2\varepsilon}\varepsilon\right) \tag{3}$$

In the equation, $G=\overline{u_i' u_j'}\left(\partial \bar{u}_i/\partial x_j\right)$ show turbulent kinetic energy produced by the velocity gradient; *k* is turbulent kinetic energy, m^2/s; ε is turbulent kinetic energy dissipation rate, m^2/s; $C_\varepsilon = 0.07 \sim 0.09$, $C_{1\varepsilon} = 1.41 \sim 1.45$, $C_{2\varepsilon} = 1.9 \sim 1.92$. The above formula forms closed equations that can describe the state of turbulent flow, which can solve the turbulent flow field by numerical methods. Pollutants convection diffusion equation can be simplified as,

$$\frac{\partial \bar{c}}{\partial t}+\frac{\partial(\overline{c u_j})}{\partial x_j}=\frac{\partial}{\partial x_j}(D_{eff}\frac{\partial \bar{c}}{\partial x_j})+S_c$$

(4)

The formula is the general form of pollutants convection diffusion equation, D_{eff} is pollutant turbulent diffusion coefficient, which indicates the effect of convection transfer and turbulent diffusion in the progress of pollutants transmission. The first item on the left is the local change of the pollutant concentration; the second is the variation of the flow, also called the convection term, the first item on the right is pollutants turbulent diffusion, the second is the generation/disappearance of pollutants. Due to the equation based on the hypothesis which is that pollutant transport flux is proportional to the average atmospheric pollutants concentration gradient, so the equation is suitable for the pollutants transport and diffusion under the action of small scale turbulence vortex, such as pollution sources of vehicle emissions. Turbulent eddy scale restricted by the ground, diffusion in the vertical direction is mainly small eddy effect. So the pollutant convection-diffusion model is suitable for solving the problem of the diffusion of the ground pollution source.

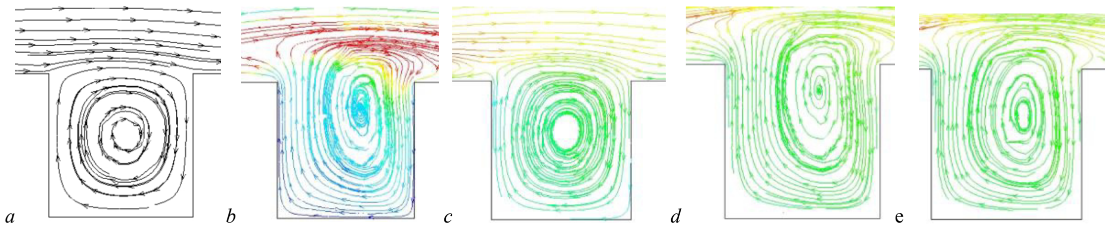
3. Results

Due to the pollutant concentration level in street canyon is mainly decided by three factors, namely the emission source, meteorological condition and the geometrical characteristics of the building on both sides of the street. This paper analyzes air flow law and rule of motor vehicle exhaust pollutant diffusion in street canyon from the aspects of meteorological condition.

3.1 The Effects of Wind on Flow Field and Pollutant Dispersion

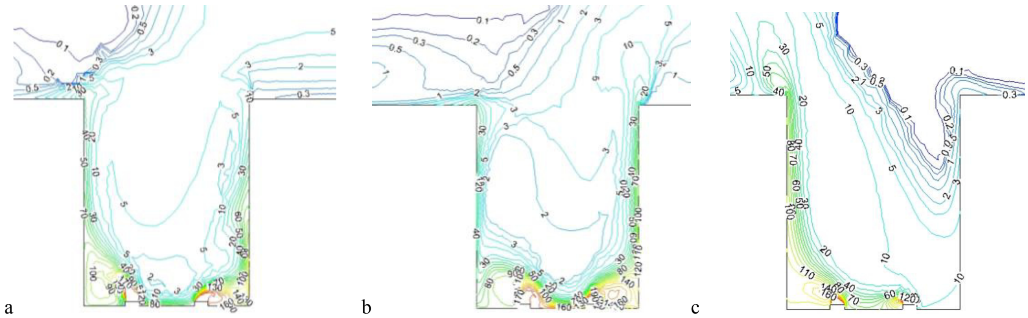
Domestic and international numerous scholar shave mostly studied the wind field and pollutant dispersion in the street canyon, which mostly just calculate wind direction perpendicular to the street and wind velocity parallel to the street two cases. When the wind and the streets into a certain angle, the effect of the wind conditions on the air flow and pollutant dispersion concentration field is more complex. In this paper, numerical simulation of the roof top wind speed at 10m/s ,wind angle is 15°, 30°, 45°, 60°, 75°and 90° respectively, that is a total of 6 cases of airflow field and concentration field of pollutant diffusion in isolated street canyon.

Fig.1 is streamline vector diagram inside the street canyon when the direction of the wind angle θ is 15°, 30°, 45°, 60°, 75°and 90° respectively. As can be seen from above the figure, the roof of the wind direction on both sides of the street canyon have a greater impact on the flow of air within the canyon. The wind affects on the flow of air inside the street leading to the difference in the diffusion of pollutants discharged street vehicle. Vertical and inclined to the wind, the leeward side of the street canyons pollutant concentrations is much higher than the windward side of the concentration of pollutants, leeward pollutant concentration and the windward side of the pollutant concentration is almost the same. Wind plays the role of transportation for the valley pollutants; the wind determines the pollutant migration direction, which makes downwind pollutant concentrations higher than upwind pollutant concentrations. Wind along the street on the top of buildings is important to the air pollutant dispersion in the streets, which is due to the different wind directions in the street roof wind will produce different air flow field. When the roof wind parallel to the street canyon, street pollutants is more easily spread and are not easy to accumulate on the building surfaces. With the wind and street canyons angle increasing, the pollutant can produce the phenomenon of the accumulation of the building surface.

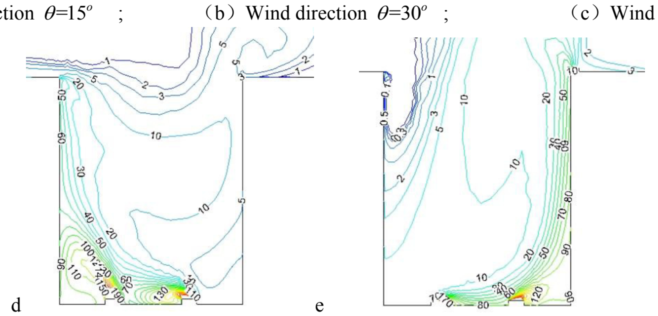


（a） θ=15^o ; （b） θ=30^o ; （c） θ=45^o ; （d） θ=60^o ; （e） θ=75^o

Fig. 1. Flow field in streets of different wind directions（Roof wind speed is 10.0m/s）



（a）Wind direction θ=15^o ; （b）Wind direction θ=30^o ; （c）Wind direction θ=45^o



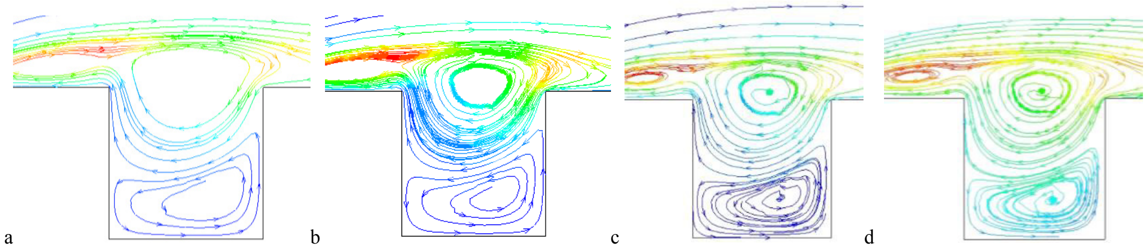
（d）Wind direction θ=60^o （e）Wind direction θ=75^o

Fig. 2. the dimensionless pollutant concentration field (Roof wind speed is10.0m/s)

3.2 The Effect of Wind Speed on Pollutant Dispersion

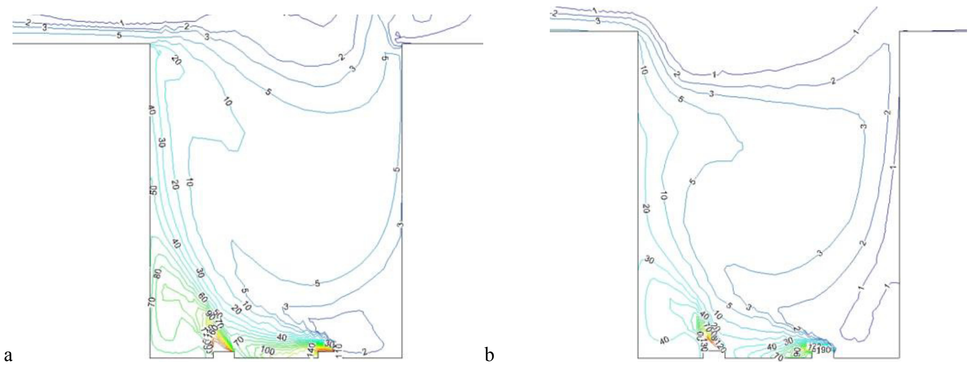
In this paper, keeping the same street geometry, with a typical street canyons (the ratio of the height and width for the H/B=1) as an example to study the impact of wind velocity on air flow field inside the canyon and the vehicular pollutant distribution and the influence of diffusion. In general, the wind speed is usually 3-15m/s, which is usually called the wind in the range of 2 to 7 levels, so the scope of this chapter research simulation of wind speed is in the range of 3 to 15 m/s.

In all types of street canyons, the velocity field is the most important factor of atmospheric pollutant dispersion. In the chapter ,on the aspect ratio of H/B = 1 street canyon under different working condition of the roof wind speed (roof wind speed V_{in} is respectively 3m/s, 5m/s, 10m/s, 15m/s), airflow velocity field were calculated within street canyon. In the cases of different roof wind speed airflow velocity vector flow inside of street canyon calculation results as shown in figure3. From the velocity vector flow chart, it can be seen that due to the effect of the air reflux, a large vortex is generated in the streets of the canyon, and the center of the large vortex is located on the central side of the street canyon. Because of the large eddies drive, there forms a more obvious secondary vortex in the bottom of the canyon.



(a) $V_{in}=3$(m/s) (b) $V_{in}=5$(m/s) (c) $V_{in}=10$(m/s) (d) $V_{in}=15$(m/s)

Fig. 3. Flow field in streets of different roof wind velocity



(a) $V_{in}=5$(m/s) (b) $V_{in}=10$(m/s)

Fig.4. Dimensionless pollutant concentration field at different wind speed

The air pollution in the street valley is diluted by wind. As the wind speed increasing, per unit time clean air flowing into the street canyon increases with the dilution effect of pollutants greater. Meanwhile, the wind can also improve the wind pressure of the street canyon building, thereby which increases the natural ventilation rate of the building. In the process of the pollutants diffusion pollutants in the street canyon, when street Valley aspect ratio is not the same, it will form different vortex, thus forming different from the flow field in the upper atmosphere of the building. But they have a common law, that is, when the upper atmosphere wind speed increase, the street canyon pollutant exchange intensifies with the upper atmosphere, so that the building surface contaminant concentration reduced in the street canyon.

4. Conclusions

This article uses the method of numerical simulation to study the typical street canyon air pollutant concentration field and flow field with variation of the meteorological conditions and the street canyon structure. Studies have shown that motor vehicle exhaust pollution is influenced by structure group and wind conditions, and indoor air quality with the increase of wind speed and building height weakened. In this paper, the main conclusions are as follows:

(1) Wind plays the role of transportation for the valley pollutants, the wind determines the pollutant migration direction, which makes downwind pollutant concentrations higher than upwind pollutant concentrations. Wind is important to the air pollutant dispersion in the streets. When the roof wind parallel to the street canyon, street pollutants is more easily spread and are not easy to accumulate on the building surfaces. With the wind and street canyons angle increasing, the pollutant can produce the phenomenon of the accumulation of the building surface.

(2) The wind has a dilution of the pollutant in the street valley, the greater the wind speed ,the more dilution of pollutants. At the same time, the increase of wind speed will enhance wind pressure on the surface of the building in street valley, thereby raising the natural ventilation rate of the building. In the street canyon pollution and upper atmospheric diffusion exchange intensifies, which makes contaminant concentration on the street building surface cut down.

(3) The wind has a dilution of the pollutant in the street valley, the greater the wind speed, the more dilution of pollutants. At the same time, the increase of wind speed will enhance wind pressure on the surface of the building in street valley, thereby raising the natural ventilation rate of the building. In the street canyon pollution and upper atmospheric diffusion exchange intensifies, which makes contaminant concentration on the street building surface cut down.

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