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Research Article

Indoor/Outdoor Airflow and Air Quality

On the comparison of the ventilation performance of street canyons of different aspect ratios and Richardson number

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Abstract

In this paper, the ventilation performances of (1) isothermal street canyons of different building-height-to-street-width (aspect) ratios (h/b) and (2) a ground-heated street canyon of h/b=1 at different Richardson numbers (Ri) are examined numerically by solving the Reynolds-averaged Navier-Stokes (RANS) equations with the use of the Renormalization Group (RNG) k-ε turbulence model. The mean ($\overline{\text{ACH}}$) and turbulent (ACH') air exchange rates (ACH) are calculated by the eddy-viscosity model instead of the turbulence kinetic energy (TKE) used elsewhere. For the isothermal street canyons, the ACH' is found to account for 90% of the total ACH for $0.5 \leqslant h/b \leqslant 2$. Similar to the previous large-eddy simulation (LES) and k-ε turbulence model, the magnitudes and shapes of the roof-level profiles of mean and fluctuating vertical winds are close to each other for different h/b. This suggests that turbulent mixing is important for the ventilation of isothermal street canyons. For the ground-heated street canyon, both the mean wind and turbulence are strengthened as illustrated by the increasing $\overline{\text{ACH}}$ and ACH' with decreasing Ri. A secondary recirculation is developed at the ground-level windward corner that pushes the primary recirculation upward and enhances and ACH as well.

Keywords

street canyons,
ventilation,
air exchange rate (ACH),
ground heating,
RNG k-ε turbulence model

Article History

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1 Introduction

1.1 Literature review

Street canyon refers to the generic unit formed by buildings and streets in urban area. As high-rise buildings are commonly erected in dense mega cities, the pollutant emitted at ground level is easily trapped inside the street canyon resulting in poor air quality. A number of studies on street canyon ventilation have been performed for decades. Various methods, including field measurements (Berkowucz et al. 1996; Croxford and Penn 1998), wind tunnel experiments (Meroney et al. 1996; Kastner-Klein and Plate 1999; Uehara et al. 2000), mathematical models (Vardoulakis et al. 2003) and computational fluid dynamics (CFD; Li et al. 2006), have been employed.

Instead of the realistic urban morphology (irregular street canyons), the configuration of an infinitely long street flanked by two buildings of equal height (also known as an idealized street canyon) is often used to study the fundamental ventilation mechanism in urban area. Previous studies mainly focused on the flow pattern inside the street canyons of different building-height-to-street-width (aspect) ratios (h/b; Oke 1988; Kim and Baik 2001; Jeong and Andrews 2002; Chan et al. 2002), building geometry (Sagrado et al. 2002; Xie et al. 2005a; Xie et al. 2005b), thermal stratification (Sini et al. 1996; Kim and Baik 2001; Xie et al. 2005b; Xie et al. 2006) and the turbulence inside street canyons (Louka et al. 2000; Kastner-Klein et al. 2001; Jeong and Andrews 2002; Baik and Kim 2002; Kim and Baik 2003; Li et. al 2005; Liu et al. 2005).

Turbulence is important in street canyon ventilation especially in skimming flow regime (Oke 1988). Using field measurements, Louka et al. (2000) found that turbulence, compared with its mean flow counterpart, dominates the ventilation inside a street canyon. Analogously, using the

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Reynolds-averaged k-ε turbulence model, Baik and Kim (2002) and Kim and Baik (2003) revealed the importance of turbulence in pollutant removal for the street canyon of $h/b = 1$.

Considering the balance of shear stress and momentum flux at roof level of the street canyon, Bentham and Britter (2003) suggested the exchange velocity (U_E) to characterize the ventilation of an array of buildings. A mathematical expression for U_E/u^*, where u^* is the friction velocity, was proposed as a function of the roughness length (z_0) of the building arrays, but the expression has not been validated with other experimental or numerical result yet.

In addition to the U_E proposed by Bentham and Britter (2003), Liu et al. (2005), based on their large-eddy simulation (LES) results, suggested using the air exchange (ACH) and pollutant exchange (PCH) rates to quantify, respectively, the ventilation and pollutant removal performance for street canyons of $0.5 \leqslant h/b \leqslant 2$. By considering the turbulent kinetic energy (TKE) along the roof level, Li et al. (2005) modified and implemented the LES ACH formulation to their k-ε turbulence modeling results. The LES and k-ε turbulence modeling results were found to be comparable. Afterward, Xie et al. (2006) applied the ACH formulation (Li et al. 2005) to the street canyon of $h/b = 1$ with ground heating. It was found that the ACH increases sharply once buoyancy is introduced into the street canyon. Additional results (Sini et al. 1996; Kim and Baik 2001; Xie et al. 2005b) have shown that heating, either on the ground or facade, substantially modifies the flow patterns inside street canyons and eventually affects the ventilation and pollutant removal rates.

In this paper, the ventilation mechanisms of isothermal and ground-heated street canyons are investigated. The Renormalization Group (RNG) k-ε turbulence model (Yakhot et al. 1986) is used to close the Reynolds-averaged Navier-Stokes (RANS) equations. In order to examine the contribution of turbulence to street canyon ventilation, the ACH is divided into the mean ($\overline{\text{ACH}}$) and turbulent (ACH') components. Instead of only based on the TKE, the eddy-viscosity model is employed to estimate the velocity fluctuations. The ventilation behaviors of two-dimensional (2D) isothermal street canyons of $h/b = 0.5$, 1, and 2, and ground-heated street canyons of $h/b = 1$ at Richardson number $Ri = -1$, -2.5, and -5 are considered.

1.2 ACH formulation

The formulation of ACH is first proposed by Liu et al. (2005) based on LES. The function of ACH is to calculate the amount of air, compared with the volume of the street canyon, being removed from the street canyon per unit time. It is an attempt to use the ACH to compare the ventilation performance of street canyon of different h/b or geometry. Alternatively, ACH is interpreted as the normalized average positive vertical velocity along the roof of street canyon. Hence, ACH is practically adopted as a representative parameter to characterize the street canyon ventilation.

However, due to the costly computer resource required by LES, Li et al. (2005) had modified the original LES-based ACH formulation which was then applied to their RANS k-ε turbulence modeling results. They used the TKE to estimate the velocity fluctuation and therefore assumed isotropic velocity fluctuations. Similar to Xie et al. (2006), the ACH is divided into the mean ($\overline{\text{ACH}}$) and turbulence (ACH') components in this paper. Unlike Li et al. (2005), the TKE is replaced by the eddy-viscosity model in estimating the velocity fluctuations and the ACH' calculation.

The mathematical expression for $\overline{\text{ACH}}$ is defined as

$$\overline{\text{ACH}} = \frac{1}{\lambda}\int_0^\lambda \int_{\Gamma_{\text{roof}}} \overline{w}_+ \mathrm{d}x\,\mathrm{d}t \tag{1}$$

where λ is the averaging time, Γ_{roof} the roof area of the street canyon and t the time. The subscript + in Eq. (1) signifies that only the upward mean velocity component ($\overline{w} > 0$) is taken into account.

Analogous to $\overline{\text{ACH}}$, the ACH' is defined as

$$\text{ACH}' = \frac{1}{\lambda}\int_0^\lambda \int_{\Gamma_{\text{roof}}} w'_+ \mathrm{d}x\,\mathrm{d}t \tag{2}$$

where w' is the vertical fluctuating velocity. From the eddy-viscosity model (Eq. (5)), the variance of the vertical velocity fluctuation can be modeled in the form

$$\overline{w'w'} = -2\nu_t\left(\frac{\partial \overline{w}}{\partial z}\right) + \frac{2}{3}k \tag{3}$$

where ν_t is the turbulent viscosity and k the TKE. Substituting Eq. (3) into (2) yields

$$\begin{aligned}\text{ACH}' &= \frac{1}{\lambda}\int_0^\lambda \int_{\Gamma_{\text{roof}}} w'_+ \mathrm{d}x\,\mathrm{d}t \\ &\approx \int_{\Gamma_{\text{roof}}} \frac{1}{2}\sqrt{\overline{w'w'}}\,\mathrm{d}x \\ &= \int_{\Gamma_{\text{roof}}} \sqrt{-\frac{1}{2}\nu_t\left(\frac{\partial \overline{w}}{\partial z}\right) + \frac{k}{6}}\,\mathrm{d}x\end{aligned} \tag{4}$$

Equations (1) and (4) constitute the ACH formulation used in this paper.

2 Methodology

2.1 CFD model

The CFD computation in this paper was implemented by the commercial package FLUENT (Fluent 2008). The RANS equations equipped with the RNG k-ε turbulence closure model were used. The Reynolds stress tensor $R_{ij} = (-\overline{u_i' u_j'})$ are modeled by the eddy-viscosity model where u' is the fluctuating velocity and the subscripts i, j denote the components of the physical quantities in the Cartesian coordinates,

$$R_{ij} = \nu_t \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \frac{2}{3}\delta_{ij} k \quad (5)$$

here, $\nu_t (= C_\nu k^2/\varepsilon)$ is the turbulent viscosity, $C_\nu (= 0.0845)$ the modeling constant and ε the TKE dissipation rate.

2.2 Computational domain and boundary conditions

The computational domain consists of 13 identical 2D street canyons regularly placed in the streamwise direction (Fig. 1). A symmetric boundary condition is used at the top of the computational domain. An inflow wind profile in the form of power law

$$U(z) = U_0 \times \left(\frac{z}{4h} \right)^{\alpha} \quad (6)$$

is employed at the upwind boundary while an outflow boundary condition is employed on the downwind side. Here, z is the height measuring from the ground, U_0 the free-stream wind speed and $\alpha (= 0.28)$ the wind profile exponent. For the outflow condition, velocity outflow with flow rate equal to the inlet is employed. No-slip boundaries are assumed on all the streets and facades. The building width is $w = b$ and the shear layer thickness measuring from the roof level of the buildings is $h_f = 3h$.

The ventilation performance of the (7^{th}) street canyon at the center is investigated in details. The rest of the street canyons, which are placed either upstream or downstream of the test street canyon, are used to model urban roughness and facilitate fully developed turbulence as well. The Reynolds number $Re (= U_0 H / \nu)$ is 10,000 where H is the building height of the street canyon of $h/b = 1$. For the isothermal cases, all the boundaries are kept at the same temperature. When thermal effect is taken into account, the ground is kept at a (higher) temperature θ_g while the free-stream is θ_0 to simulate the daytime (unstable) stratification. The (dimensionless) Richardson number $Ri [= gH(\theta_0 - \theta_g)/(\theta_0 U_0^2)$, where g is the gravitational acceleration] is used in this paper to measure the relative contributions of the wind- and buoyancy-driven flow. Negative Ri corresponds to unstable stratification. More negative (less negative) Ri represents a larger (smaller) contribution from the buoyancy.

The grid was generated by the commercial package GAMBIT (GAMBIT 2008). More than two million of grid points were used in all the cases of h/b considered (Table 1). Meshes with smaller grid size were used inside the street canyon while those of larger were used near the upper boundary.

Table 1 Mesh size for the computational domain of street canyons of $h/b = 0.5$, 1, and 2

h/b	Mesh size	Minimum grid spacing/H	Maximum grid spacing/H
0.5	2,200,000	0.02	0.2
1	2,200,000	0.03	0.2
2	2,500,000	0.02	0.1

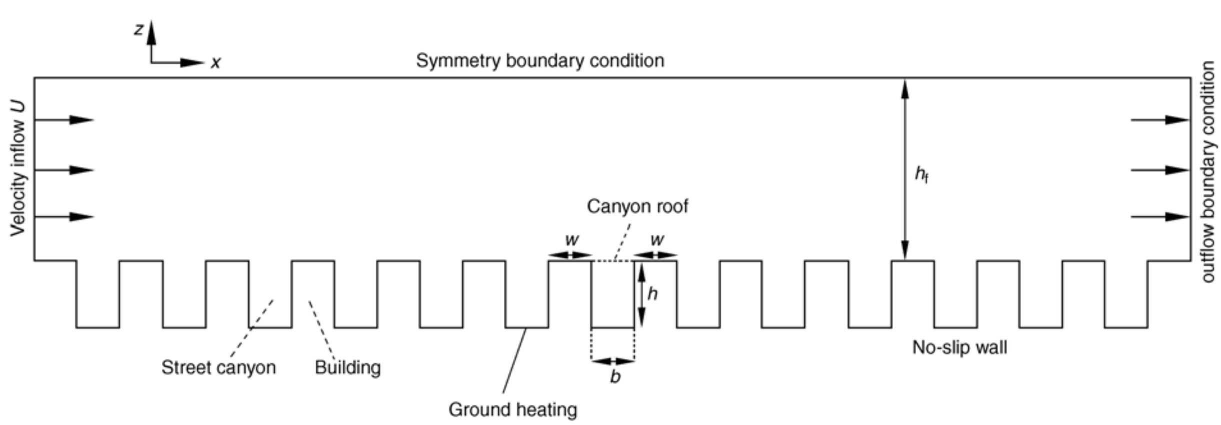

Fig. 1 The computational domain

3 Model validation

The current CFD model under the isothermal conditions was validated with the water channel experiment (Li et al. 2008). The experiment was performed in a 10 m (long) × 0.3 m (width) × 0.5 m (height) laboratory flume. The height of the building models is 0.1m and the Reynolds number based on the building height is $Re = 5.6 \times 10^4$. The vertical mean $\overline{w}$ and fluctuating $(\overline{w'w'})^{1/2}$ wind along the roof of the street canyon of $h/b = 1$ are compared (Fig. 2). In addition to the water channel experiment, the 3D LES (Liu et al. 2005) and 2D k-ε turbulence modeling (Li et al. 2005) results are shown. For the mean vertical wind, the current 2D k-ε turbulence modeling results agree well with the previous results. A mild discrepancy is observed for the vertical fluctuating wind between the current k-ε turbulence model and the water channel experiment. This is likely due to the inherent limitation of the eddy-viscosity model. Although the magnitudes of the vertical fluctuating wind exhibit slight difference, the shape of the profile of the current model shows better agreement with the LES (Liu et al. 2005) compared with that of Li et al. (2005). This evidently suggests the merit of using the eddy-viscosity model for $\overline{w'w'}$ over the TKE approach. Moreover, it is demonstrated that the accuracy of the current model is acceptable for comparing the ventilation performance of street canyon of different aspect ratios.

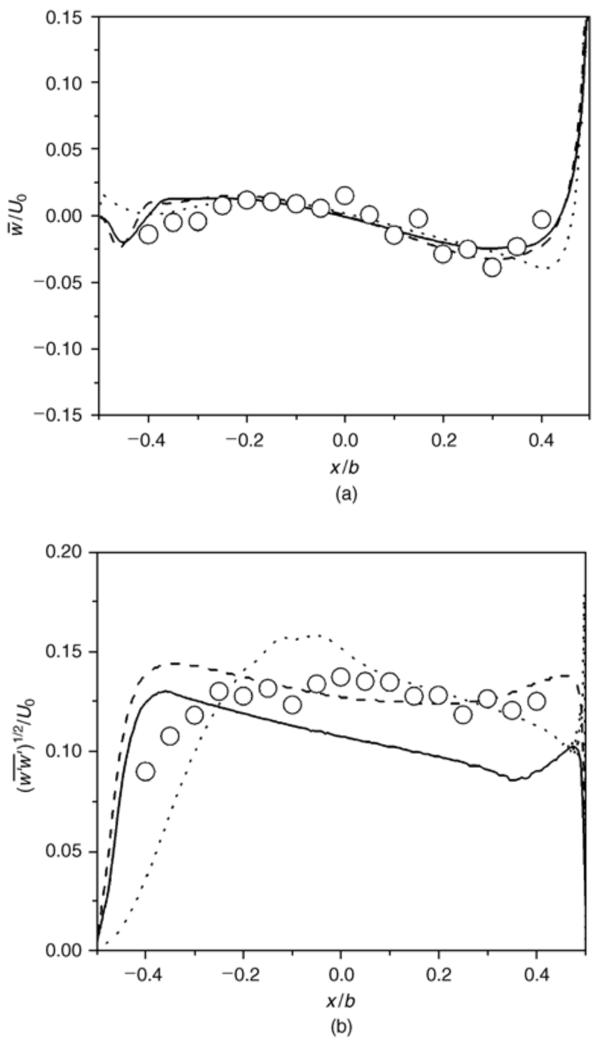

Fig. 2 (a) Dimensionless vertical mean wind $\overline{w}/U_0$ and (b) fluctuating wind magnitude $(\overline{w'w'})^{1/2}/U_0$ along the roof of the street canyon. The current RANS RNG k-ε turbulence model: —; the water channel experiment (Li et al. 2008): ○; the LES result (Liu et al. 2005): ········; and the RANS RNG k-ε turbulence model (Li et al. 2005): – – –

For the ground-heated street canyon, the wind tunnel results of Uehara et al. (2000) were used in the model validation exercise. The experiment was performed at the Japanese National Institute for Environmental Studies (Ogawa et al. 1981). The test section of the wind tunnel is 2 m (height) × 3 m (width) × 24 m (long). Arrays of cubic building models, each with dimensions 0.1m, were placed 0.1m apart in the streamwise direction and 0.05m apart in the spanwise direction to construct a street canyon of $h/b = 1$ (in the streamwise direction). The wind tunnel data at bulk Richardson number $Rb = -0.19$ were used in the model validation exercise. Here, $Rb = gH(\theta_H - \theta_g)/(\theta_g U_H^2)$, where θ_H and U_H are, respectively, the temperature and streamwise velocity at the center of the roof of the street canyon. A CFD model consisting of a ground-heated 2D street canyon at $Rb = -0.21$ replicates the configuration of the wind tunnel experiment. The calculated dimensionless streamwise velocity $\overline{u}/U_0$ and temperature $(\overline{\theta} - \theta_0)/(\theta_H - \theta_0)$ along the vertical centerline of the street canyon agree well with the wind tunnel results (Fig. 3). A gentle peak near the roof level is observed in the current CFD calculation but not in the wind tunnel results. This discrepancy is mainly due to the 3D isolated street canyons used in the wind tunnel experiment but the 2D infinitely long street canyons were considered in the current CFD. This gives rise to the different ground heating configurations.

4 Results and discussion

4.1 ACH for isothermal street canyons of different *h/b*

As shown in Fig. 4, the velocity fields calculated by the current CFD model show that the flow patterns of the street canyons of $0.5 \leqslant h/b \leqslant 2$ fall into the skimming flow regime (Oke 1988). Hence, the recirculation inside the street canyon is isolated from the prevalent wind in the shear layer. As shown in Fig. 4(b), only one recirculation is observed in the street canyon of $h/b = 1$ while two counter-rotating recirculations are observed in the street canyons of $h/b = 0.5$ (Fig. 4(a)) and 2 (Fig. 4(c)). For the

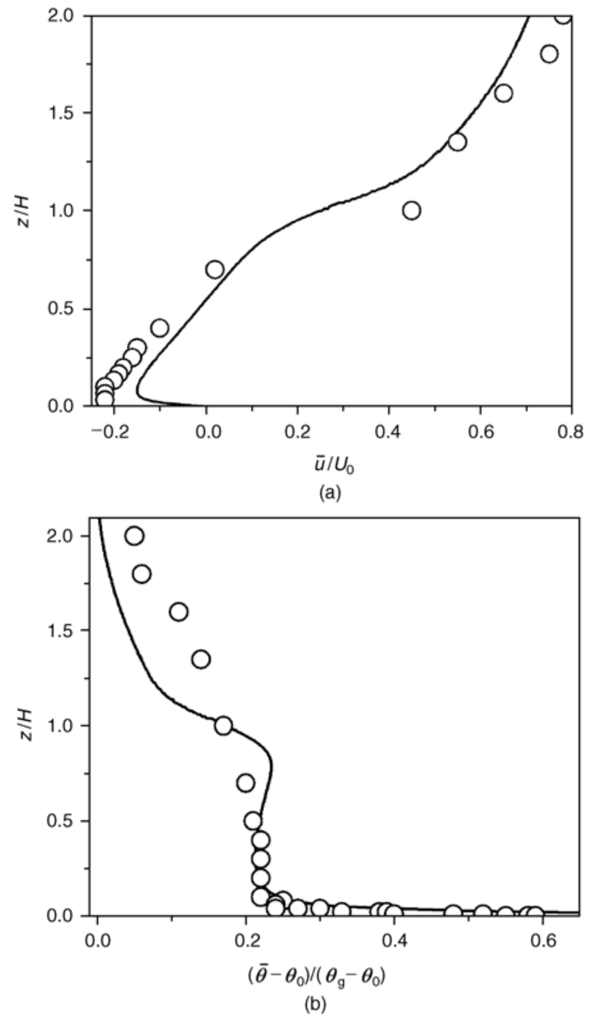

Fig. 3 (a) Dimensionless streamwise mean wind $\overline{u}/U_0$ and (b) average temperature $(\overline{\theta}-\theta_0)/(\theta_g-\theta_0)$ along the vertical centerline of the street canyon. The current RANS RNG k-ε turbulence model $(Rb=-0.21)$: — and wind tunnel experiment $(Rb=-0.19$; Uehara et al. 2000): ○

wider street canyon of $h/b=0.5$, a large clockwise-rotating recirculation is formed at the center core together with a small counterclockwise-rotating recirculation developed at the ground-level leeward corner (Fig. 4(a)). For the narrower street canyon of $h/b=2$, two vertically aligned counter-rotating recirculations are developed (Fig. 4(c)). The characteristic skimming flow patterns observed suggests that the ventilation by the mean flow is negligible while the turbulent transport is a dominant factor affecting the air quality inside the street canyon.

The above qualitative discussion of air quality inside a street canyon can be further explored by comparing the values of $\overline{\mathrm{ACH}}$ and ACH′ (Table 2). Here, the dimensionless variable ACH/(V/T) (Liu et al. 2005) is reported, where V is the volume of the street canyon of $h/b=1$ and $T\,(=H/U_0)$ the reference time scale. For all the h/b considered, ACH′

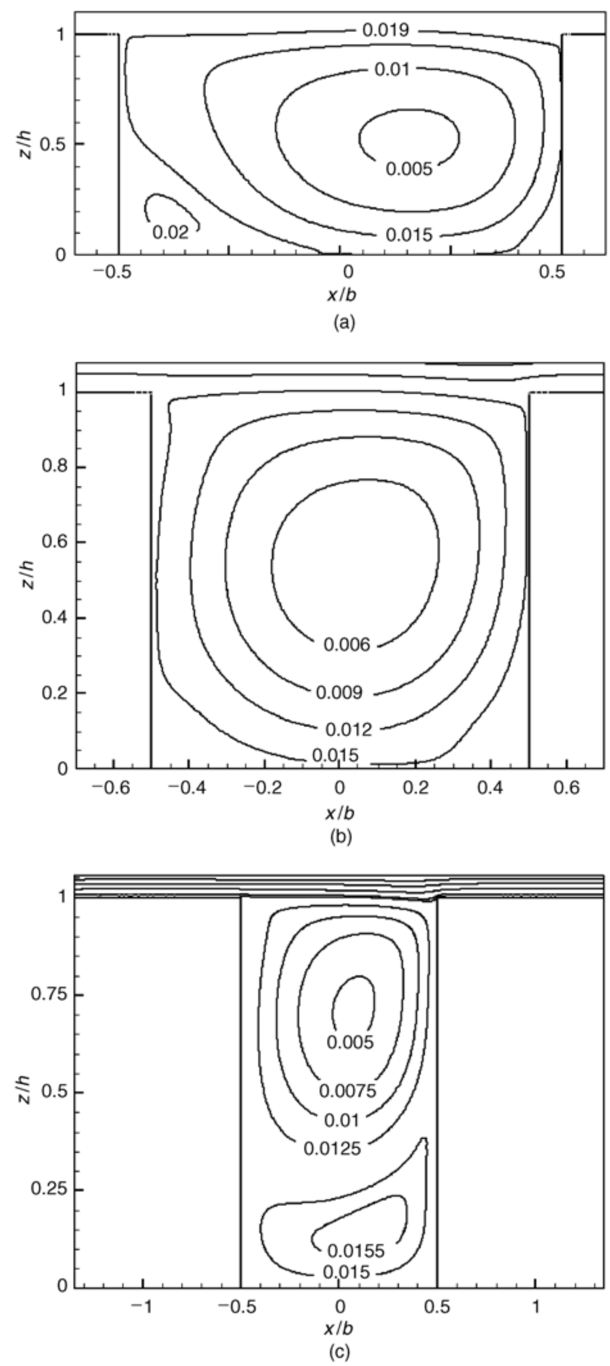

Fig. 4 Stream-function for isothermal street canyons of $h/b=$ (a) 0.5, (b) 1, and (c) 2

accounts for about 90% of the total ACH that in turn signifies the importance of turbulence to the ventilation. The current results are consistent with the previous work done which also found that turbulence is important to street canyon ventilation (Louka et al. 1998; Baik and Kim 2002; Kim and Baik 2003). The values of ACH for the street canyons of $h/b=0.5$ and 1 are almost the same and are about two folds of their $h/b=2$ counterpart. These results are in line with those of Li et al. (2005) and LES (Liu et al. 2005; Table 3) as well. The largest deviation, compared with the LES, is about 20% for both the eddy-viscosity (current result) and the isotropic turbulence (Li et al. 2005) approaches. Therefore, the velocity fluctuation estimated by both approaches is of acceptable accuracy.

The profiles of the dimensionless vertical mean $\overline{w}/U_0$ and fluctuating $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ velocities along the roof of the street canyons of different h/b are compared in Fig. 5. For the mean wind profiles, sharp peaks near the windward boundary are observed for all the h/b tested. It is because the free-stream wind flow hits the windward wall directly and subsequently causes the singular peak. In addition to the sharp peaks observed, the upward mean wind on the leeward side and the downward mean wind on the windward side are consistently observed for all the h/b tested. This is influenced by the clockwise-rotating recirculation which is generated inside the street canyon (Fig. 4). For the vertical fluctuating velocity, larger magnitude is observed on the leeward side for all the h/b tested. A slight increase in the magnitude of fluctuating velocity is observed with increasing h/b, but the difference is not obvious.

Both the shape and magnitude of the mean wind and turbulence are found to be similar to each other for the street canyons of $0.5 \leqslant h/b \leqslant 2$. This could be due to the characteristic flow patterns (skimming flow regime) for all the h/b tested in this paper. According to Oke (1988), the other two flow regimes, the wake interference and the isolated roughness, would be observed for further reduction in h/b. The different flow regimes partially contributes to the distinction observed in the wind profiles of street canyon of $h/b = 0.5$ compared with the other two cases.

Table 2 Dimensionless $\overline{\text{ACH}}$, ACH′, and ACH calculated by the current k-ε turbulence model for street canyons of different h/b in isothermal conditions where V is the volume of the street canyon of $h/b = 1$ and T is the reference time scale

h/b	$\overline{\text{ACH}}/(V/T)$	$\overline{\text{ACH}}$/ACH	ACH′/(V/T)	ACH′/ACH	ACH/(V/T)
0.5	0.006	10.3%	0.052	89.7%	0.058
1	0.007	11.9%	0.052	88.1%	0.059
2	0.003	9.7%	0.029	93.5%	0.031

Table 3 Comparison of the dimensionless ACH calculated by the current k-ε turbulence model (eddy-viscosity model), LES (Liu et al. 2005) and k-ε turbulence model (isotropic turbulence assumption, Li et al. 2005) where V is the volume of the street canyon of $h/b = 1$ and T is the reference time scale

	Liu et al. (2005)	Current study		Li et al. (2005)	
h/b	ACH/(V/T)	ACH/(V/T)	Deviation	ACH/(V/T)	Deviation
0.5	0.06	0.058	3%	0.063	5%
1	0.05	0.059	18%	0.058	16%
2	0.025	0.031	24%	0.020	20%

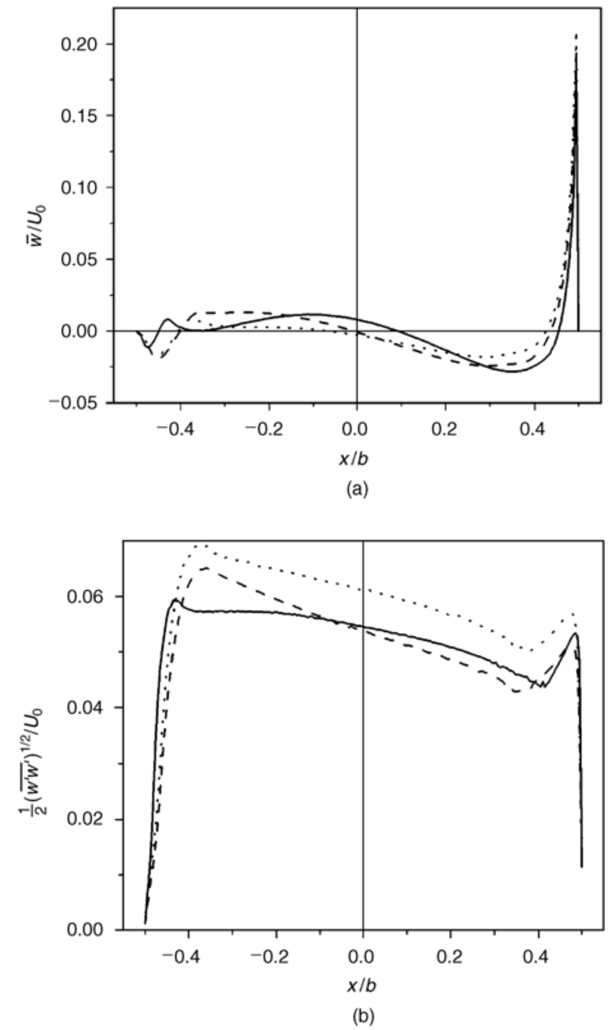

Fig. 5 Dimensionless (a) vertical mean wind $\overline{w}/U_0$ and (b) fluctuating wind magnitude $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ along the roof of the street canyons. $h/b = 0.5$: —; $h/b = 1$: – – –; $h/b = 2$: ········

4.2 ACH for ground-heated street canyon at different *Ri*

The wind flow patterns for a ground-heated street canyon of $h/b = 1$ at $Ri = -1$, -2.5, and -5 are shown in Fig. 6. Upon ground heating, a secondary counterclockwise-rotating recirculation is initiated at the ground-level windward corner. The size (strength) of the secondary recirculation increases with decreasing Ri (more buoyancy-driven). As a result, the buoyancy-driven flow pushes up the clockwise-rotating primary recirculation at the center core. This change in mean flow structure leads to an improved ventilation performance of the street canyon. The dimensionless variable ACH/(V/T) is found to increase from 0.059 to 0.128 while Ri decreases from 0 to -5 (Table 4). Both the $\overline{\text{ACH}}$ and ACH′ are found to increase implying that both the mean wind and the turbulence are strengthened by buoyancy. Moreover, as Ri decreases from 0 to -5, $\overline{\text{ACH}}$/ACH increases from 11.9%

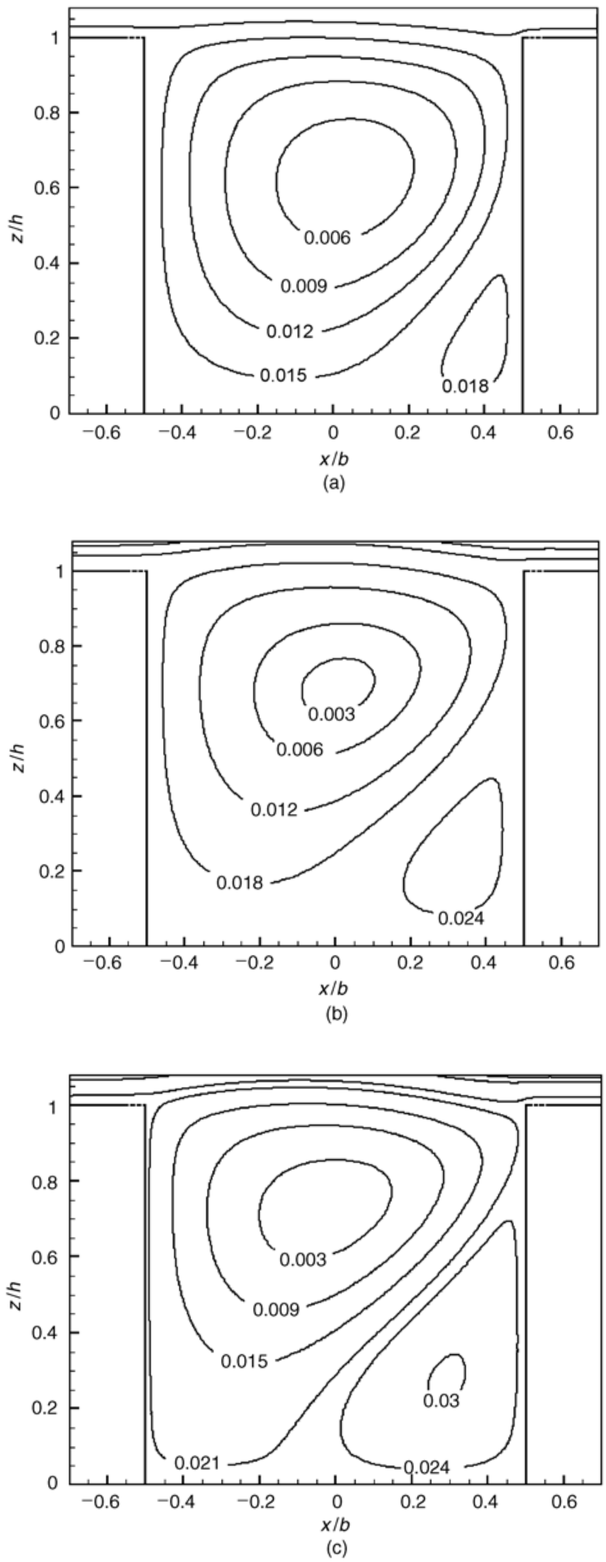

Fig.6 Stream-function for ground-heated street canyons of $Ri =$ (a) -1, (b) -2.5, and (c) -5

Table 4 Dimensionless $\overline{\text{ACH}}$, ACH′, and ACH calculated by the current k-ε turbulence model for the ground-heated street canyon ($h/b = 1$) at different Ri where V is the volume of the street canyon of $h/b = 1$ and T is the reference time scale

Ri	$\overline{\text{ACH}}/(V/T)$	$\overline{\text{ACH}}$/ACH	ACH′/(V/T)	ACH′/ACH	ACH/(V/T)
0	0.007	11.9%	0.052	88.1%	0.059
–1	0.012	17.6%	0.056	82.4%	0.068
–2.5	0.028	28.3%	0.071	71.7%	0.099
–5	0.039	30.5%	0.089	69.5%	0.128

to 30.5%. The mean wind is thus becomes increasingly important as ground heating is introduced into the street canyon.

The values of ACH calculated by the current CFD are compared with the previous results (Fig. 7). Xie et al. (2006) analyzed their RANS k-ε turbulence modeling results to develop the empirical correlation between ACH and Ri. An improved agreement is observed for larger Ri. It is because Xie et al. (2006) focused on the lower Ri ($0 \geqslant Ri \geqslant -50$) and therefore concentrated more on the results at lower values of Ri.

The dimensionless vertical mean $\overline{w}/U_0$ and fluctuating velocity $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ along the roof of the street canyons at different Ri are also compared (Fig. 8). The vertical mean velocity on the windward (leeward) side decreases (increases) with decreasing Ri. Owing to the ground heating, the primary recirculation at the center core of the street canyon is pushed up by the secondary recirculation originated at the ground-level windward corner. The clockwise-rotating primary recirculation therefore enhances the upward and downward $\overline{w}$, respectively, on the leeward and windward sides.

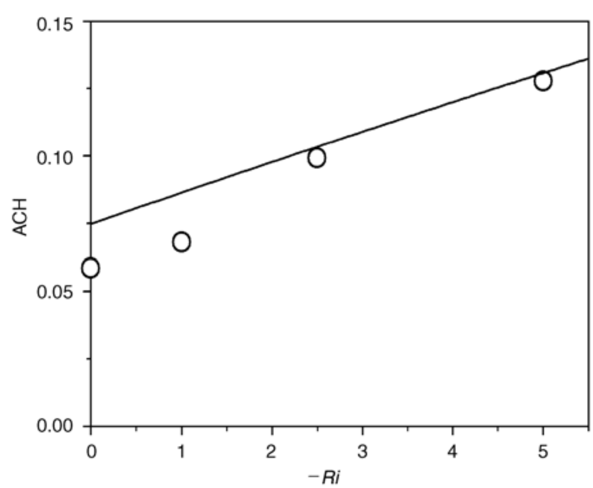

Fig. 7 ACH expressed as a function of Ri for the ground-heated street canyon of $h/b = 1$. The current RANS RNG k-ε turbulence model: ○ and the linear regression using the k-ε turbulence modeling results of Xie et al. (2006): ——

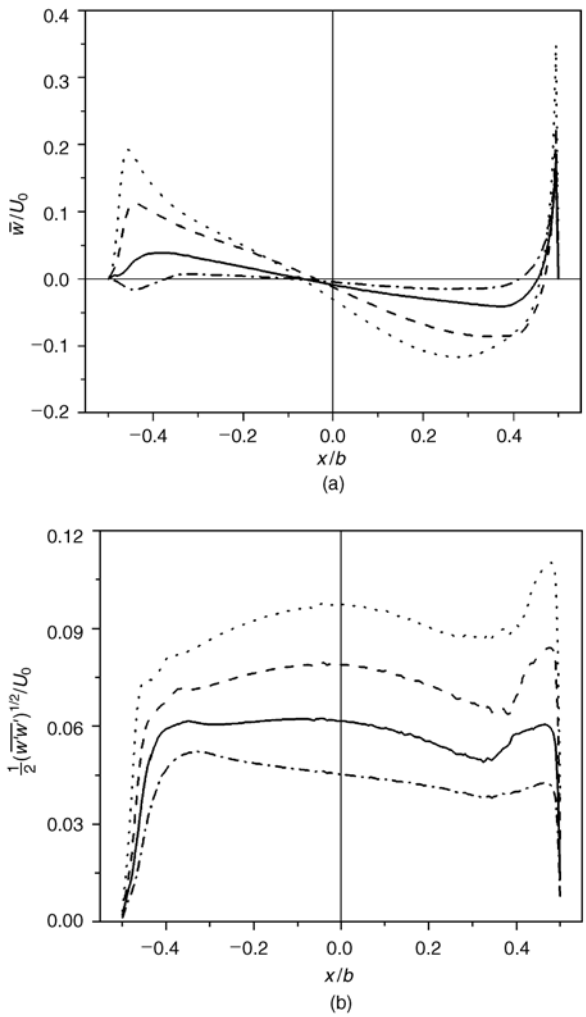

Fig. 8 Dimensionless (a) vertical mean wind $\overline{w}/U_0$ and (b) fluctuating wind magnitude $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ along the roof of the street canyon of $h/b=1$ at $Ri=-1$: ——; $Ri=-2.5$: – – –; $Ri=-5$: ········; $Ri=0$: –·–·–

The magnitude of the fluctuating wind velocity along the roof of the street canyon also increases with decreasing Ri (Fig. 8(b)). The profiles of $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ are of similar shape while the magnitude increases with decreasing Ri. This finding signifies that the velocity fluctuation is activated by buoyancy with similar magnitude along the entire roof of the street canyon rather than only on the leeward or windward side.

5 Conclusions

The ventilation for the street canyons of different h/b and Ri are investigated numerically by solving the RANS equations equipped with the RNG k-ε turbulence model. To quantify the contributions of the mean wind and turbulence to street canyon ventilation, the $\overline{\text{ACH}}$ and ACH′ are compared.

As shown in the CFD results, the flow of the street canyons of $h/b=0.5$, 1, and 2 in isothermal conditions belong to the skimming flow regime. The $\overline{\text{ACH}}$ and ACH′ for the street canyons of $h/b=0.5$ and 1 are about the same; however, they are larger than their $h/b=2$ counterpart by two folds. The ACH′ is much larger than the $\overline{\text{ACH}}$ for all the h/b studied. The results suggest that the street canyon ventilation is driven mainly by the turbulence rather than the mean wind. The dimensionless vertical mean $\overline{w}/U_0$ and fluctuating $[\frac{1}{2}(\overline{w'w'})^{1/2}]/U_0$ wind velocities along the roofs of the street canyons of $0.5 \leqslant h/b \leqslant 2$ exhibit similar shape and magnitudes. These similarities are mainly due to the alike flow patterns in the skimming flow regime in which the cases tested fall into.

For the ground-heated street canyon of $h/b=1$, a secondary recirculation is formed at the ground-level windward corner because of buoyancy. Its size (strength) increases with decreasing Ri that pushes the primary recirculation at the center core upward to the roof-level leeward corner. Both the roof-level mean wind and turbulence are enhanced by the ground heating as demonstrated by the increasing $\overline{\text{ACH}}$ and ACH′ with decreasing Ri. At $Ri=-5$, the $\overline{\text{ACH}}$ accounts for 30.5% of the total ACH demonstrating a substantial contribution from the mean flow at buoyancy-driven flow.

Acknowledgements

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