Integrated Effects of Street Layouts and Wall Heating on Vehicular Pollutant Dispersion and their Reentry Toward Downstream Canyons

Lin Lin1,2, Jian Hang1*, Xiaoxue Wang3, Xuemei Wang1**, Shaojia Fan1, Qi Fan1, Yonghong Liu2

1 School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, China
2 Guangdong Provincial Engineering Research Center for Traffic Environmental Monitoring and Control, Sun Yat-sen University, Guangzhou, China
3 Department of Mechanical Engineering, the University of Hong Kong, Hong Kong

ABSTRACT

Vehicle emission is becoming one of the major sources of gaseous pollutants and aerosol particles in urban air environments. Apart from pollutant source control, sustainable street design is another significant technique to reduce street air pollution. Under the validation by wind tunnel data, this paper conducts computational fluid dynamic (CFD) simulations by RNG k-ε model to investigate the impacts of typical street layouts and wall heating on the dispersion of gaseous pollutants and particles (diameter $d = 1 \, \mu m$, $5 \, \mu m$, $20 \, \mu m$) in the target street canyons and their reentry toward downstream streets.

The dispersion processes of gaseous pollutants and fine particles ($d = 1 \, \mu m$) are found similar. For uniform street layouts (aspect ratio $H/W = 1$) with small Froude number ($Fr = 0.19–0.38$), leeward-wall heating, ground heating and all-wall heating significantly enhance the primary clock-wise vortex and improve pollutant dispersion, but windward-wall heating does not. Taller upstream buildings ($H_1/W = 2–3$) produce a clockwise vortex over the target canyon and a much weaker counter-clockwise vortex within it, seriously weakening the capacity of pollutant dispersion. For large particles ($d = 20 \, \mu m$), the major fraction deposits onto street ground because the gravity force dominates particle transportation. For particles of $d = 5 \, \mu m$, the dispersion dynamics are more complicated: In the isothermal case less particles of $d = 5 \, \mu m$ suspend in the target canyon than $d = 1 \, \mu m$ because the gravity force and particle deposition are more important, however, with all-wall heating more particles of $d = 5 \, \mu m$ float in the target canyon because the upward thermal buoyancy force reduces particle deposition onto the ground. Finally for both gaseous pollutants and particles, their bulk concentrations in downstream streets decrease exponentially with increasing distance from the target canyon, whose decreasing rates are quantified. Although further investigations are still required to propose a practical framework, this paper is one of the first attempts to quantify the capacity of street particle dispersion for street design purpose.

Keywords: CFD; Street canyon; Wall heating; Particle dispersion; Pollutant reentry.

INTRODUCTION

Apart from regional pollutant transport (Fan et al., 2014), vehicle pollutant emission such as oxides of nitrogen (NO$_x$), volatile organic compounds (VOCs), carbon monoxide (CO), and fine particles with aerodynamic diameters less than 2.5 μm (PM$_{2.5}$) in street networks is becoming one of the main sources of gaseous pollutants and particle pollution in modern cities (Fenger, 1999; Krecl et al., 2015). Serious street air pollution can increase personal exposure for both pedestrians and people in nearby buildings (Luo and Li, 2010; Ng and Chau, 2014) and cause adverse impacts on human health (Zhou et al., 2013; Ji and Zhao, 2015), for example, nitrogen dioxide (NO$_2$) may act as an irritant affecting the mucosa of the nose, eyes, throat and the respiratory tract, and fine particles can penetrate deep into the lungs and induce health problems such as aggravated asthma and premature deaths in people with lung or heart disease. Apart from reducing vehicular emissions, improving street pollutant dispersion has been confirmed as one of the effective technique to reduce such health risk, thus it has become a hot research button over the last three decades.

The transport of pollutants mainly depends on the flow structures determined by street layouts and meteorological conditions. For two-dimensional (2D) street canyons, the street aspect ratio i.e., building height/street width ($AR$ or
et al. investigated particle dispersion in street canyons (Morena mainly for case studies. Only a few studies numerically influence air quality in downstream streets of the busy street Habilomatis and Chaloulakou, 2015) and less were conducted been studied by a number of field measurements (Kumar force and deposition effect also influence the particle Differing from gaseous pollutant dispersion, the gravitation airflows surrounding seven cubic buildings. (2013) used more than seven million grids to simulate 3D (2014). They found that, if Ri (or Fr) is relatively large (small), thermal buoyancy force can significantly affect or dominate street pollutant dispersion. As two examples, Xie et al. (2007) studied the effects of ground heating on pollutant dispersion in 2D street canyons with uniform heights (AR = 0.1 to 2). Allegirini et al. (2013) experimentally confirmed that windward-wall heating weakened the single main vortex in a typical street canyon (H/W = 1), but leeward-wall heating, ground heating and all-wall heating can enhance this vortex. Most previous studies investigated the impacts of uniformly heated surfaces with arbitrary air-wall temperature difference, as also employed in this paper. It is a big challenge to simulate three-dimensional (3D) non-isothermal airflow within a group of buildings for two reasons. Firstly, it is difficult to attain reliable wind tunnel data of 3D non-isothermal flow in a building array (Richards et al., 2006). Secondly, enormous computer resources are usually required due to the requirement of fine grids to resolve the viscous sub-layer near wall surfaces (Luo and Li, 2011; Liu et al., 2012, 2013). As an example, Liu et al. (2013) used more than seven million grids to simulate 3D airflows surrounding seven cubic buildings. The dispersion capacity of gaseous pollutants and aerosol particles can be strengthened by improving street design. Differing from gaseous pollutant dispersion, the gravitation force and deposition effect also influence the particle dynamics. Particle dispersion and their distribution have been studied by a number of field measurements (Kumar et al., 2011; Zhang et al., 2012; Krecl et al., 2015) which were mainly for case studies. Only a few studies numerically investigated particle dispersion in street canyons (Morena et al., 2009; Zhang et al., 2011; Scungio et al., 2013; Habilomatis and Chaloulakou, 2015) and less were conducted for street design purpose. Finally, street layouts possibly influence air quality in downstream streets of the busy street with heavy traffic flows. But such studies are still rare so far.

It is worth noting that the process of particle dispersion includes turbulent mixing and pollutant dilution, particle deposition, nucleation, coagulation and condensation (Kumar et al., 2011). At street scale, the effect of nucleation, coagulation and condensation can be disregarded because the processes of the coagulation and condensation are much slower than the dilution and deposition time scales (Kumar et al., 2011). Thus it is reasonable to treat particles as inert pollutants and this paper mainly considers the effects of turbulent mixing, dilution and particle deposition. This set-up of particle dispersion has been widely adopted in indoor environment (Qian and Li, 2010) and outdoor street canyon (Zhang et al., 2011; Habilomatis and Chaloulakou, 2015; Lin et al., 2016).

In this context, by performing CFD simulations validated by wind tunnel data, this paper comprehensively investigates how various street layouts and wall heating conditions influence pollutant dispersion of gaseous pollutants and particles with various diameters (d = 1 µm to 20 µm) in typical street canyons and their reentry toward downstream street canyons, for street design purpose.

**METHODOLOGIES**

**Model Descriptions and CFD Flow Modelling**

**Numerical Models**

It is also known that, the flow and pollutant dispersion in street canyons is transient due to turbulence. Large Eddy Simulations (LES) have been confirmed better in predicting transient turbulence than the Reynolds-Averaged Navier-Stokes (RANS) approaches in the flow and pollutant dispersion modelling in street canyons (Cai, 2012; Li et al., 2012; Liu and Wong, 2014; Liu et al., 2015). However there are still challenges to the applications of LES models including the longer computational time for transient simulation with fine grid arrangements, the difficulty in specifying appropriate time-dependent inlet and wall boundary conditions etc. In spite of their limitations in predicting turbulence, steady RANS turbulence models require much less computational resources and have been successfully validated and evaluated in predicting time-averaged mean flows. Furthermore, the RNG k-ε model employed here has been one of the most widely-adopted RANS turbulent models. Many researchers have successfully validated its application in predicting turbulent flow and dispersion of gaseous pollutants (Tominaga and Stathopoulos, 2007; Xie et al., 2007; Hang et al., 2012, 2013) and particles (Zhang et al., 2012; Habilomatis and Chaloulakou, 2015; Lin et al., 2016) in street canyons, as well as those indoor (Qian and Li, 2010).

Ansys Fluent (Fluent, 2006) with RNG k-ε model (Yakhot and Orszag, 1987) is used to solve the steady flow field. The Boussinesq model is adopted to model the buoyancy effect (Xie et al., 2007; Cai, 2012), in which the air density is regarded as a constant except in the momentum equation of vertical velocity. As a start, this paper mainly emphasizes the coupling effect of urban turbulence and heat transfer between air and wall surfaces. For 2D street canyon models, most previous studies considered a uniformly heated
surface with arbitrary air-wall temperature difference (Sini et al., 1996; Kim and Baik, 2001; Xie et al., 2007; Cai, 2012; Liu et al., 2012; Allegrini et al., 2013, 2014; Li et al., 2015; Hang et al., 2016), as also employed in this study. The simulation of heat radiation will be carried out in the future research.

The mathematical model is based on numerical calculation of a set of governing fluid flow and transport equations (Eqs. 1(a)–1(e)) in incompressible turbulent flow as below.

The continuity (mass conservation) equation:
\[ \frac{\partial u_i}{\partial x_i} = 0 \]  

The momentum conservation (Navier-Stokes) equation:
\[ -u_j \frac{\partial u_i}{\partial x_j} = \left( \frac{\rho - \rho_0}{\rho} \right)g - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} - u_j u_i \right) \]

The energy conservation equation:
\[ \frac{\partial}{\partial x_i} \left( \rho c_v T \right) = \frac{\partial}{\partial x_i} \left( \rho c_v \frac{\partial u_i}{\partial x_j} \right) + \frac{2}{3} k \frac{\partial \theta}{\partial x_j} \]

The conservation equations for turbulent kinetic energy (k) and dissipation (ε):
\[ -u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_k \frac{\partial k}{\partial x_i} \right) + \frac{1}{\rho} \left( \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} - u_j u_i \right) \right) + G_k - \epsilon \]
\[ -u_i \frac{\partial \epsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_\epsilon \frac{\partial \epsilon}{\partial x_i} \right) + \frac{1}{\rho} \left( \frac{\partial P_e}{\partial x_i} + C_\epsilon \frac{\partial \theta}{\partial x_j} \right) - C_{\epsilon 2} \frac{\epsilon^2}{k} \]

where \(-u_j u_i = v_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \) is the Reynolds stress tensor, \( v_i = C_{\mu} \frac{k^2}{\epsilon} \) is the kinematic eddy viscosity, \( P_e = v_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the turbulence production term, \( G_k = \rho \beta g \frac{v_i}{Pr} \frac{\partial \theta}{\partial x_j} \) in which \( \beta \) is the thermal expansion coefficient in the form of \( \beta = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p \) = \( \frac{1}{T_{\text{ref}}} \)
c and \( g \) is the gravitational acceleration.

Model Descriptions and CFD Set-ups

A total number of 25 buildings and 24 two-dimensional (2D) street canyons are used in CFD (Fig. 1(a)). The scale ratio of CFD models to those in full-scale is 1:10. Both street width \( W \) and building breadth \( B \) are constants of 2 m (Fig. 1(b)), corresponding to full-scale street of 20 m wide. Street-level pollutants are released in the target street canyon (Canyon No. 8). Seven identical buildings of No. 1 to No. 8 (\( H_2/W = 1, 2 \) or 3) are located upstream of the target street canyon to explicit reproduce roughness elements, while seventeen buildings of No. 9 to No. 25 with a constant uniform height (\( H_2/W = 1 \)) are located downstream to investigate pollutant reentry into downstream streets (Canyon No. 9 to No. 24).

All test cases are summarized in Table 1. The case name is defined as ‘Heating type’ [\( H_2/W - H_2/W \), \( U_{\text{ref}}, \Delta T \)]. Four types of ‘Heating surface’ denotes various thermal effects by solar radiation and heat release from buildings, i.e., ‘N’- No wall heating (isothermal and neutral condition), ‘G’-Ground heating, ‘L’- Leeward-wall heating, ‘W’-Windward-wall heating, ‘A’- All surfaces heating. As an example, Fig. 1(c) shows the model description of leeward-wall heating and ground heating. The air temperature at the domain inlet is \( T_{\text{ref}} = 300 \) K for all test cases. The same surface temperatures are uniformly distributed over the heated walls (leeward wall, windward wall, ground or all these three walls). \( \Delta T \) represents the air-wall temperature difference (\( \Delta T = 10 \) K or 20 K). \( U_{\text{ref}} = 2 \) or 0.5 m s\(^{-1}\) is the reference freestream velocity at the domain inlet at the height of \( z = W \) above the building rooftop.

The importance of buoyancy force is evaluated by the Froude number:
\[ F_r = \frac{U_{\text{ref}}^2}{g z_{\text{ref}} \Delta T / T_{\text{ref}}} \]  

where \( g \) is the gravitational acceleration, \( z_{\text{ref}} = H_1 = 2 \) m is the reference building height.

Thus the Froude number ranges from 0.19 to 6.12. The respective Reynolds number (\( Re = \rho U_{\text{ref}} H/\mu \)) is 174.978 and 34.965 for \( U_{\text{ref}} = 2 \) m s\(^{-1}\) and 0.5 m s\(^{-1}\) respectively, which is much greater than 11.000 ensuring Reynolds number independence (Snyder, 1972). Here \( \rho \) is the air density (1.177 kg m\(^{-3}\)) and \( \mu \) is the air dynamic viscosity (1.568 \times 10\(^{-5}\) N s m\(^{-2}\)).

Fig. 1(a) displays computational domain in Case [2-1]. Zero normal gradient conditions are imposed at the domain roof (i.e., symmetry) and domain outlet (i.e., full-developed outflow). No slip wall boundary is used at building walls. The SIMPLE scheme is used for the pressure and velocity coupling. For all transport equations, the second-order scheme is used to provide better numerical accuracy. At the domain inlet, vertical profiles of stream-wise velocity (\( U_0 \)), turbulent kinetic energy (\( k \)) and its dissipation rate (\( \epsilon \)) are set as below.

\[ U_0(z) = U_{\text{ref}} \left( \frac{z - z_{\text{ref}}}{z_{\text{ref}}} \right)^\vartheta \]
\[ k_0(z) = (U_{\text{ref}}(z) \times I_0) \]
\[ \epsilon_0(z) = \frac{C_{\mu} k^{3/2}}{\kappa z} \]
Fig. 1. (a) Computational domain and boundary conditions, (b) enlarged view of the target street canyon, (c) description of leeward-wall heating and ground heating as two examples, (d) grid arrangement in Case $[2-1, U_{ref}, \Delta T]$. 

**Air volume of pedestrian region, $V_{ol}(y \text{ from } 0 \text{ to } z_p=0.1W)$**

**Entire air volume of target street, $V_{ol}(y \text{ from } 0 \text{ to } W)$**

$H_f$: height of building No 1 to No 8; $H_g$: height of building No 9 to No 25

Building breadth $B = \text{street width } W$
where \( U_{ref} = 2 \) or \( 0.5 \) m s\(^{-1} \), \( z_{ref} = H_t = 2 \) m, \( \alpha = 0.22 \) denotes the underlying surface roughness depending on terrain category, \( I_0 = 0.1 \) is the turbulence intensity, \( C_\mu \) is 0.09 and \( \kappa \) is the von Karman constant (0.41).

It is worth mentioning that, the main purpose of adopting eight upstream buildings and eighteen downstream buildings of the target street canyon is to explicitly reproduce roughness elements and develop an urban boundary layer. Thus even the constant turbulence intensity is used at the domain inlet, the profile of turbulence can be adjusted to a flow balance by the upstream buildings. Similar CFD arrangement of upstream and downstream elements with constant turbulent intensity at the domain inlet were employed in previous studies (Xie et al., 2007; Liu et al., 2015; Lin et al., 2016), e.g., four upstream buildings in Xie et al. (2007) and seven in Lin et al. (2016).

In addition, the purpose of adopting 2D small-scale street canyon models \((H = 2 \) m\) with the scale ratio of 1:10 to full-scale models \((H = 20 \) m\) is to reduce the required grid number. The total number of structural cells ranges from 310,867 to 521,866 which is of the same order with those in the literature (386,924 cells in Lin et al. (2016) and 321,572–444,571 cells in Xie et al. (2007)). The grids are sufficiently refined near the wall surfaces with the minimum grid size of 1 mm (Fig. 1(d)) to ensure the dimensionless wall distance \( Y' \) of the first cell near walls is in order of 1 and satisfy the requirement of enhanced wall functions to capture the viscous sub-layer near wall surfaces (Xie et al., 2007; Liu et al., 2012, 2013; Allegrini et al., 2014; Lin et al., 2016). To ensure grid independency, in the example case (Case [1-1,2, 0 K]), we also used a finer grid arrangement with constant grid size of 0.5 mm at wall surfaces to perform a mesh-dependency test, finding that there is little difference of CFD results between two grid arrangements. We are also aware that, no-slip boundary is used at building walls where roughness is simplified and assumed to be zero, similar with previous wind tunnel studies and CFD simulations (e.g., Meroney et al., 1996; Kim and Baik, 2001; Chang and Meroney, 2003; Richards et al., 2006; Xie et al., 2007; Li et al., 2009; Cai, 2012; Hang et al., 2012; Allegrini et al., 2013; Allegrini et al., 2014, 2015; Yang and Li, 2015; Lin et al., 2016). In realistic street canyons, the surfaces of building walls and roofs are quite rough, moreover there are some obstacles such as windows, balconies etc. to make the heat transfer and turbulence at wall surfaces more complicated. Thus this simplification produces smaller friction force and less complicated physical processes in contrast to realistic street canyons.

**CFD Setups in Dispersion Modelling**

For Gaseous Pollutant Dispersion Modelling

In CFD simulations, the pedestrian height is defined as 0.1 \( W \) which corresponds to 2 m in full-scale streets. Gaseous pollutant (carbon monoxide (CO)) and particles are released from a line pollutant source (0.7 \( W \) wide) in the middle of the target street canyon (Fig. 1) and at the height of \( z = 0.045 \) \( W \)-0.05 \( W \) above the ground. The sidewalks are 0.15 \( W \) wide on both margins. The CO emission rate \((S_c = 10^{-7} \) kg m\(^{-3}\) s\(^{-1}\)) is small to ensure the source release little affects the flow field (Hang et al., 2012).

The steady-state governing equation of CO concentration is:

\[
P \frac{\partial c}{\partial t} = \nabla \cdot \left( K_c \nabla c \right) = S_c
\]

where \( c \) denotes pollutant concentration (kg m\(^{-3}\)), \( K_c \) is turbulent diffusivity of pollutants. Here \( K_c = \nu / S_c \), \( \nu \) is the kinematic eddy viscosity and \( S_c \) is the turbulent Schmidt number.

It is known that \( S_c \) may vary depending on different flow pattern and locations in the flow field, but in CFD simulations it is usually considered as a constant ranging from 0.2 to 1.3 (Tomlinaga and Stathopoulos, 2007). Chavez et al. (2011) confirmed that variations of \( S_c \) have less impact on pollutant dispersion in the presence of adjacent buildings. Here we use \( S_c = 0.7 \) according to the literature (Chavez et al., 2011; Hang et al., 2012).

For Eq. (4), we use the zero normal flux condition at wall surfaces and zero normal gradient condition at the domain outlet and domain roof. At the domain inlet, the inflow concentration is set zero. The normalized CO concentration is defined as:

\[
C^* = \frac{c U_{ref} WL/Q}{\bar{c} W / L}
\]

where \( U_{ref} \) is a constant of 0.2 m s\(^{-1} \), \( L \) is the source length (0.7 \( W \)) and \( Q \) is the total mass release rate (kg s\(^{-1} \)).

To quantify the effectivenss of pollutant removal, the normalized spatial mean concentration within the entire target street canyon or downstream canyons is defined as:

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**Table 1. Summary of test cases conducted by CFD simulations.**

| Case name* | \( H/W-H/W \) | Velocity \( U_{ref} \) (m s\(^{-1} \)) | \( \Delta T \) (K) | Gaseous (CO) / particle size (\( \mu m \)) |
|------------|----------------|-------------------------------------|------------------|----------------------------------|
| N[H/W-H/W, \( U_{ref} \), \( \Delta T \)] | 1-1, 2-1, 3-1 | 0.5, 2.0 | 0 | Gaseous, 1, 5, 20 |
| G[H/W-H/W, \( U_{ref} \), \( \Delta T \)] | 1-1 | 0.5, 2.0 | 10, 20 | Gaseous, 1, 5, 20 |
| L[H/W-H/W, \( U_{ref} \), \( \Delta T \)] | 1-1 | 0.5, 2.0 | 10, 20 | Gaseous, 1, 5, 20 |
| W[H/W-H/W, \( U_{ref} \), \( \Delta T \)] | 1-1 | 0.5, 2.0 | 10, 20 | Gaseous, 1, 5, 20 |
| A[H/W-H/W, \( U_{ref} \), \( \Delta T \)] | 1-1, 2-1, 3-1 | 0.5, 2.0 | 10, 20 | Gaseous, 1, 5, 20 |

* 'N', 'G', 'L', 'W' and 'A' denote 'Isothermal', 'Ground heating', 'Leeward wall heating', 'Windward wall heating' and 'All surfaces heating', respectively. \( H_1 \) and \( H \) represent the heights of upstream and downstream buildings of the target street canyons. \( W \) means street width.
integrating the force balance on the particle (Fluent, 2006).

\[ C^* > \int_{Vol} C^* dxdy / Vol \]

where \( Vol \) is air volume at pedestrian level \((y = 0)\) or in entire street \((y = 0–1 \, \text{H})\).

For Particle Dispersion Modelling

After the steady flow field without particles is first solved, the particles are injected into the street canyon through line source (Fig. 1(b)) at a rate of 106 particles per second for each particle size \((d = 1 \, \mu\text{m}, 5 \, \mu\text{m}, 20 \, \mu\text{m})\) as the flow field keeps steady (i.e., airflow does not change). The transient particle trajectory is calculated by a Lagrangian method by or in entire street (literature, see for example Zhao et al. 2013). Dispersion with steady airflows has been adopted in the particle distribution. Such technique of transient particle dispersion keeps steady (i.e., airflow does not change). The transient dispersion of each particle size \((d = 1 \, \mu\text{m}, 5 \, \mu\text{m}, 20 \, \mu\text{m})\) as the flow field is modelled by the discrete random walk method. The equation of particle transport is as below (Fluent, 2006).

\[ \frac{d\bar{u}}{dt} = \sum \vec{F} = \vec{F}_{\text{drag}} + \vec{F}_g + \vec{F}_a \]

where \( \bar{u} \) is the particle velocity vector \((\text{m s}^{-1})\), all external forces \( \sum \vec{F} \) exerted on the particle (per unit particle mass) whose unit is \( \text{m s}^{-2} \) consist of the drag force \( \vec{F}_{\text{drag}} \), the gravity force \( \vec{F}_g \), the additional forces \( \vec{F}_a \). Following the literature (Zhao et al., 2004; Qian and Li, 2010; Zhang et al., 2012; Hang et al., 2016), for components of \( \vec{F}_a \) only Brownian force and Saffman’s lift force are considered (the other forces are sufficiently small and are neglected).

For boundary conditions of particles, particle trap conditions (or entrapment) are defined at wall surfaces. Escape conditions are set at the domain outlet, the domain top and the domain inlet. Some assumptions are made to simplify the simulation, i.e., we neglect the interaction among particles and the influence of particles on airflows, the heat and mass exchange between air and particles, assuming the particles are ideal spherical ball-shaped.

**CFD VALIDATION AND EVALUATION BY WIND TUNNEL DATA**

**Validation Study of Isothermal and Non-Isothermal CFD Flow Modelling**

Allegrini et al. (2013) conducted some wind tunnel experiments on buoyant flows in a cavity-shaped street canyon (Fig. 2(a)) with the same street width and building height \((W = H = 0.2 \, \text{m})\). Apart from isothermal case, leeward-wall heating, windward-wall heating, ground heating and all wall heating were included. Various freestream velocities \((U_{FS} = 2.32 \, \text{to} \, 0.68 \, \text{m s}^{-1})\) were used corresponding to the reference Reynolds number \((Re)\) of 9,000 to 30,700. Airwall temperature differences were 47 K to 107 K. Thus the Froude number \((Fr)\) ranged from 0.65 to 17.29.

CFD flow modelling are first evaluated by wind tunnel data in Allegrini et al. (2013). The computational domain has the same dimension of the wind tunnel setup (Fig. 2(a)). All CFD arrangements are similar with those in Section 2. The grid number was 58,085 with a minimum cell size of 1mm \((\delta_r)\) is in order of 1). A finer grid with 190,016 cells and a minimum cell size of 0.5 mm is also adopted to verify the grid independence. In addition, the \(x\)-Component ‘wall shear stress’ of \(\tau_w\) is introduced to simulate the friction effect of upstream and downstream surface and avoid TKE decay in the stream-wise direction (Allegrini et al., 2014). At the domain inlet, the measured vertical profiles of stream-wise velocity \(U(z)\) and turbulent kinetic energy \(k(z)\) are used (Fig. 2(b) as two examples from Allegrini et al. (2013)). As some examples, Figs. 2(c) and 2(d) show validation profiles of mean vertical velocity \(U\), mean stream-wise velocity \(U\) and turbulent kinetic energy \((TKE)\) or \(k\) in isothermal \((\Delta T = 0 \, \text{K}, U_{FS} = 1.45 \, \text{m s}^{-1}, Re = 19,200)\) and non-isothermal \((Re = 19,200, \text{all-wall heating}, Fr = 6.75)\) cases. CFD results have good agreements with wind tunnel data in terms of mean flows, while turbulent kinetic energy is slightly under-predicted. The fine and finer grids attains almost the same results (Fig. 2(c)). Thus the RNG \(k\) model is confirmed effective to simulate isothermal/non-isothermal flows in 2D street canyons.

As described in Section 2, this paper uses eight upstream buildings to apparently simulate the upstream approaching flow over urban roughness elements. Thus constant wall shear stress is not used in the following case studies.

**Validation of Pollutant Dispersion Modelling**

This paper adopts wind tunnel data from Meroney et al. (1996) to evaluate CFD dispersion modelling in 2D street canyons. This CFD validation study uses the same model geometry and boundary conditions with wind tunnel experiments (Fig. 3(a)), consisting of 28 parallel street canyons (building height \(H = \text{street width} \, W = 60 \, \text{mm}\)) with a perpendicular wind to street axis. Twenty street canyons exist in the upstream of the target street canyon and eight in the downstream. A steady-state line pollutant (ethane) source is fixed in the target canyon. The normalized concentration is defined \(C^* = \bar{c} UHL/Q\), where \(\bar{c}\) is the concentration, \(U\) is the freestream velocity measured at \(z = 8.3H\) above wind tunnel floor, \(L\) is line source length and \(Q\) is the source.
emission rate. The total grid number is 372,889 with sufficiently fine grid near wall surfaces (Fig. 3(a)). With $V_{in} = 3 \text{ m s}^{-1}$ at the domain inlet (Fig. 3(b)), vertical profiles of $C^*$ along windward/leeward walls by CFD are in good agreement with wind tunnel data, and windward-side $C^*$ profile is much lower than leeward-side.

Fig. 2. (a) Wind tunnel model in Allegrini et al. (2013). (b) $U(z)$ and $k(z)$ at Line O measured in free flow by Allegrini et al. (2013). Comparison of wind tunnel data and CFD results in two examples (c) for isothermal case, and (d) with all-wall heating.
Fig. 2. (continued).
RESULTS AND DISCUSSION

The impacts of street layouts and wall heating on the dispersion and reentry of gaseous pollutants and particles (Table 1) are investigated for street design purpose.

Flow and Pollutant Dispersion/Re-Entry with Uniform Height (H_1 = H_2 = W)

Figs. 4 and 5 show the flow patterns in Case [1-1,0.5, \Delta T] and Case [1-1,2, \Delta T]. Similar with Allegrini et al. (2013, 2014), a single main clockwise vortex exists in the

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Fig. 3. (a) CFD set-up and grid for validation by wind tunnel data from Meroney et al. (1996). (b) Vertical profiles of C* along windward wall and leeward wall.
Fig. 4. Streamline and velocity in target canyon (NO.8) of Case [1-1, 0.5, ΔT].
isothermal case (Figs. 4(a) and 5(a)). As $Fr = 0.38$ ($U_{ref} = 0.5$ m s$^{-1}$, $\Delta T = 10$ K), thermal buoyancy force induced by wall heating can substantially modify the vortex formation. The main vortex breaks into two counter-rotating horizontally-aligned vortices for all-wall heating (Fig. 4(b)) and windward-wall heating (Fig. 4(e)). In addition, with ground heating (Fig. 4(c)) and leeward-wall heating (Fig. 5(d)), the main clockwise vortex is enhanced comparing to isothermal case. As $Fr = 6.12$ ($U_{ref} = 2$ m s$^{-1}$), the main clockwise vortexes are similar in all isothermal and non-isothermal cases (Fig. 5).

Fig. 6 shows $C^*$ in the target street canyon (No. 8) for Case [1-1, 0.5, 0 K] with isothermal and various wall heating. As a result of the above flow patterns, the leeward-side $C^*$ is higher than windward-side due to the clockwise vortex in the isothermal case (Fig. 6(a)). In contrast, windward-wall heating attains higher $C^*$ since the main vortex is weakened (Fig. 6(e)), in addition, ground heating, leeward-wall heating and all-wall heating cases experience lower $C^*$ because they enhance the main vortex (Figs. 6(b) to 6(d)). Among the four heating types, $C^*$ with leeward-wall heating is the lowest.

Then Fig. 7 exhibits the particle distribution with different diameters ($d = 1$ µm, 20 µm) at $t = 700$ s in Case [1-1, 0.5, 10 K] and Case [1-1, 0.5, 10 K] (particle release starts at $t = 0$ s). In the isothermal case, the dispersion of fine particles ($1$ µm) strongly depends on the path of the primary vortex (Fig. 7(a)) similar with gaseous pollutants. However for large particles ($d = 20$ µm, Fig. 7(b)), little fraction reenters downstream canyons because most large particles deposit onto wall surfaces of the target street canyon. In contrast, both fine particles ($d = 1$ µm) and large ones ($d = 20$ µm) with all wall heating (Figs. 7(c) and 7(d)) can more easily disperse out of the target street and reenter the downstream streets, moreover, more particles can be vertically dispersed to upper levels. Obviously the upward buoyancy force overcomes the gravity force and reduces the particle deposition effect.
Effects of Upstream Taller Buildings ($H_1 = 2W$ or $3W$, $H_2 = W$)

This subsection selects Case [2-1, 0.5, $\Delta T$] and Case [3-1, 0.5, $\Delta T$] ($H_1 = 2W$ or $3W$ for No. 1 to No. 8, $H_2 = W$ for No. 9 to No. 25, $\Delta T = 0$ or 10 K) as two examples to investigate how upstream taller buildings affect the flow, dispersion and reentry of gaseous pollutant and particles with or without wall heating conditions.

In contrast to the single-main-vortex flow in Case [1-1, 0.5, 0 K] (Fig. 4(a)), upstream taller buildings in Case [2-1, 0.5, 0 K] produce a massive clockwise-rotating chunk vortex above the No. 8–No. 10 canyons and much weaker counterclockwise vortices within the target canyon (No. 8) and its neighboring streets (No. 9 and 10) (Fig. 8(a)). With all-wall...
Fig. 7. Particle dispersion in Case [1-1, 0.5, 0K] and [1-1, 0.5, 10K] (d = 1 and 20 µm).
Fig. 8. Streamline and velocity in Case [2-1, 0.5, ΔT] and Case [3-1, 0.5, ΔT].
heating (Fig. 8(b)), the clockwise chunk vortex is measurably enhanced due to thermal buoyancy force, and its size over downstream canyons is shortened. Subsequently the single-main-vortex flows beneath the chunk vortex inside canyons of No.8–No.10 are enhanced and these vortex centers also change (Fig. 8(b)).

If the upstream buildings become much taller ($H_1 = 3W$, Case [3-1, 0.5, $\Delta T$]), a clockwise-rotating chunk vortex covers larger area above the No.8–No.13 downstream canyons (Fig. 8(c)). Similarly all-wall heating ($\Delta T = 10$ K, Fig. 8(d)) slightly strengthens the chunk vortex flow and those within the canyons below it.

(b) Dispersion of Gaseous Pollutant and Particles with Various Diameters

Fig. 9 shows $C^*$ in the target street canyon of Case N[2-1, 0.5, 0 K] and Case A[2-1,0.5,10 K] ($H_1/W = 2$). Due to the counter-clockwise vortex in the target street canyon, windward-side $C^*$ is higher than leeward-side. Moreover, the ground-level $C^*$ in Case N[2-1, 0.5, 0 K] (maximum 11,000, Fig. 9(a)) is found extremely higher than that in Case N[1-1, 0.5, 0 K] (700, Fig. 6(a)). It confirms that for isothermal condition, taller upstream buildings greatly reduce the capacity of ground-level pollutant dispersion. With all wall heating ($\Delta T = 10$ K, Fig. 9(b)), $C^*$ in Case A[2-1, 0.5, 10 K] is substantially decreased (maximum 320) because all wall heating can enhance the vortex flows within and above the target street canyon as confirmed by Figs. 8(a)–8(b).

Fig. 10 displays dispersion behavior of fine particles ($d = 1$ $\mu$m) at time of 35 s, 100 s, 700 s in Case N[2-1, 0.5, 0 K] and Case A[2-1, 0.5, 10 K]. Similar with gaseous pollutants, more fine particles exist in the windward side of the target canyon due to the counter-clockwise vortex within it. The particle dispersion with isothermal condition (Fig. 10(a)) is much slower than that with all wall heating (Fig. 10(b)) because the isothermal vortex flow is weaker, moreover with all-wall heating fine particles can be dispersed to a much upper level than isothermal case.

Quantitative Analysis of Gaseous Pollutant Dispersion and Re-Entry Toward Downstream Canyons

Fig. 11(a) depicts $<C^*>_{ped}$ in the target (No. 8) canyon in all test cases. For example, the triangle symbols means Case [3-1, $U_{ref}$, $\Delta T$] (i.e., $H_1 = 3W$) and its first and second one in the left side denote Case N[3-1, 0.5, 0 K] and N[3-1, 2, 0 K] (isothermal cases). Circle symbols for $H_1 = 2W$, and square symbols for $H_1 = W$. $<C^*>_{ped}$ in Case N[3-1, 0.5, 0 K] is the highest among all test cases. Most wall heating conditions significantly reduce $<C^*>_{ped}$ for cases with $U_{ref} = 0.5$ m s$^{-1}$ except Case W[1-1, 0.5, 10 K], but that with $U_{ref} = 2$ m s$^{-1}$ wall heating only affect $<C^*>_{ped}$ a little. In addition, $<C^*>_{ped}$ with taller upstream buildings (Case [2-1] and [3-1], $H_1 = 2W$ and $3W$) are always higher than those with uniform street layout (Case [1-1], $H_1 = W$) no matter what kinds of heating scenarios are imposed. Thus it is not recommended to design tall buildings in the upstream of busy roads with heavy traffic emissions.

Fig. 11(b) displays $<C^*>_{bulk}$ in the target street and its downstream streets in all cases of Case [1-1, 0.5, $\Delta T$], and Fig. 11(c) depicts $<C^*>_{bulk}$ in some example cases with upstream taller buildings. It is interesting to find that $<C^*>_{bulk}$ always decreases exponentially with increasing distance toward downstream canyons. To quantify such process, Table 2 summarizes $<C^*>_{bulk}$ in target canyon and in the adjacent canyon (No. 9) as well as the exponential decay rate $b$ ($C^*(x) = C^*_9e^{-x/(W \times b)}$, $C^*_9$ is $<C^*>_{bulk}$ in Street No. 9) in all test cases.

(a) With Uniform Street Layouts (Case [1-1], Fig. 11(b) and Table 2)

As $Fr = 0.19$ or $0.38$ ($U_{ref} = 0.5$ m s$^{-1}$), $<C^*>_{bulk}$ in the target canyon (No. 8) of Case N[1-1, 0.5, 0 K] (isothermal)
Fig. 10. Particle dispersion in Case [2-1, 0.5, ΔT].
is 322.1. It decreases with windward-wall heating (232.0 for $\Delta T = 10$ K), ground heating (151.4 for $\Delta T = 10$ K), all-wall heating (125.3 and 74.3 for $\Delta T = 10$ or 20 K) and leeward-wall heating (107.1 for $\Delta T = 10$ K). Thus assuming $<C^*>_{bulk}$ in isothermal cases as 1.00, wall heating conditions reduce $<C^*>_{bulk}$ from 1.0 to 0.23–0.72. Moreover, $<C^*>_{bulk}$ in Street No. 9 and its downstream canyons are the highest in isothermal case (41.5 in No. 9) and the least for all wall

Fig. 11. (a) $<C^*>_{ped}$ in target canyon at pedestrian level; (b) and (c) $<C^*>_{bulk}$ in street canyons for some example test cases.
heating with $\Delta T = 20$ K (6.9 in No. 9). In addition, with $U_{ref} = 2$ m s$^{-1}$ ($Fr = 3.06$ or 6.12, Table 2), wall heating conditions only slightly change $<C^*>_{bulk}$ in the target canyon (No. 8, 75.4–96.5) and in street No. 9 (8.8–11.3). Finally, the concentration decay rates $b$ from Street No. 9 toward downstream streets range from 3.03 to 3.33, i.e., $<C^*>_{bulk}$ decreases $e^t$ times for the distance of about $3.0W$ toward downstream canyons.

(b) With Taller Upstream Buildings (Case [2-1, 0.5, 10 K])

As $Fr = 0.19$ or 0.38 ($U_{ref} = 0.5$ m s$^{-1}$), $<C^*>_{bulk}$ in the target canyon of Case [2-1, 0.5, 10 K] and [3-1, 0.5, 0 K] are 1316.5 and 3727.9, which are much higher than 322.1 in Case [1-1, 0.5, 0 K] (uniform height). Assuming $<C^*>_{bulk}$ in isothermal case as 1.00, all-wall heating obviously reduce $<C^*>_{bulk}$ in the target street canyon from 1.0 to 0.04–0.14. However as $Fr = 3.06$ or 6.12 ($U_{ref} = 2$ m s$^{-1}$), all-wall heating only reduce $<C^*>_{bulk}$ in the target street from 1.0 to 0.22–0.56. $<C^*>_{bulk}$ in Street No. 9 and the exponential decay rate ($b$) toward downstream canyons are summarized.

Overall Analysis of Particle Dispersion and Re-Entry ($U_{ref} = 0.5$ m s$^{-1}$)

Table 3 summarizes particle number concentration (PNC) in the target canyon (No. 8) and its adjacent canyon (No. 9) as well as the exponential decay rate $b$ toward downstream canyons ($PNC(x) = PNC_0e^{-bx}$). PNC$\_0$ is PNC in Street No. 9. The particle dispersion are found more complicated than gaseous pollutants.

(a) With Uniform Street Layouts (Case N[1-1, 0.5, 0 K] and Case A[1-1, 0.5, 10 K])

In Streets No. 8 and No. 9 in isothermal case ($\Delta T = 0$ K), particle numbers (PNCs) of $d = 1$ µm (329,768) are similar with $d = 5$ µm (306,987), but with all-wall heating ($\Delta T = 10$ K, $Fr = 0.38$) PNC of $d = 5$ µm (942,493) is much greater than that of $d = 1$ µm (148,264), moreover all-wall heating basically reduces PNC for $d = 1$ µm but increases that of $d = 5$ µm. These phenomena can be explained that the thermal upward buoyancy force due to all-wall heating enhances the single-main-vortex flow and disperses more particles of $d = 1$ µm out, which is similar with gaseous pollutants, but weakens the deposition effect for particles of $d = 5$ µm induced by the gravity force and leads to more particles of $d = 5$ µm floating in the canyon space. For large particles ($d = 20$ µm), the gravity force and deposition effect are more important than other forces, thus less number of large particles suspend in the target canyon. In the target canyon, the PNCs of large particles are one order smaller than fine particles ($d = 1$ µm and 5 µm), and in Street No. 9 it can be 2–4 order smaller. Moreover the exponential decrease rates $b$ of large particles (1.61 and 2.62) are less than those of fine particles (2.69–3.21).

(b) With Taller Upstream Buildings (Case [2-1, 0.5, 0 K], Case [3-1, 0.5])

Because the upstream taller buildings produce much
Table 3. Particle number concentration (PNC) in target canyon and the exponential decay rate \( b \) toward downstream canyons.

| Case name       | Co or Particle size (\( \mu m \)) | PNC in street No. 8 (target canyon) | PNC in Street No. 9 | Decay rate \( b \) |
|-----------------|-----------------------------------|-------------------------------------|----------------------|-------------------|
| \( N[1-1, 0.5, 0K] \) CO | 1                                | 329768                              | 25821                | 3.33              |
|                 | 5                                | 306987                              | 21855                | 2.75              |
|                 | 20                               | 36548                               | 94                   | 2.69              |
| \( A[1-1, 0.5, 10K] \) CO | 1                                | 148264                              | 10503                | 3.20              |
|                 | 5                                | 942493                              | 43505                | 3.16              |
|                 | 20                               | 27096                               | 822                  | 2.62              |
| \( N[2-1, 0.5, 0K] \) CO | 1                                | 1636678                             | 30811                | 4.79              |
|                 | 5                                | 198270                              | 1107                 | 3.08              |
| \( A[2-1, 0.5, 10K] \) CO | 1                                | 107544                              | 6430                 | 4.70              |
|                 | 5                                | 1311632                             | 41888                | 3.54              |
| \( N[3-1, 0.5, 0K] \) CO | 1                                | 3443529                             | 7978                 | 6.70              |
|                 | 5                                | 91419                               | 1                    | 5.03              |
| \( A[3-1, 0.5, 10K] \) CO | 1                                | 99170                               | 3688                 | 6.70              |
|                 | 5                                | 1077674                             | 19017                | 5.39              |

* Here \( b \) denotes the concentration decay rate from the street No. 9 toward downstream street canyons \((PNC(x) = PNC_9 e^{-x/(W \times b)}))\), \( PNC_9 \) is PNC in street No. 9.

Weaker vortex flow in the target street canyon (Figs. 8 and 9), PNCs of \( d = 1 \) \( \mu m \) in Case \( N[2-1, 0.5, 0 K] \) and \( N[3-1, 0.5, 0 K] \) are 5–10 times greater than that in Case \( N[1-1, 0.5, 0 K] \) (isothermal cases, Table 3). This finding is similar with gaseous pollutants. However, for particles of \( d = 5 \) \( \mu m \), PNCs in Case \( N[2-1, 0.5, 0 K] \) and \( N[3-1, 0.5, 0 K] \) are only about 30%–65% of that in Case \( N[1-1, 0.5, 0 K] \), differing from gaseous pollutants. It confirms the gravity force and deposition effect are more important for particles of \( d = 5 \) \( \mu m \) as street vortex flow is weakened by taller upstream buildings. By comparing all-wall heating (Case \( A[2-1, 0.5, 10 K] \) and \( A[3-1, 0.5, 10 K] \)) with isothermal cases (Case \( N[2-1, 0.5, 0 K] \) and \( N[3-1, 0.5, 0 K] \)), it is interesting to find that, PNCs for \( d = 1 \) \( \mu m \) with \( \Delta T = 10 \) K are 14.2 and 33.7 times smaller, but PNCs for \( d = 5 \) \( \mu m \) are 5.6 and 10.8 times greater. It verifies that, the upward thermal buoyancy force induced by all-wall heating disperse more fine particles \((d = 1 \mu m)\) out, but reduces the particle deposition of \( d = 5 \mu m \) and induces more particles float in the target canyon.

**Limitations and Discussions**

We are aware that the idealized 2D street canyons are simplified and may not be appropriate for realistic 3D street canyons which are characterized by much larger complexity. Recirculation zones which leads to the removal of pollutants by the lateral ends of the 3D street canyons are disregarded. No-slip boundary with zero roughness at building walls is assumed and the obstacles such as windows, balconies etc. are disregarded which lead to smaller flow resistances and simplified physical processes at wall surfaces. Further studies of 3D urban geometries with heat radiation and more realistic conditions are required in the future. Nevertheless, idealized street canyons can represent simplified urban geometries and can act to synthesize the physical and chemical processes in urban air environment (Li et al., 2006) which is an infinitely long street surrounded by buildings on both sides with a perpendicular approaching wind to its street axis. It has been and is currently still commonly adopted in the literature (Cai, 2012; Allegrini et al., 2014; Ng and Chau, 2014; Ho et al., 2015; Habilomatis and Chaloulakou, 2015; Liu et al., 2015; Li et al., 2015; Hang et al., 2016). In this context, although further studies are still required before providing a practical framework for street design purpose, we have analysed some important phenomena which is still limited in the literature, i.e., the effects of various wall heating and street layouts on pollutant dispersion of both passive scalar pollutants and aerosol particles with various diameters in the target canyon and their re-entry toward downstream street canyons.

**CONCLUSIONS**

Pollutant dispersion of gaseous pollutants and particles in street canyons have become a hot research button. This study investigates the role of various building layouts and wall heating on the dispersion of gaseous pollutants and particles (diameter \( d = 1 \mu m, 5 \mu m, 20 \mu m \)) within the target canyon and their re-entry into downstream canyons. Four types of wall heating are included, i.e., windward-wall heating, leeward-wall heating, ground heating and all-wall heating. Froude number \((Fr)\) varies from 0.19 to 6.12. Street layouts, air-wall temperature difference, the gravity force and deposition effect are found key factors for particle dispersion,
whose characteristics are more complicated than gaseous pollutants.

For street canyons with uniform height (aspect ratio $H/W = H_2/W = 1$), a primary clock-wise vortex exists in isothermal condition. As $Fr = 3.06$ or $6.12$, thermal effects hardly affect this flow pattern. As $Fr = 0.19$ or $0.38$, windward-wall heating and all-wall heating produce two horizontally aligned vortices. Moreover windward-wall heating weakens the capacity of ground-level pollutant dispersion and the other three heating conditions improve pedestrian pollutant removal. Taller upstream buildings ($H/W = 2$ and $3$) produce a clockwise chunk vortex over the target canyon and induce a much weaker counter-clockwise vortex within the target canyon. Thus in contrast to uniform heights ($H/W = 1$), taller upstream buildings cause much higher concentration of gaseous pollutants and fine particles ($d = 1 \mu m$) inside the target canyon, moreover all-wall heating can significantly strengthen the vortex flows and reduce their concentrations. However for particles of $d = 5 \mu m$, much less particles suspend in the isothermal street canyon because the gravity force and particle deposition are more important than wind-driven flows, but with all-wall heating more particles of $d = 5 \mu m$ float since the upward buoyancy force reduces particle deposition. For large particles of $d = 20 \mu m$ the gravity force and deposition effect always dominate its dispersion dynamics, so much less number of large particles suspend in the target canyon. Finally, no matter for particles and gaseous pollutant, the bulk pollutant concentration toward downstream canyons decreases exponentially with increasing distance from the target canyon. Such exponential decay rates are quantified. These results indicate that special more attention should be paid on how to reduce pollutant exposure in street canyons with heavy traffic emissions and its near-by buildings by street design technique since the concentration in streets far from the busy road can be much lower.

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