The influence of vapor on the particle transport in high humid neighborhood environment

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Abstract—The particle transport characteristics have a significant effect on the exposure of residents and pedestrians to traffic pollutants in the street canyon. Around the lakeside environment, the diffusion of water vapor affects the flow characteristics of the gas mixture, which has a considerable influence on particle transport in the street canyon. A computational domain containing water bodies from which droplets were emitted by evaporation, a lakeside avenue and architectural groups were constructed. The RNG k-ε turbulence model and discrete phase model were applied to study the velocity, pressure, density of the airflow and particle transport characteristics in the street canyon with the absolute humidity increase (AHI) of 0, 3.8×10^{-4} g/kg, 1.7×10^{-3} g/kg, 3.1×10^{-3} g/kg. The saturated vapor pressure on the surface of droplets was modified by the pressure correction equation, which can limit the evaporation rate of the droplets. The simulation results demonstrated that, the diffusion of vapor could reduce the airflow velocity and increase the air pressure and density. The particle concentration in the street canyon increased with the AHI. Most of the pathogens in the air are transmitted with the flow of particle, and the study has some guiding significance to prevent the transmission of viruses.

1. Introduction

With the quality of life improving, the residential buildings beside urban water bodies become the best choice for people to live in because of its beautiful landscape, suitable air humidity and so on. However, the particulate matter exhausted from vehicles on the avenue along the bank of the river inevitably invades the surrounding living environment.

In the urban environment, pools, ponds and rivers are small water bodies. Hathway and Sharples[1] have paid attention to the temperature decreasing by evaporation cooling of water bodies in the micro-scale environment by the field monitoring. It found that the annual temperature was reduced by 1.5°C averagely beside the river. Some other studies have simulated the micro-climate of the city within water bodies on the urban or regional scale[2-4]. It was found that the heat release rate of the domain surface was significantly reduced by 9.3% under the impact of urban water bodies.

In addition to the above studies on the influence of water bodies on local hot and humid climate, the effects of humidity gradient on particle transport have been extensively studied. Yu[5] conducted outdoor monitoring near the East Lake and the Yangtze River and found that the humidity was an important factor leading to the occurrence or intensification of gray haze. In outdoor atmospheric environment, Chen[6] studied the effect of air relative humidity on the number of the nanoparticles exhausted by vehicles in the streets of Stockholm, Sweden. The results showed that the relative humidity was positively correlated with the number of particulate matter which aerodynamic diameter
was in 126-400 nm. Cui\cite{1} studied the effect of air humidity on the indoor particulate matter distribution. It was found that there was an obvious coagulation phenomenon when air relative humidity was over 65%. Nevertheless, these studies pay attention to the relationship between humidity and particulate matter coagulation phenomenon, humidity and gaseous pollutants diffusion process. The mechanism and relationships between vapor diffusion and outdoor particulate matter transmission have not been explored.

The computational domain containing water bodies from which droplets were emitted by evaporation, a lakeside avenue and architectural groups was constructed. On the one hand, the multi-component Euler-Lagrange approach was employed to simulate the evaporation and diffusion of droplets in the flow field, and the vapor pressure on the surface of droplets was constantly modified to obtain accurate evaporation rate. Compared with the existing models reported in the literature, the approach is unique as a continuity equation was explicitly solved for the water vapor. On the other, the influence of building height difference on particle transportation at the high humidity condition was explored. The purpose of this paper is to rationally plan the buildings layout and thus accelerates the particle transport or reduces the local particulate concentration.

2. Materials and methods

2.1 Computational domain and geometric model

In the lakeside residence, the step-up high-rise building layout as our research objective was extremely common. According to the characteristics of increasing the height of buildings, the arrangement layout of the incremental building was designed.

The geometric model of the lakeside building group was shown in Fig. 1. The computational domain measured 400 (H) × 2000 (L) m, comprised a urban water body (a lake in the city) with the width \(l_1 = 200\) m and a height difference of 2 m from the ground level. The width of the avenue adjacent to the lake was \(w = 80\) m, and the particle matter source of automobile exhaust was located in the center of the avenue. Along the X direction there were three buildings which the heights of were gradually increased. The Y direction represented vertical direction. The height of the first building was defined as \(h = 20\) m. The street width was \(w_1 = 20\) m. The extension distance behind buildings was \(Le = 1420\) m. Moreover the height of computational domain was sufficient for the development of a free-stream wind layer at a constant inflow wind speed.

![Fig. 1 Computational domain and geometric model](image)

2.2 Mathematical and physical model

Assuming that the saturated humid air with pure water droplets was emitted from the surface of the lake, its generation could be described by the following process: the water vapor produced on the lake surface was dispersed into the unsaturated air until the air reached saturation, and then the water vapor was condensed into droplets. As time went on, the temperature of droplet particles decreased continuously when dispersed in the non-isothermal flow field, so the partial pressure of water vapor on
the droplet surface increased gradually.

2.3 Droplet evaporation model
Kukkonen[8] proposed a droplet evaporation model that considered Stefan flow and diffusion coefficient and temperature. The mathematical expression of the model was as follows:

\[ m_d = \frac{Sh}{2nD_tKMC} \ln\left(\frac{p_{\text{vap},d}}{p_{\text{vap},\infty}}\right) \]

where \( m_d \) was the evaporation rate of the droplets on the lake surface, kg/s. \( p \) was the pressure, pa. \( R \) was the gas constant, \( R = 8.314 \text{ J/mol} \). \( K \) was diffusion coefficient, \( K = 0.834 \text{ m}^2/\text{s} \). \( D_d \) was the diameter of droplet, \( D_d = 20 \mu\text{m} \). \( M \) was molar mass of steam, kg/mol. \( p_{\text{vap},d} \) was vapor pressure on the surface of the particles, Pa. \( p_{\text{vap},\infty} \) was pressure of vapor in the environment, Pa. \( C \) was correction factor due to temperature effect on diffusion coefficient, \( C = 1 \).

The saturated vapor pressure on the surface of droplets was modified by the pressure correction equation, which can limit the evaporation rate of the droplets. The equation for the sub-pressure fitting of saturated water vapor on the surface of the droplet was[9]:

\[ p_{\text{vap},d} = \exp\left[77.34 - \frac{323}{T_d} - 8.2ln(T_d + 0.005711T_d)\right] \]  

2.4 Governing equations
Based on the Navier-Stokes RNG k-\( \varepsilon \) turbulence model, the mathematical equations of mixed convective heat and mass transfer due to temperature and humidity gradient were described as follow:

\[ \frac{\partial}{\partial x_i} \rho u_i = S_m \]  

(3)

\[ u_i \frac{\partial}{\partial x_j} \rho u_i = -\frac{\partial p}{\partial x_i} + \rho g_i \]  

(4)

\[ \frac{\partial}{\partial x_i} \left( \frac{\rho \alpha}{\sigma_j} \right) \frac{\partial T}{\partial x_j} \]  

(5)

where \( u_i \) was the fluid velocity in the direction, m/s. \( x_i \) was the coordinate, m. \( \rho \) was the density of a mixture composed of air and droplets emitted from the lake, kg/m\(^3\), and \( \mu \) was the dynamic viscosity, kg/(m·s). \( S_m \) was the quality source item produced by evaporation of lake and represented the evaporation rate (\( m_d \)) within lake unit cubic, kg/(m\(^3\)·s). \( \alpha \) was the thermal diffusivity, \( \alpha = 1.98 \times 10^{-5} \text{ m}^2/\text{s} \). \( Q \) was the heat transfer between water droplets and mixed gas, J/(m\(^3\)·s).

2.5 Particle transport
The discrete phase model (DPM) was applied to simulate the droplet phase and pollutant particle phase. Considering the movement of the droplet phase and the contaminant particle phase in the air was affected by gravity, drag, Saffman lift and buoyancy, the force equation of droplets and particles were as follows:

\[ \frac{du_i}{dt} = -F_D(u_i - u_p) + \frac{g\cdot(\rho_d - \rho_p)}{\rho_p} + E \]  

(7)

Among them, the drag force was the most important force in the force of droplets and particles, and its expression was:

\[ F_D = \frac{18 \mu d_i}{\rho_d Re_i} \]  

(8)

where \( Re_i \) was the droplet and particle Reynolds number. \( u_p \) and \( u_d \) were the particle and droplet velocity. \( \rho_d \) and \( \rho_p \) were the droplet and particle density. \( d_i \) was the diameter of droplet and particle. \( C_D \) was drag coefficient.

2.6 Boundary Conditions
Velocity boundary conditions: the inlet of the computational domain was the natural wind flow at
constant speed of \( u = 1 \) m/s. The outlet of the computational domain was set as the pressure outlet. The top layer of the domain was set to the free-slip boundary condition. The no-slip boundary condition was applied to all of the buildings walls, roofs, and ground of the street canyons.

Thermal boundary conditions: the inlet air temperature was \( T_{in} = 313 \) K and the initial temperature of water was \( T_{w} = 303 \) K. The lake surface was set as the injection source of the droplet, the injection velocity was 0.3 m/s, and the droplet diameter was 20 μm.

Source of particle emission: according to the traffic statistics of a lakeside avenue in Wuhan, the initial concentration of particulate from the source was defined as \( C_p = 0.02 \) mg/s. The injection velocity was 0.3 m/s, and the particle diameter was 2.5 μm.

3. Results and discussion

3.1 The effect of the AHI on the flow field

The absolute humidity increase (AHI) was defined as the initial absolute humidity was subtracted from the absolute humidity of the calculation result, which represented the increase in the absolute humidity due to evaporation of droplets on the lake surface. In order to explain and express results conveniently, four representative lines 1, 2, 3, 4 were selected in the street canyon. Line 1 and 2 were at the height of pedestrian level (1.5 m above ground), and Line 3, 4 were 2 m (0.1 \( w_1 \)) from the windward side and the same height as the building.

3.1.1 The effect of the AHI on the air density

Similar to the data processing of the AHI, the density increase (\( \Delta \rho \)) was defined as the initial density was subtracted from the density of the calculation result. When the AHI was \( 3.1 \times 10^{-3} \) g/kg, the distribution of \( \Delta \rho \) was shown in Fig. 2. The diffusion of water vapor had a more significant effect on \( \Delta \rho \) in the leeward area of the buildings. In the leeward area, \( \Delta \rho \) was larger than the windward area and up to as much as \( 1.00 \times 10^{-5} \) kg/m\(^3\).

![Fig.2 The density increase (\( \Delta \rho \)) contour in the street canyon with the AHI of \( 3.1 \times 10^{-3} \) g/kg.](image)

(a) Pedestrian level in street I  
(b) Pedestrian level in street II
The $\Delta \rho$ at windward side at different AHI were illustrated in Fig. 3. The $\Delta \rho$ was positively correlated with the AHI. When the AHI equaled to $3.1 \times 10^{-3}$ g/kg, $\Delta \rho$ was approximately $8.50 \times 10^{-6}$ kg/m$^3$. However, when the AHI equaled to $0$, $3.8 \times 10^{-4}$ g/kg, $1.7 \times 10^{-3}$ g/kg, almost all $\Delta \rho$ was limited within $2.50 \times 10^{-6}$ kg/m$^3$, which were obviously lower than that case of AHI at $3.1 \times 10^{-3}$ g/kg. The preceding analysis demonstrated that $\Delta \rho$ was significantly reduced with the AHI decreasing.

3.1.2 The effect of the AHI on the relative pressure

Fig. 4 showed the spatial distribution of the pressure in the street canyon in the geometric when AHI = $3.1 \times 10^{-3}$ g/kg. Other results were similar to the AHI at $3.1 \times 10^{-3}$ g/kg. There were significant variations in the distribution of the relative pressure in street canyon areas, especially on the surface of buildings. The relative pressure on the surface of low-rise buildings in the front row was positive, and the relative pressure on the surface of the back row of high buildings was negative. In the street canyon, from top to bottom, the relative pressure showed a tendency to decrease initially and follow by an increase. The higher-pressures areas were formed at the top of the building due to violent separation spawning by air flow around the apex of the front edge of the building.

Fig. 4 The pressure contour in the street canyon with the AHI = $3.1 \times 10^{-3}$ g/kg.
Fig. 5 presented the relative pressure at different AHI. It revealed that the relative pressure in the street canyon increased as the AHI increasing and the relative pressure variation was similar, about 0.026 Pa. When AHI = 3.1 × 10^{-3} g/kg, the relative pressure in the street canyon reached the maximum compared with other cases of AHI. It meant that the relative pressure increased gradually as the vapor diffused through the street canyon.

3.1.3 The effect of the AHI on the air velocity

The velocity contour in street canyon in the geometric model (a) was shown in Fig. 6. Due to the obstruction of buildings, the slow velocity area were formed in the street canyon and the velocity near the ground and the central area was lower than that of other areas in the street canyon.

Fig. 6 The velocity contour in the street canyon with the AHI of 3.1 × 10^{-3} g/kg.

In the Fig. 7, the Y axis \( \Delta u \) represented the decrement of the air velocity at windward side based on the case of AHI = 0, and the X axis was vertical height. As the AHI increased, the \( \Delta u \) of the street canyon increased. So the air velocity at AHI = 0 was the maximum and that at AHI = 3.1 × 10^{-3} g/kg was the smallest. As such, it demonstrated that the diffusion of vapor in the street canyon could reduce the airflow velocity.
3.2 The effect of the AHI on pollutant concentration

When AHI was 0, $3.8 \times 10^{-4}$ g/kg, $1.7 \times 10^{-3}$ g/kg and $3.1 \times 10^{-3}$ g/kg, the simulation results of particle concentration were shown in Fig. 8. At the pedestrian level of the first street canyon (Fig. 8 (a)), when the AHI was equal to 0, the average particle concentration was 0.05 ppm; while when the AHI was equal to $3.8 \times 10^{-4}$ g/kg, $1.7 \times 10^{-3}$ g/kg and $3.1 \times 10^{-3}$ g/kg, the average particle concentration was 0.06, 0.1 and 0.14 ppm. The results showed that the particle concentration increased with the AHI at different locations in the street canyon.

Fig. 7 The velocity decrease when AHI = 0, $3.1 \times 10^{-3}$ g/kg, $1.7 \times 10^{-3}$ g/kg, $3.8 \times 10^{-4}$ g/kg.

Around the lakeside environment, the diffusion of vapor reduced the airflow velocity and increased the density and pressure of the surrounding area. Particle transport was mainly affected by the airflow velocity and the buoyancy effect caused by the density and pressure gradient. Therefore, the influence of vapor diffusion on particle transport requires special concerns.

Fig. 8 Concentration of particle when AHI=0, $3.8\times10^{-4}$g/kg, $1.7\times10^{-3}$g/kg, $3.1\times10^{-3}$g/kg respectively.
When the AHI was equal to 3.1×10⁻³ g/kg, the airflow velocity was the minimum, which resulted in the worst convection diffusion in street canyon. Thus, the particle aggregated and the concentration of particle was larger in the street canyon.

4. Conclusion
In high humidity environment, the diffusion of water vapor has an important effect on the particle concentration in atmospheric environment. The flow field and particle concentration distribution in street canyon under four kinds of the absolute humidity increase (AHI) were studied by numerical simulation. Conclusions are as follows:

(1) The diffusion of vapor had a significant effect on the flow field characteristics of the street canyons. The airflow velocity decreased with the increase of the AHI in the street canyon, while the pressure and density were reversed. Particle transport was mainly affected by the airflow velocity and the buoyancy effect caused by the density and pressure gradient. Therefore, the influence of vapor diffusion on particle transport required special concerns.

(2) The diffusion of water vapor also hindered the particle transport in the street canyon. When water vapor entered the street canyon, it reduced the air velocity and the effect of convective diffusion became smaller, causing the accumulation of particle in the street canyon. The particle concentration increased with the AHI in the street canyon.

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