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The Impact of Viaduct on Traffic-Related Particle Pollution in the Street Canyon

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ABSTRACT

We investigated the effect of viaduct on the particle dispersion in a symmetry street canyon by means of Computational Fluid Dynamic (CFD) simulations. Results show that viaduct affects the airflow, therefore affects the dispersion of particles. Particle concentrations are increased because of the structure of viaduct and the additional emission cause by the traffic on the viaduct. Fine particles (PM1 and PM2.5) are more suspended in the street canyon while the deposition could be observed on large particles (PM10). The combined effect of viaduct and emission will increase the concentration about 40% on windward side and about 80% on leeward side. Although further investigations and field measurement a still required, this paper propose the general trends of particle dispersion that be help to understand the impact of viaduct on air quality.

Keywords: *Particulate matter (PM), Viaduct, Traffic emission, Air quality.*

INTRODUCTION

Air pollution is a severe problem facing urban environment. Specifically, particulate pollution has been attracting significant attention. Studies have validated that particle pollution have an adverse impact on human health (1). Researches show that PM_{10} (particles with diameter less than 10μm) can deposit in the respiratory tract, $PM_{2.5}$ can get into bronchi, and PM_1 can get into respiratory alveoli. Vehicular emission is the major source of particulate pollution (2), thereby traffic pollution can be extremely damaging to the health of pedestrian and residents. Many researchers have been done on traffic pollution through the methods of field measurement experiment and numerical simulation. The major factors that have been studied, which affect air flow and pollutant dispersion are geometry factors including street aspect ratios (3) and building roof shape (4), metrological condition including wind direction (5), ground and wall heating (6), and solar radiation (7), other factors like road barrier (8,9), vegetation (10,11), and car parking (12,13). Less research has been done to study the impact of viaduct on pollutants dispersion (14).

Urban viaduct is a normal road structure in large and medium-sized cities in China. It has significance in increasing space utilization and in promoting traffic efficiency. However, viaduct act as a barrier, affecting the air flow nearby, also has effect on the overall vehicular emission as the extra emission will be brought by the traffic flow on it. The assessment of how the viaduct would influence the particulate pollution can help to understand the pollution distributions and improve the roadside air quality.

By three dimensional（3D）numerical, this study aims to investigate the impact of viaduct on the dispersion of particulate matter dispersion compare to the dispersion in the case without viaduct in the street canyon. Furthermore, the distributions of particles in different diameters (PM_1, PM_{25} and PM_{10}) are analyzed to further investigate the pollution effect brought by viaduct.

METHODOLOGY

Turbulent Flow Transport Model

The standard $k-\varepsilon$ model has been successfully validated to reproduce turbulent patterns in the street canyon scale environment (15). In this study, the standard $k-\varepsilon$ model is adopted to simulate the flow field in the street canyon with viaduct.

The governing equations are shown as below:

The equation of continuity.

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \qquad (1)$$

The equation of momentum conservation.

$$\frac{\partial \overline{u_i}}{\partial x} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{1}{\rho} \cdot \frac{\partial \bar{p}}{\partial x_j} + \frac{\partial}{\partial x_j}[v\frac{\partial \overline{u_j}}{\partial x_j} - \overline{u_i' u_j'}] \qquad (2)$$

The transport equation of turbulent kinetic energy (TKE), k.

$$\frac{\partial \rho k}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}] + G_k + G_b - \rho \cdot \varepsilon - Y_M + S_K \qquad (3)$$

The transport equation dissipation rate of TKE, ε.

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial(\rho \cdot \varepsilon \cdot u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho \cdot C_1 \cdot S_\varepsilon - \rho \cdot C_2 \cdot \frac{\varepsilon^2}{k+\sqrt{v \cdot \varepsilon}} + C_{1\varepsilon} \cdot \frac{\varepsilon}{k} \cdot C_{3\varepsilon} \cdot G_b + S_\varepsilon \qquad (4)$$

Where u_i and u_j are the mean velocity components in ith and jth direction coordinates, respectively, $\overline{u_i' u_j'}$ the Reynolds average stress, μ the laminar viscosity, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε , respectively, the turbulent viscosity $\mu_t = \rho \cdot C_\mu \frac{k^2}{\varepsilon}$, G_k, the generation of turbulent kinetic energy due to the mean velocity gradients, G_b, the generation of turbulent kinetic energy due to buoyancy, S_K and S_ε, the source terms, Y_M, represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, and the values of the constants were C_1=0.43, $C_{1\varepsilon}$=1.44, C_2=1.9, $C_{3\varepsilon}$=1.44, C_μ=0.09, σ_k=1.0, σ_ε=1.2, and the turbulent Schimidt number S_{ct}=0.7. A commercial CFD software FLUENT is applied to solve the equations mentioned above using the finite volume method in the form of discredited algebraic equations with a second-order upwind scheme. The SIMPLE algorithm is employed to couple the pressure and velocity fields.

Particle Transport Model

Vehicles running in the street canyon directly inject particle pollutants from the vehicle exhaust plume. To simplify the particle dynamic and improve simulation efficiency, the particles are treated as inert spherical particles with constant density during the simulation. As particle volume fraction in the vehicle exhaust plume was very low, this study neglects the effect of particles on turbulent flow, so the steady flow field without particles is first solved, and then the particles are injected into the street canyon through line sources which represented the vehicles. Such method is also adopted by Gao et al. (16) and Zhang et al. (17)

A Lagrangian method that integrated the force balance on particle is employed to calculate the transient particle trajectory. The equation of particle transport is:

$$\frac{d\overrightarrow{u_p}}{dt} = F_D\left(\vec{u} - \overrightarrow{u_p}\right) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \qquad (5)$$

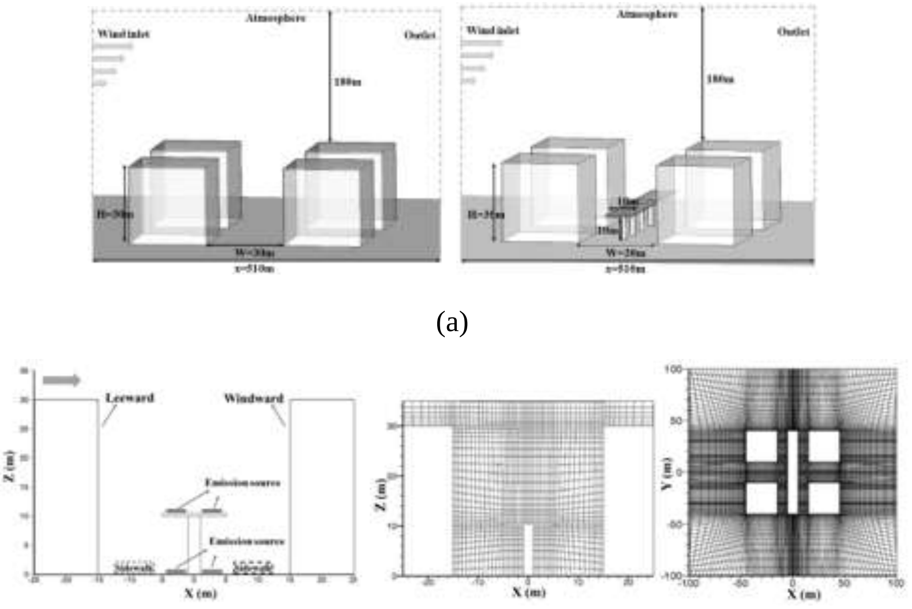
Where $\vec{u}$ is the fluid phase velocity, $\overrightarrow{u_p}$ is the particle velocity vector, ρ is the fluid density, ρ_p is the density of particle, $F_D\left(\vec{u} - \overrightarrow{u_p}\right)$ is the drag force and $F_D = \frac{18\mu}{\rho_p {d_p}^2}\frac{C_D R_e}{24}$, d_p is the particle diameter. R_e is the relative Reynolds number and $R_e = \frac{\rho d_p \left|\overrightarrow{u_p} - \vec{u}\right|}{\mu}$. $\vec{F}$ is the additional force, the Saffman's lift force and Brownian force are considered for particles in this study (the other forces are sufficiently small and are neglected).

Note that the process of nucleation is not included in the study as the particles are already formed after 0.7s residence time in the near wake region.

Particle coagulation is neglected as the coagulation of particles which diameter above 10nm is too slow to affect the number concentrations (18).

Case Set-Up

In order to analyze the effect of viaduct and particle diameter on the dispersion process of particles in a street canyon, a typical symmetry urban street canyon construction is selected. As shown in Fig.1, physical models of street canyon without viaduct and street canyon with a viaduct through are designed to make the comparison. The street canyon layout is based on the street canyon in Guangzhou Renmin road (street canyon with viaduct) which is consist of two buildings of each side of the street, the dimensions of the building are H×H×H, in which H=30m is the building height. Therefore the aspect ratio of the canyon equals to one, which a common scenario in the urban building environment. Note that the buildings of each side also separated by a distance of 20m. For case with a viaduct, the viaduct is set in the middle of the street and the geometry is simplified as deck which is 10m in width and the pier is 10m in height.



(a)

(b) (c)

Figure1. *(a) Computational domain and boundary conditions (b) Model description (c) Mesh construction in the domain.*

Computational Domain and Mesh Discretization

The computational domain was designed as per the COST guidelines (19). As shown in Fig.1, the lateral boundaries of the domain were taken at eight times the height of the building from the street canyon which is 510m across the street in total.

The vertical extent of the domain was taken six times above the building which is 210m in height. The domain was using structured meshes, finely grid near the building walls and gradually coarser away from the walls (Fig.1c). Studies for grid independency have been performed to ensure the solution to be independent of grid size. From this the smallest grid size of 0.5m and a growth rate of 1.2 were selected. Thus, the discredited domain had 767443 cells in total.

Boundary Conditions

Velocity inlet and pressure outlet boundary condition were specified for the ambient wind inlet and outlet, respectively. The wind direction is set as perpendicular to the street which causes the most poor dispersion condition within the street canyon and the wind speed is 2m/s at 10m in height which is the common wind condition on a sunny day in Guangzhou. The wind profile at the inlet was simulated with the logarithmic law profile.

Lateral and upper planes of the domain are set symmetry boundaries. No-slip wall conditions were applied at all walls. Specifically, for particles condition on the boundaries, the walls are all set to trap the particle and particle escape from the inlet and outlet.

two line sources and four line sources (in the case of street canyon without viaduct and with viaduct), simulating the vehicular exhausts, were placed in the models as lanes at a height of 0.2m above ground and above the deck of viaduct. The particle emission was specified in kg/s. Furthermore, the turbulent induced by the movement of vehicles can account up to 80% of the total dispersion of pollutants in the on-road region (20).

It is significant to take the vehicle induced turbulence (VIT) into consideration in the process of simulation. The VIT was simulated using an extra TKE production term (TKE per unit length) in the model acting up to a height of 5m above ground and the deck of viaduct. The parameterization is proposed by Petra Kastner Klein et al. (21) Equation (6) is the equation of vehicle induced turbulence:

$$VIT = \frac{\delta \cdot C_d \cdot A_T \cdot \eta_T \cdot v^3}{B \cdot H} \quad (6)$$

Where δ is the air density, C_d is the drag coefficient of the vehicle, A_T is the vehicle frontal area, v is the average vehicle velocity, η_T is the number of vehicles per unit length of the street, and B and H are the width of the street canyon and characteristic height, respectively. The VIT was calculated from C_d=0.3 and A_T=3.2 m^2 by Murena et al. (22) and Thaker and Gokhale (23). The key parameters used in the simulation models are summarized in Table 1.

Values of the key parameters (wind speed and traffic data) in boundary conditions are taken by field measurement in a street canyon in GuangZhou. The COPER-IV methodology was used to estimate the emission rates in numerical simulation.

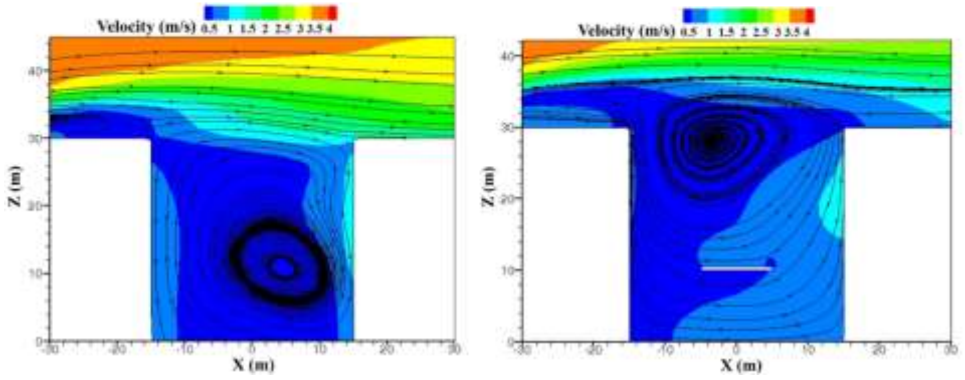
Table1. *Summary of traffic data and key parameters used in numerical simulation*

Type	Name	Value	Unit	Description
Street canyon	Aspect ratio	1		
Meteorology	Wind velocity	2.0	m/s	At 10m height, perpendicular to street
	Temperature	298	K	Isothermal domain
Traffic data	Traffic volume	2396	veh/h	On the viaduct
		1377		On the road
	Vehicle speed	30	km/h	On the viaduct
		25		On the road
Emission rate	PM_1	7.4e-4	g/s	On the viaduct
		4.8e-4		On the road
	$PM_{2.5}$	3.1e-4		On the viaduct
		2.5e-4		On the road
	PM_{10}	7.1e-4		On the viaduct
		4.2e-4		On the road

RESULTS AND DISCUSSION

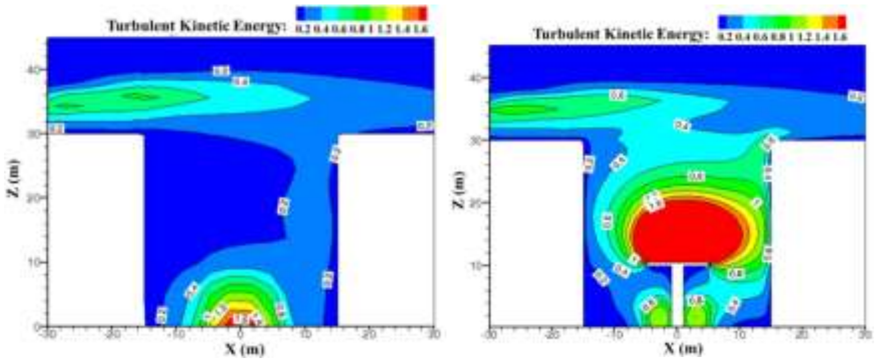
Effects of Viaduct on Airflow

Extracting the air flow velocity lateral slice, which is perpendicular to the street in the middle length of the buildings on both sides? As shown in Fig.2, these two slices represent the smallest strength of flow field in the street canyon. For the normal street canyon, there is a main clockwise vortex in the middle of the street canyon (24). The main clockwise vortex is driven up while there is a viaduct exists in the street canyon, and the flow in the bottom part is weak due to the effect of the viaduct's deck and piers. The flow recirculation is filled in the street canyon and the vortex is in the lower right side while there is no viaduct. When the viaduct exists, however, the flow recirculate zone is slightly beyond the street canyon due to the vortex is driven up to the upper left side in the street canyon. Note that the general trend of air flow in the lower portion is consistent sweep from the windward side to the leeward side. Further, the viaduct actives as a barrier in the street canyon, the vertical transport of the air flow is hindered in the lower portion which could have a considerable influence on the dispersion of pollutants from vehicles on road traffic.



(a) (b)

Figure2. *Streamlines and velocity magnitude in the lateral central plane for (a) street canyon without viaduct (b) street canyon with viaduct.*



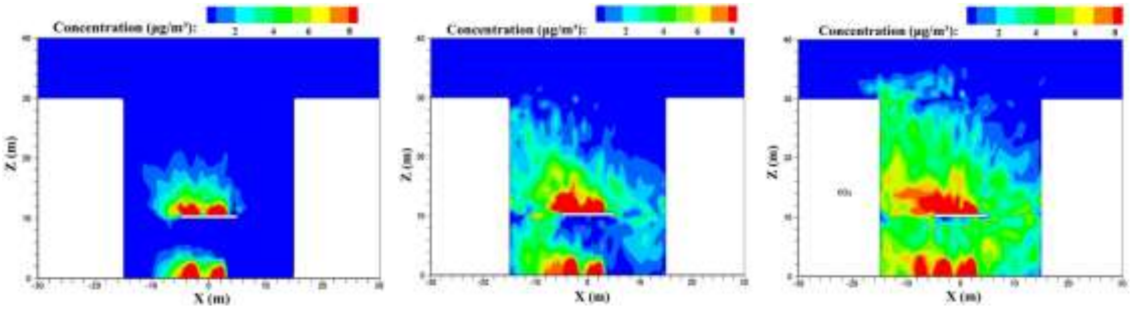
(a) (b)

Figure3. *Turbulent kinetic energy (TKE) distribution for (a) street canyon without viaduct (b) street canyon with viaduct.*

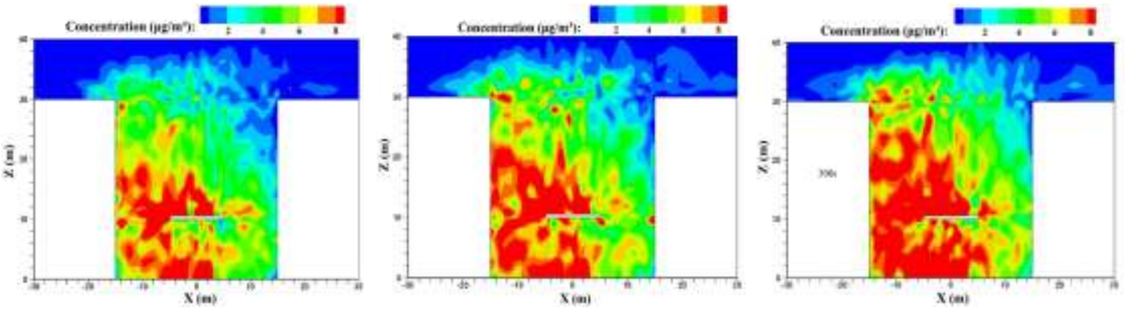
Fig.3 shows the TKE distribution in the street canyon. It can be observed that vehicular turbulence produces higher TKE. In the case that without the viaduct shown in Fig.3 (a), TKE is the highest in the vehicular zone and decreases away. Moreover, TKE in the windward side is higher than the leeward. This indicates that the vehicular movement produced extra turbulence which thus will allow more pollutant dispersion. With viaduct in the street canyon in Fig.3 (b), a considerable increase of TKE in the upper zone in the street canyon is observed due to the stronger vehicular movement on the viaduct traffic. While the TKE is smaller in the lower portion compare to the no viaduct case, the difference might be the weaker air flow cause by the viaduct and lead to the weaker relative movement between the vehicle and air flow.

Particle Dispersion Characteristic

To observe how the viaduct affect the dispersion of particles, Fig.4 shows the total particle mass concentration (PM_1, $PM_{2.5}$ and PM_{10}) distribution in the street canyon with viaduct at 10s, 30s, 60s, 120s, 180s and 300s after the beginning of vehicle exhaust. The results indicated that the particles disperse generally in accordance with the air flow. The particles exhausted from on-road traffic and viaduct traffic transport towards the leeward side within about 10s, then particles were uplifted and disperse on the leeward side about 30s. The recirculation in the street canyon of particles could be observed about 60s, which leads to the particle distribution on the windward side. As exhaust time increased, no obvious particle concentration distribution change is observed after 300s. Particles accumulated on the leeward side of the street canyon, which might have severe impact on health of pedestrians and residents.



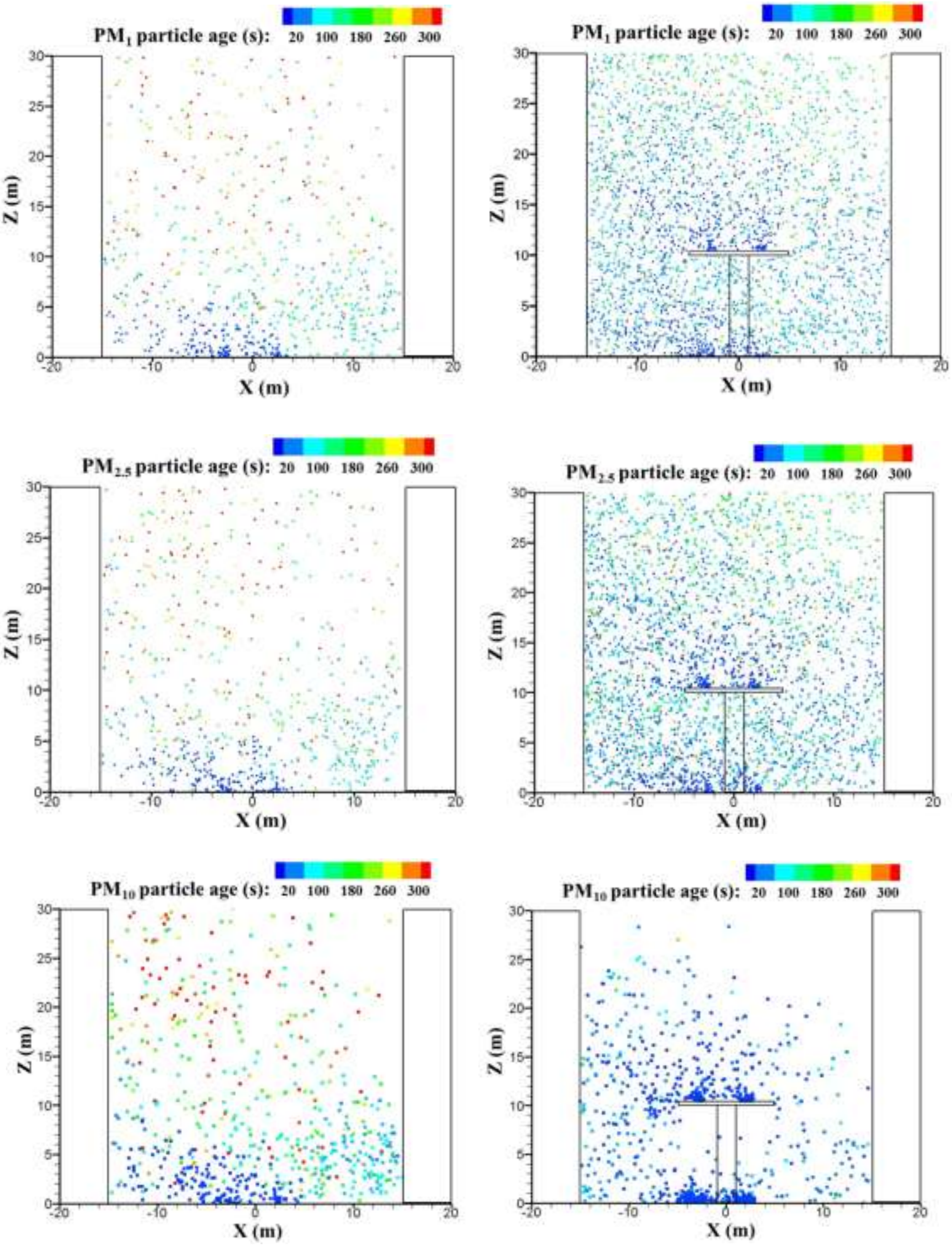
(a) 10s (b) 30s (c) 60s



(d) 120s (e) 180s (f) 300s

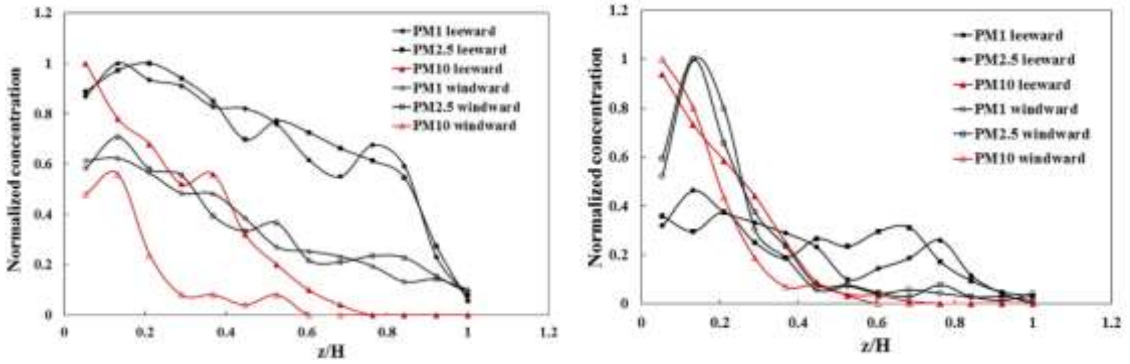
Figure4. *Particle mass concentration (μg/m^3) in the street canyon with viaduct at the representative time.*

To investigate the distribution details of particles, Fig.5 shows the particle age in the street canyon, in general, the particles in the case without viaduct are less than those with viaduct. Distribution of PM_1 and $PM_{2.5}$ are similar, with their lifetime longer than PM_{10}. It is because the buoyancy force of PM_1 and of $PM_{2.5}$ mainly balances the deposition effect caused by gravity force. Fig.6 shows the vertical profile of particle concentration in the case with viaduct and without viaduct. For case with viaduct, as expect, the concentration of leeward side is more severe than that of windward side, and the concentration vertical curve of PM_1 and of $PM_{2.5}$ is consistent. As the height increases, the concentration of PM_{10} drop dramatically, compared with the slight decline of PM_1 and $PM_{2.5}$. In particular, due to vehicular turbulence, the pollutant concentration reached a peak value before its subsequent decline. Specially, affected by deposition character of PM$_{10}$, its maximum concentration appears at the bottom of leeward side. For case without viaduct, in the lower portion of the street canyon, the particle concentration of PM$_1$ and of PM$_{2.5}$ on the windward side are higher than those on the leeward side respectively, and they also reached a peak value before subsequent decline, which might be caused by the vehicular turbulence on the road. In general, the decline of particle concentration in the case without viaduct is more obvious than that in the case with viaduct.



(a) (b)

Figure5. *Particle ages(s) in the street canyon (a) without viaduct, (b) with viaduct.*



(a) (b)

Figure6. *Vertical profile of normalized particle number concentration in the street canyon (a) with viaduct, (b) without viaduct.*

Further comparison of the spatial-average concentration on the either side of the street were done and quantified by the following equation:

$$\langle C\rangle = \iiint \frac{c^{*}\cdot dx\cdot dy\cdot dz}{V} \qquad (7)$$

Where $c^{*}$is the pollutant concentration in the domain at a given point and V is the volume of pedestrian zone on each side of the street.

Comparing to the case that without viaduct, Table 2 shows the increase in particle number concentration of the effect of 1) the viaduct alone without any new emissions 2) the viaduct with additional vehicle traffic and associated emissions. The particle number concentration increase percentages on the windward side are about half level compare to leeward side for PM_1 and $PM_{2.5}$. Whereas the effect of viaduct on concentration increase for PM_{10} is much higher on the windward side, the concentration increase about 40% on windward side and only about 4% on leeward. The difference in the concentration increase level might be due to the deposition process is dominant during the dispersion on of PM_{10} on the bottom part in the street canyon, PM_{10} concentration is severe in both with and without the viaduct cases. Combined the effect of emission, the concentration of PM_1 and $PM_{2.5}$ are increased 10%~20% on both windward and leeward side. No considerable change in PM_{10} concentration is observed on the windward side while the emission could cause a tremendous concentration increase on the leeward side.

Table2. *Increase in particle number concentration*

Sides of the canyon	Effect of viaduct			Effect of viaduct and emission		
	PM_1	$PM_{2.5}$	PM_{10}	PM_1	$PM_{2.5}$	PM_{10}
windward	22%	32%	40%	38%	42%	39%
leeward	46%	61%	4%	79%	83%	79%

SUMMARY

The impact of viaduct on the dispersion and distribution of particles in the street canyon is investigated in this study. Based on the numerical simulation results, three key conclusions can be reached. Firstly, the viaduct would affect the air flow in the street canyon.

The recirculation remains in the upper zone and the flow in lower zone would be weak which causes the poor dispersion condition for the pollutants below the viaduct. Secondly, the concentration level on the leeward side is far more severe than windward side when the viaduct exists in the street canyon, and the vertical profile shows that PM_1 and $PM_{2.5}$ would be more suspended. Finally, the effects of viaduct and emission on the pollution in sidewalk pedestrian are also evaluated. Results reveal that combine the effects of viaduct and emission, the concentration level will increase about 40% on windward side and about 80% on leeward side. Although the cases are specific in this study, the generally trends and referenced effects can provide recommendations to traffic control and management and help the improvement of air quality.

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