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Modeling the impact of the viaduct on particles dispersion from vehicle exhaust in street canyons

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In this paper, the impact of the viaduct on flow and traffic exhausting particles dispersion within urban street canyons was numerically simulated using a computational fluid dynamics (CFD) model. Two-dimensional flow and dispersion of particles from traffic exhausts were modeled using the standard k-ε turbulence model. The street canyons with a viaduct at different widths and different heights above the ground are simulated. The results show that the airflow in street canyon is evidently influenced by the viaduct: The position of the main vortex center is changed, especially there are two strong vortexes when the viaduct is placed at 10 m height above the ground. It is found based on the study of the particles number concentrations (PNCs) that the viaduct may mitigate the pollution level in the street canyon sometimes. The impact of the viaduct width on PNCs is stronger than that of the height. The study of PNDs reveals that the mean PNCs at the wall of upwind building increase when a viaduct is placed in street canyon. In addition, it is found based on the study of mean particles residence time (PRT) that the removal of the particles strongly correlates to the mean PNCs. The results indicate that the viaduct is an important factor to influence the flow patterns and particles dispersion in street canyons.

street canyon, viaduct, particles number distribution, CFD simulation, mean particle residence time

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1 Introduction

Within street canyon, pedestrians and residents are likely to be exposed to hazardous substances exceeding current air quality standards due to the increasing traffic emissions. Since traffic is accepted to be a major emission source of air pollutants in urban areas, and further increase of city traffic is expected, investigations of dispersion processes in street canyons have become a focal point in environmental research.

Particles with aerodynamic diameter below 10 μm (PM10) and especially the fine particles with aerodynamic diameter below 2.5 μm (PM2.5) were found to associate with daily mortality, pulmonary, trachea diseases and asthma as well as epidemiological diseases [1–4]. The ultrafine particles (aerodynamic diameter below 100 nm) contribute little to particle mass concentrations but significantly to particle number concentrations. In recent years, toxicological and epidemiologic studies show strong correlations between adverse health effects and exposure to ultrafine particles at high number concentrations [5, 6]. This suggests the need of mitigation strategies to regulate the particles on a number basis in urban areas.

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So far, a great deal of air quality studies in urban areas has been performed. Leitl and Meroney [7] and Xie et al. [8] evaluated the pollutant concentration in two- and three-dimensional urban street canyons using the standard and the RNG k-ε turbulence models. Neofytou et al. [9] investigated the pollution levels in a real urban street canyon using the Reynolds averaged Navier-Stocks (RANS) under realistic condition. Garcia Sagrado et al. [10] compared the numerical simulation and experiment results of smoke dispersion. Yassin et al. [11] simulated the impact of the street intersections on flow and gaseous pollutions. Kumar et al. [12] investigated the impact of tree planting on wind flow and pollution dispersion. Gromke et al. [13, 14] and Gu et al. [15] studied the dispersion in a street canyon with tree planting by means of wind tunnel and numerical simulations. Ahmadi and Li [16] simulated the flow and particulate pollution transport near an isolated building using a Lagrangian particle tracking model. Santiago and Martin [17] simulated pollutant dispersion in street canyons by a new Lagrangian particle model. The impact of building configuration on pollutant dispersion was modeled by CFD modeling [8, 18]. Numerical modeling was applied to predicting air temperature and its effects on the flow and pollutant dispersion in street canyons [19–21]. Most of the studies mentioned above dealt with prevailing atmospheric wind perpendicular to the street axis, since this wind regime provides minimal ventilation of the canyon and is relatively ineffective in removing pollutants. However, only a few studies dealt with street canyons with a viaduct, and the impact of viaduct on pollution dispersion process is not clear so far. Recently, Kondo and Tomizuka [22] investigated the influence of viaduct on dispersion of NO_x.

Many viaducts are built in metropolitans in order to mitigate the traffic blocking. Some viaducts through street canyon will lead to a new pollution pattern. The aim of this study is to develop a two-dimensional CFD model with the standard k-ε turbulence model and assess the environmental impact of the viaduct on flow patterns and dispersion of particles in urban street canyon. This may help us to find out critical viaduct condition which results in better pollution dispersion.

2 Methodology

2.1 Turbulence model

In this study Reynolds averaged Navier-Stokes (RANS) equations with the standard k-ε turbulence model [23] are used to predict the airflow field. The standard k-ε turbulence model which has successfully solved street canyon airflow fields represents the effects of turbulence by including two more variables: the turbulent kinetic energy k and its dissipation rate ε. The governing equations of the model are shown below.

Continuity equation:

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0. \tag{1}$$

Momentum equation:

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_i} - \frac{\partial}{\partial x_j}\overline{u_i u_j}, \tag{2}$$

k and ε transport equation:

$$\frac{\partial k}{\partial t} + \bar{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + \nu_t\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\frac{\partial \bar{U}_i}{\partial x_j} - \varepsilon, \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial x}{\partial x_j}\right) + \frac{\varepsilon}{k}\left[C_{\varepsilon 1}\nu_t\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\frac{\partial \bar{U}_i}{\partial x_j} - C_{\varepsilon 2}\varepsilon\right], \tag{4}$$

where Reynolds stress tensor $-\overline{u_i u_j}$ is modeled by the eddy-viscosity model

$$-\overline{u_i u_j} = \nu_t\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}, \tag{5}$$

where $\nu_t = C_\mu \frac{k^2}{\varepsilon}$, δ_{ij} is Kronecker delta. C_μ=0.9, $C_{\varepsilon 1}$=1.44, $C_{\varepsilon 2}$=1.92, σ_k=1.0, σ_ε=1.3, and σ_k=1.0.

The semi-implicit method is used in this study for pressure-linked equation (SIMPLE) algorithm described by Patankar to couple pressure and velocity.

2.2 Pollutant transport model

The Lagrangian method is normally used to model the particles dispersion by tracking a large amount of particles transiently. Each particle follows an independent trajectory for each time step. The method starts from solving the transient momentum equation for each particle:

$$\frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = F_{\mathrm{D}}(\boldsymbol{u} - \boldsymbol{u}_p) + \frac{\boldsymbol{g}(\rho_p - \rho)}{\rho_p} + \boldsymbol{F}_a, \tag{6}$$

where $\boldsymbol{u}_p$ and $\boldsymbol{u}$ are the particle velocity vector and the air velocity vector, respectively, F_{D} is the inverse of relaxation time, ρ_p and ρ are the densities of the particles and the air, respectively, and F_a stands for additional forces (per unit mass).

For particles with aerodynamic diameter from 1 to 10 μm, the drag force is the most significant force and it follows the

Stokes law:

$$\boldsymbol{F}_{\text{drag}} = F_{\text{D}}(\boldsymbol{u}-\boldsymbol{u}_p) = \frac{18\mu}{\rho_p d_p^2 C_c}(\boldsymbol{u}-\boldsymbol{u}_p), \tag{7}$$

where μ is fluid viscosity and d_p is particle diameter. The Cunningham correction factor C_c is calculated using

$$C_c = 1+\frac{2\lambda}{d_p}(1.257+0.4\mathrm{e}^{-1.1d_p/2\lambda}), \tag{8}$$

where λ is the molecular mean free path.

The air velocity u consists of time-averaged part $\bar{\boldsymbol{u}}$ that is computed by solving the standard k-ε turbulence equation and the instantaneous velocity $\boldsymbol{u}' = u_i'$ which needs modeling. This investigation uses the discrete random walk (DRM) model to simulate the velocity fluctuations. The DRM model assumes that the fluctuating velocities follow a Gaussian probability distribution. The fluctuating velocity u_i' correlates the particle turbulent dispersion with the flow turbulent kinetic energy k:

$$u_i' = \zeta\sqrt{2k/3}, \tag{9}$$

where ζ is a Gaussian random number. The instantaneous air velocity accounts for particle's turbulent dispersion, and the turbulent dispersion is much more significant than the Brownian dispersion due to the large particle size considered in the present study.

The Lagrangian method calculates new trajectories in each time step. The total number of generated trajectories in the simulation is $N_{\text{sum}} = \sum_i n(i)\mathrm{d}t^i$, where $n(i)$ is the number of trajectories generated in each time step $\mathrm{d}t^i$.

2.3 Computational domain and boundary conditions

In order to assess the impact of the viaduct on the dispersion of particles, in this study a two-dimensional (2D) domain is used to simulate an infinitely long street canyon. Figure 1 shows the 2D schematic diagram of street canyon with viaduct. Simulations were performed for wind velocity of 3 m/s and temperature of 300 K. The wind flow pattern inside street canyons depends on their geometries, especially on the aspect ratio H/W where H is the building height and W is street width. In this study, the aspect ratio H/W is assumed as 1. The smallest dimensions of the grids are $\delta x_{\min}$=0.01W, $\delta y_{\min}$=0.01H in the street canyon, and there are about 10,000 grids within the street canyon.

A uniform velocity profile was set as a boundary condition at the inlet; pressure outlet was set as a boundary condition at the outlet. A symmetry condition is assumed at the top of the flow domain; no-slip wall conditions are considered at the building walls and roofs, street floor, and the viaduct. Simply, a reflecting wall boundary condition with no loss of momentum is set in the discrete phase model. In this study, the convergence criteria of k, ε, x and y velocities are set as 10^{-6}.

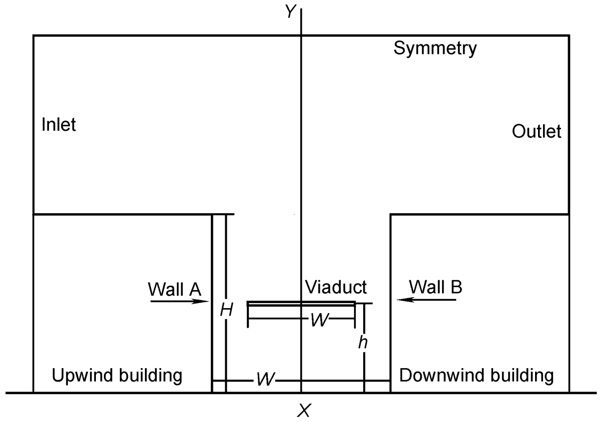

Figure 1 Schematic diagram of street canyon with a viaduct.

3 Results and discussion

3.1 Street canyon without viaduct

3.1.1 Airflow

In this named case 1, a square street canyon where W=H=20 m is implemented without viaduct. The velocity vectors calculated by the current CFD models show that the flow patterns of the street canyon fall into the skimming flow regime [24]. As shown in Figure 2(a), only one clockwise-rotating recirculation is observed in the street canyon. The wind speed in the center of the vortex circulation is very slow, and it becomes faster near the walls of the buildings, the ground and the roof of the canyon.

3.1.2 Particles number distributions

Because carbon is the main composition of particles from traffic emissions, carbon was set as the material of the particles. The gravity has been taken into account when dispersion of particles is simulated. In this paper, only particles from traffic emission on ground are considered. Six line sources are set at x=±1 m, ±3 m, ±5 m while y from 0.3 to 1.1 m in the discrete phase model in order to simulate mixed source due to the wake region close to the vehicles. The CFD model ran until the flow field converged, with no particles source. And then, the constant sources of particles were introduced and the simulations finished when the concentrations converged.

All concentrations are presented here in dimensionless form:

$$K = CU_{\text{H}}HL_{\text{Q}}/Q, \tag{10}$$

where C is the actual concentration, H is the height of the

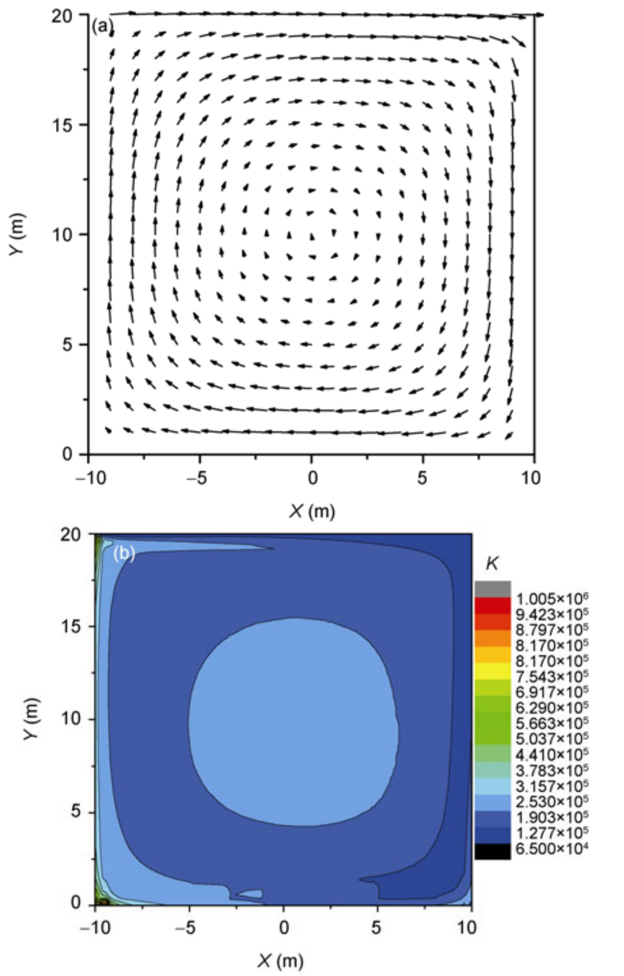

Figure 2 (a) Mean velocity vectors; (b) distribution of normalized concentrations.

street canyon, U_H is the flow velocity at height H in the undisturbed approaching flow, L_H is the line source length, and Q is the source strength.

As shown in Figure 2(b), the highest PNC can be found at the upwind-building corner. The PNCs in the center of the vortex are higher than those around the center. The PNCs inside the street have a direct correlation with the velocity field. The near-ground released particles get advected by the canyon vortex towards the wall of upwind building (wall A). Thus, the particles concentration resulting from near-ground released emissions is evidently lower at the wall of downwind building (wall B) than at wall A. The wall-average concentrations differ by a factor of 2.58. The factor is smaller than the result reported by Christof Gromke [12], which probably is caused by a different profile of velocity inlet and the height of emission source.

Figure 3 shows the PNCs at wall A resulting from emission source with different aerodynamics diameters. Vertical profiles of PNCs are similar when the aerodynamics diameter is smaller than 2.5 μm which was verified by the results of Kummar et al. [25]. The results suggest that the influence of the aerodynamics diameter on the particle dispersion can be ignored when the diameter is smaller than 2.5 μm. For particles (1–10 μm), it can be found that the drag force is in direct proportion to d_p from eqs. (7) and (8), while the gravity is in direct proportion to d_p^3. The gravity can influence the dispersion when the diameter becomes larger than 2.5 μm. The mean normalized 10 μm-particle number concentration is 7% larger than that of particles with size of 0.1 μm. Because the proportion of particles above 300 nm number was negligible compared to total PNCs [26], the particle diameter is set as 0.1 μm instead of a continuous distribution diameter in the following simulations.

An additional simulation shows that the impact of the Brownian motion can be ignored compared with turbulent for the particles with diameter above 0.01 μm.

3.2 Street canyons with a viaduct

In this part, wind flow and particles dispersion in the street canyon with a viaduct are simulated. Various street canyons with viaduct shown in Table 1 are modeled. The influences

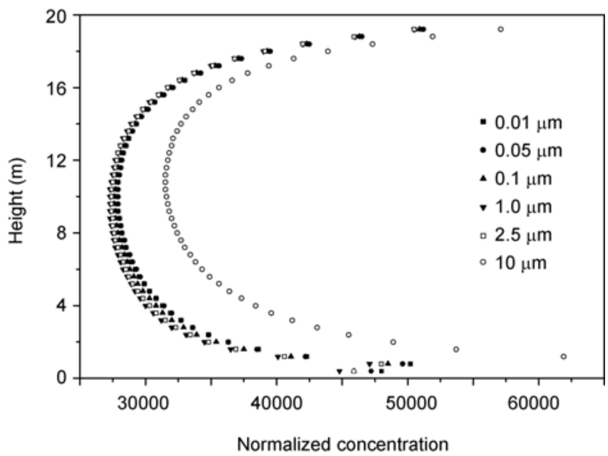

Figure 3 Particles number distributions at wall A in case 1 with different aerodynamic diameters.

Table 1 Parameters of the viaduct in street canyon a)

	Height *h* (m)	Width *w* (m)
Case 1	0	0
Case 2	5	8
Case 3	5	12
Case 4	5	16
Case 5	10	8
Case 6	10	12
Case 7	10	16
Case 8	15	8
Case 9	15	12
Case 10	15	16
Case 11	10	15
Case 12	10	17
Case 13	10	17.5
Case 14	10	18

a) *h* is the height above ground and *w* is the width of the viaduct as shown in Figure 1.

of the width and the height above ground of viaduct on particles dispersion are considered. The same source described in Section 3.1 is set to model the impact of viaduct on the flow and dispersion of particles exhausted from traffic on ground.

3.2.1 Airflow

The different stream lines derived from street canyons with a 12 m-width viaduct are shown in Figure 4. The airflows are disturbed at the region around the viaduct, whereas there are no significant differences from case 1 near the walls of the buildings and ground, the ground and the roof of the canyon. It is found that there are two strong vortexes when the viaduct is placed at 10 m, but only one strong vortex which can be compared to the vortex in street canyon without viaduct and one very weak vortex when the viaduct is placed at the height of 5 m or 15 m.

3.2.2 Particle number distributions

The PNDs patterns in street canyon with a viaduct are similar to that in case 1. The highest PNC can be found at the upwind-building corner, and the PNCs at wall A are much higher than those at wall B.

The mean PNCs of the whole street canyon domain are shown in Figure 5. Only the mean PNCs in case 2, case 3 and case 8 are larger than that in case 1. The mean PNCs in street canyons with viaduct at 10 m are smaller than those at other heights. It is found that the mean PNCs in street canyons decrease with increasing width, which may be caused by the blocking of viaduct when the particles re-enter into the street canyon. It means that the impact of the viaduct width on the mean PNCs is more important than that of the height above the ground. The results indicate that the viaduct will sometimes mitigate the pollution level in street canyon if only source on ground is considered.

In order to study the impact of the wide viaduct on the mean PNCs, four more cases (street canyons with viaducts of 15 m, 17 m, 17.5 m, and 18 m) were simulated when the viaduct is placed at 10 m high above the ground. Figure 6 shows the impact of the width of viaduct on the mean PNCs. It is found that the mean PNCs decrease with the increase of the width of viaduct. The mean PNCs reach the smallest which is only 75% of that in case 1 when the width of viaduct is 17 m. And then the mean PNCs will increase when the width of the viaduct is 18 m. This phenomenon may be due to the strong blocking of such a wide viaduct when the particles rise up in front of wall A. The result suggests that a moderately wide viaduct will lead to a low pollution level.

The positions of openings or air inlets are an important factor when the contamination of the indoor air is considered. If the openings are placed where the pollution concentration is high then the indoor concentration can reach a

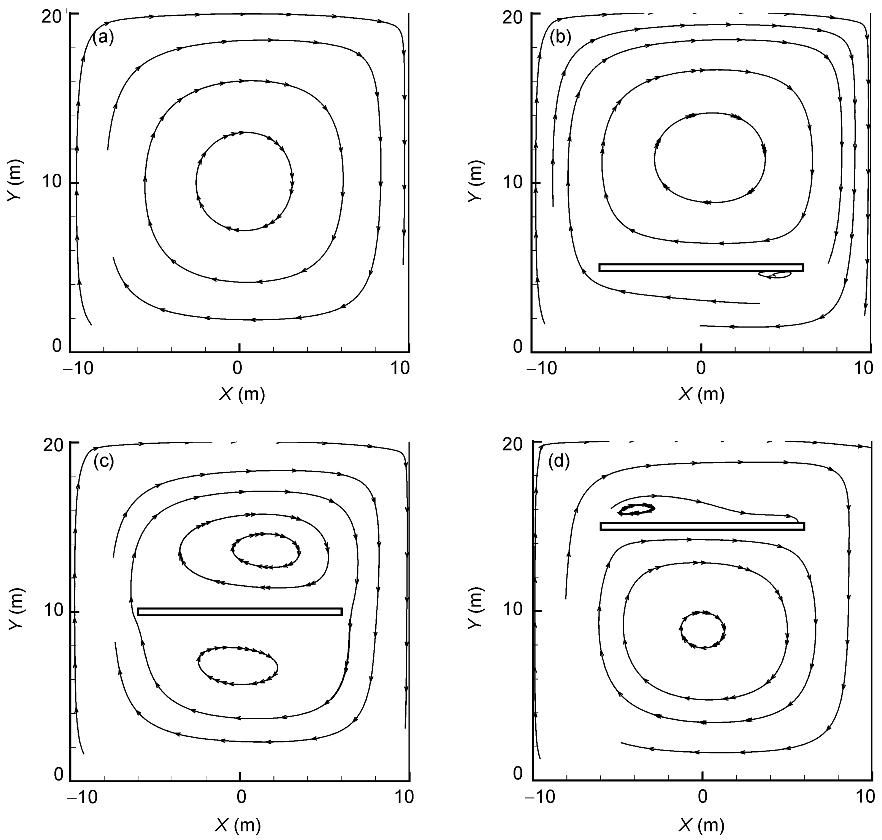

Figure 4 The stream lines in street canyons with viaduct at different heights above ground. (a) Case 1; (b) case 3; (c) case 6; (d) case 9.

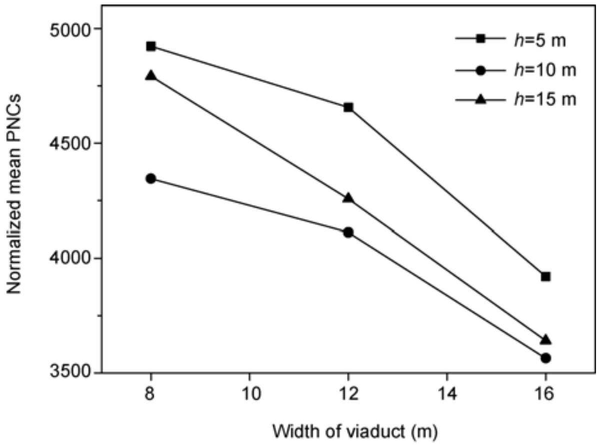

Figure 5 The mean particles number concentrations in street canyons with a viaduct (dash line: the mean PNCs in case 1).

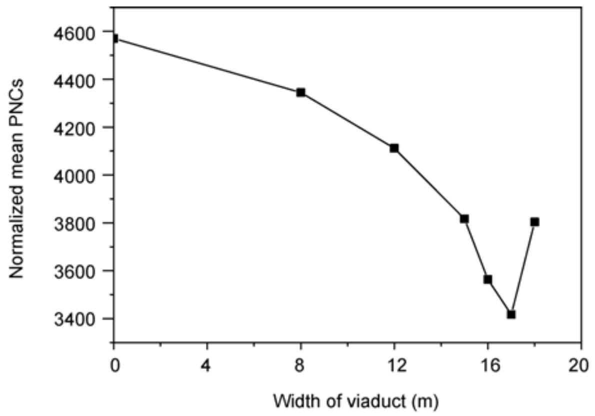

Figure 6 The mean PNCs in street canyons with different width viaducts when *h* is 10 m.

similar high level because of the air exchange [27, 28]. Figure 7(a) shows the impact of the height above ground on the PNDs at wall A when the width of viaduct is 12 m. The particle number distributions around the viaduct are disturbed due to the change of airflow. Compared to the street canyon without a viaduct, numerical results showed no fundamental modifications in PNDs profiles. The highest PNC in street canyons with a viaduct is larger than that of case 1. The mean PNCs at wall A in street canyon with a viaduct are larger than that in case 1, which reveals that residents will suffer from a higher pollution level when a viaduct is placed in street canyon.

Figure 7(b) shows the impacts of the different viaduct widths on the PNDs at wall A. The PNCs at wall A become larger when the viaduct is placed in street canyon. There is a little difference of the PNDs between case 5 and case 1, which is caused by the little influence of narrow viaduct on particles dispersion. In case 7, at the part of wall A below viaduct, the concentrations of the street canyons with viaduct are markedly larger than that street canyon without viaduct, which is due to the blocking of the viaduct. The mean PNC of wall A in case 7 is larger than others in Figure 7, but there is a smallest mean PNC as shown in Figure 5. It indicates that the influence of viaduct will become more evident when the width of viaduct becomes larger. Similar to the results obtained from Figure 7(a), the mean PNC at wall A in street canyon with a viaduct is larger than that in case 1, revealing that residents will suffer from a higher pollution level, too.

3.3 Mean particle residence time

Atmospheric pollutions are responsible for both acute and chronic effects on human health. To study the residence time of the particles in street canyon would be important to evaluate the human exposure to hazardous substances.

When the emission sources are shut down, the mean PNCs in the street canyon would decrease due to particles escaping from the roof. In this study, the mean particle residence time (PRT) calculated by the following equation is used to study the particles removal from street canyon,

$$C(t) = C_0 \mathrm{e}^{-t/\mathrm{T}}, \tag{11}$$

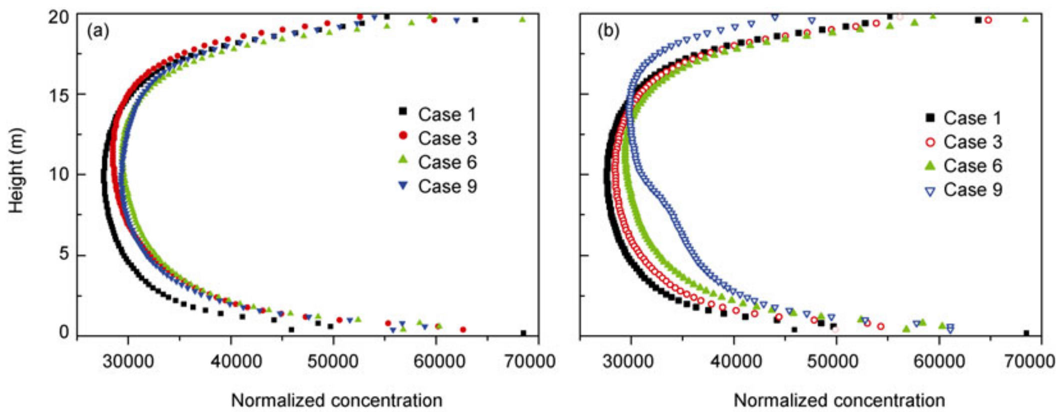

Figure 7 Vertical profiles of the normalized PNCs at wall A. (a) Street canyons with a 12 m-width viaduct; (b) street canyons a with 10 m-height viaduct.

where C_0 is the mean PNCs of the steady state which is assumed as time t=0, $C(t)$ is the mean PNCs after time t which can be obtained from the results of simulations.

The results of the mean particle residence time are summarized in Table 2 and the value is between 500 s and 800 s. The results of PRT are very similar to those of the mean PNCs. It is found that the correlation coefficient between the PNCs and PRT is 0.998, which means that the PRT has a high correlation with the PNCs and the impact of PNDs can be ignored. Smaller PRT can be found in street canyons with a 16 m-width viaduct and the smallest PRT can be found in case 7 which is 76.5% of that in case 1. The PRT is smaller when the viaduct is placed at 10 m than other heights, too. The PRT in case 2 is larger than the values in other street canyons with a viaduct. It is suggested that the removal of particles in case 2 is the most difficult. The result indicates that the impact of viaduct width on the PRT is stronger than the viaduct height above the ground. Sometimes the removal of particles can be strengthened by building a viaduct in street canyon.

4 Conclusion

A numerical model based on the RANS equations coupled with the standard k-ε turbulence model was used to simulate the airflow and particles dispersion within street canyon with and without viaduct.

In general, the effects of the viaduct are rather complicated. There are two vortexes in street canyon when a viaduct is placed in street. The characteristics of pollution dispersion are affected by the location and width of viaduct. The impact of the viaduct's width on particles dispersion is more significant than that of the height where the viaduct is placed, meanwhile the impact of the height on flow patterns is more significant. The viaduct will mitigate the pollution level in street canyons under special conditions. Especially, the mean PNCs will reduce 25% compared to street canyon without a viaduct when a 17 m-width viaduct is placed at 10 m above the groud (0.5H). But, the PNCs at wall A will always increase to lead to a more serious pollution level to residents. Under a steady state, a strong correlation between the mean PRT and PNCs up to 0.998 is present. The time which particles transport in street canyon will be shortened when a 0.8W-width viaduct is built in street canyon.

Finally, it is suggested that the viaduct will lead to a new pollution pattern and the impact of viaduct on human exposure to traffic emission should be considered when the viaduct is built in street canyons.

Table 2 Mean particle residence times in street canyons

Case	PRT (s)
1	699±29
2	754±42
3	726±36
4	598±32
5	668±23
6	621±29
7	535±25
8	742±41
9	650±30
10	558±36

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