# CFD ANALYSIS OF POLLUTANT REMOVAL MECHANISM IN URBAN STREET CANYONS

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## Abstract

A series of parametric tests were performed in this study to elucidate the mechanisms of ventilation and pollutant removal from an urban canopy layer. Idealized two-dimensional (2D) street canyons of different building-height-to-street-width (aspect) ratios ($h/b$) were considered to investigate how the street canyon geometry affects the recirculating wind, flow regimes and pollutant transport. We focused on a wide range of aspect ratio $0.067 \leq h/b \leq 2.5$ in which a variety of flow regimes, namely skimming, wake interference and isolated roughness, were covered. Computational fluid dynamics (CFD) based on the Reynolds-averaged Navier-Stokes (RANS) equations with the Renormalization Group (RNG) $k$-$\varepsilon$ turbulence model was used. The CFD results revealed the relationship among aspect ratio, recirculation development, ventilation, and pollutant removal and re-entrainment. The ventilation rate and pollutant removal rate were partitioned into their mean and fluctuating components to examine the effectiveness of contaminant removal from street canyons of different aspect ratios.

**Key words:** ventilation rate (VR), pollutant removal rate (PRR), street canyon

## 1 INTRODUCTION

Street canyon is the basic morphological unit that constructs the whole city. A typical street canyon's geometric is a narrow street with continuous buildings on both sides. Micro-scale meteorological processes lead to a distinct local climate in these units (Oke 1988). In an idealized 2D street canyon where the prevalent wind is perpendicular to the infinitely long street, those local micro-scale meteorological processes can generate persistent recirculating wind below the canopy level. Hence, the ventilation and pollutant removal can only take place vertically through the roof of street canyon (DePaul 1986, Nakamura 1988). In this situation, because of the blockage of leeward and windward buildings, the ground-level air quality is often very poor. Street canyon aspect ratio, *h/b,* (*h* is the building height and *b* the street width; Kim and Baik 2001, Jeong and Andrews 2002, Baik et al. 2003) is one of the major environmental parameters for an idealized 2D street canyon determining the regime of micro-scale climate, ventilation and pollutant removal. This paper focuses on the relation between aspect ratio, and air ventilation and pollutant removal performance in idealized 2D street canyons under isothermal conditions. CFD simulations for street canyons of aspect ratio in the range $0.067 \leq h/b \leq 2.5$ covering the three flow regimes, namely skimming flow, wake interference and isolated roughness (Oke 1988), were performed. The ventilation rate (VR) and pollutant removal rate (PRR) were also calculated based on the CFD results.

## 2 METHODOLOGY

The RANS RNG $k$-$\varepsilon$ turbulence model (Yakhot and Orszag 1986) was used in isothermal and incompressible conditions. The computational domain (Figure 1) consists of 13 identical street canyons evenly placed in the streamwise direction under the shear layer with fully developed turbulence before approaching the core of the computational domain (Meroney et al. 1996). The prevalent wind is prescribed by an inflow with a streamwise velocity profile $U = 0.1753(z_f/h_f)^\alpha$ m s$^{-1}$ at the upstream boundary of the shear layer. An outflow boundary is adopted at the downstream outflow. No-slip wall boundary conditions are used on all walls, roofs and streets. An area source of uniform pollutant concentration $\Phi_0 = 1$ is set on the ground of the central street. The street canyon aspect ratio is in the range of 0.067 to 2.5. Nineteen sets of CFD simulations, in which each domain was discretized into meshes over 1 million grid points, were performed.

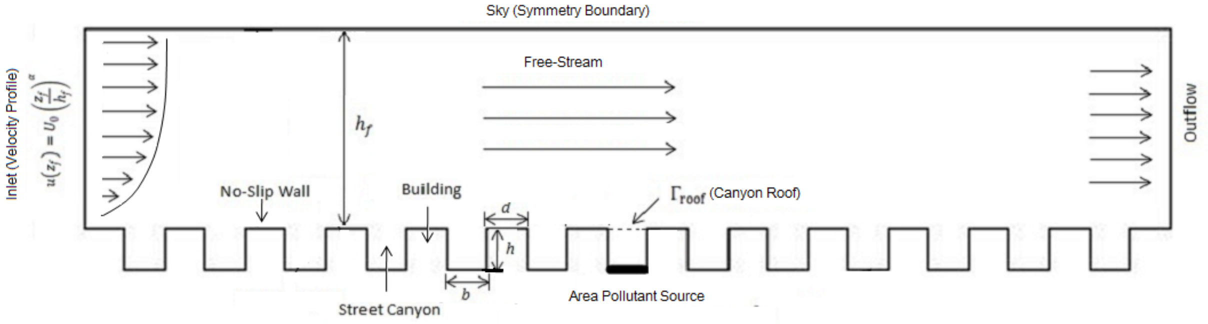

Figure 1. Schematic of the CFD computational domain and boundary conditions for wind flow and pollutant transport in idealized 2D street canyons.

The parameters used to estimate the ventilation and pollutant removal performance are ventilation rate (VR) and pollutant removal rate (PRR) proposed by Cheng et al. (2008). VR and PRR are further divided into their respective mean and fluctuation components as below

$$\mathrm{VR} = \overline{\mathrm{VR}} + \mathrm{VR}' \int_{\Gamma_{roof}} \overline{w}_{+} + \int_{\Gamma_{roof}} \sqrt{-\frac{1}{2}\nu_t \frac{\partial \overline{w}}{\partial z} + \frac{1}{6} k}\, dx \tag{1}$$

$$\mathrm{PRR} = \overline{\mathrm{PRR}} + \mathrm{PRR}' \int_{\Gamma_{roof}} \overline{w}\overline{\Phi} - \int_{\Gamma_{roof}} D_t \frac{\partial \overline{\Phi}}{\partial z} dx\,. \tag{2}$$

## 3 VENTILATION AND POLLUTANT REMOVAL PERFORMANCE

The CFD results (both VR and PPR) are decomposed into their mean and fluctuating components (Figure 2). Apparently, over 80% of the total VR is contributed from $\mathrm{VR}'$ that demonstrates the dominance of turbulent transport in the ventilation in all regimes and so does $\mathrm{PPR}'$ to PPR except in the isolated roughness regime. The result in turn suggests the importance of turbulence in both ventilation and pollutant removal in street canyons. In the skimming flow regime (*h/b*≥0.25), the (normalized) VR has nearly no change ($\approx 0.05 U_0 b$), this in fact shows that the ventilation is less dependent on aspect ratios. The (normalized) PRR achieves its maximum ($\mathrm{PRR}/U_0 \Phi_0 b = \Omega \approx 0.0026$) in the range of 0.6≤*h/b*≤0.8 and then decreases gradually after *h/b*≥1. In the wake interference regimes (0.125≤*h/b*≤0.25), the VR (both $\overline{\mathrm{VR}}$ and $\mathrm{VR}'$) increases with decreasing aspect ratio. Moreover, the PRR shows a local minimum in this regime. In the isolated roughness regime (*h/b*≤0.125), almost no change in VR is found but a slight bounce back of PRR with reducing aspect ratio is observed. These different mechanisms of ventilation and pollutant removal will be explained in detail in the next section.

### 3.1 Isolated roughness regime

When the street canyon is sufficiently wide to allow the free-stream air in the shear layer entraining down to the ground level (aspect ratio in the range of *h/b*≤0.125), the micro-scale climate in most of the street canyon, especially on the windward side, is aligned with the prevalent one (Figure 4I-III). The wider street and more fresh air entrainment improves PRR (Figure 2b) in which the mechanism is divided into two aspects. On the leeward side, the pollutant is emitted from the ground level, carried upward along the leeward façade and finally diluted quickly around the roof-level leeward corner. On the windward side, pollutant emitted from ground level and then be carried by the entraining free-stream air that promotes both VR and PRR directly. With the enhancement of mean flow, the $\overline{\mathrm{VR}}$ and $\overline{\mathrm{PRR}}$ increase with decreasing aspect ratio (Figure 2b). While the entrainment carries fresh air down to the street canyon that improves the air quality, its drawback is the pollutant re-entrainment at roof-level: the pollutant originated from the street canyon turns back into the street canyon. As shown in Figure 3I-II, the mean vertical wind $\overline{w}$ carries the mean vertical pollutant flux $\overline{w}\overline{\Phi}$ along the roof level. Thus, the pollutant re-entrainment follows the free-stream air entrainment and ends up with prolonged pollutant residence. $\overline{\mathrm{PRR}}$ is the area (integral) below the mean vertical pollutant flux shown in Figure 3. Due to the obviously larger positive area of $\overline{\mathrm{PPR}}$, the (net) impact of pollutant re-entrainment is insignificant (Figure 2b).

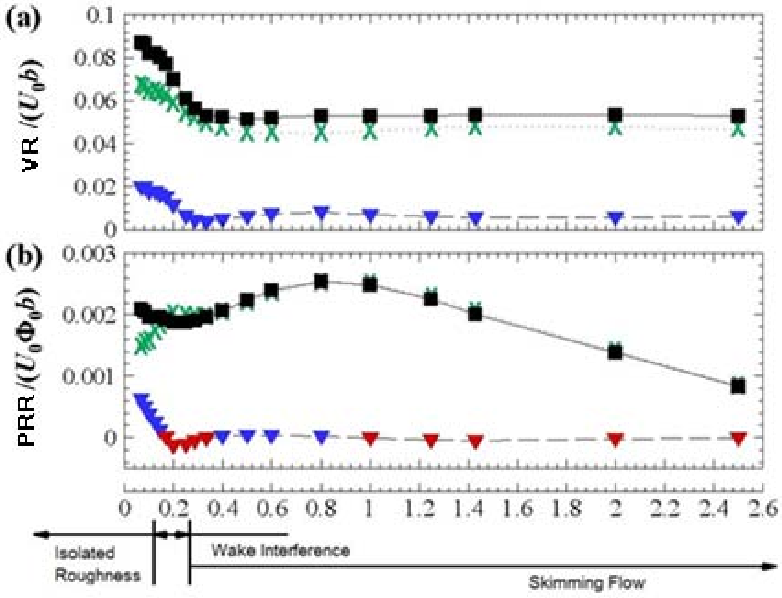

Figure 2. Ventilation and pollutant removal for idealized 2D street canyons of aspect ratio in the range 0.067≤h/b≤2.5. (a). Normalized ventilation rate VR; (b). normalized pollutant removal rate PRR. ▼: mean component; **X**: turbulent component; ■: total calculated by the current *k-ε* RNG RANS CFD. Filled red symbols represent negative value (i.e. pollutant re-entrainment).

### 3.2 Wake interference regime

Street canyon of aspect ratio in the range of 0.125≤*h/b*≤0.25 falls in the wake interference regime (Figure 4IV-VI). In this regime, the street is only wide enough to accommodate two clockwise-rotating recirculations in the streamwise direction, but cannot allow the free-stream air in the shear layer entrains down to the ground level of the street canyon. On the leeward side, the ventilation and pollutant removal mechanism is similar to those in isolated roughness regime. On the windward side, as the fresh air entrainment does not touch down on the ground level, this results in a poor pollutant removal by prevalent wind. Therefore, $\mathrm{VR}'$ and $\mathrm{PRR}'$ have important effects in ventilation and pollutant removal in this flow regime, respectively. The negative mean vertical wind $\overline{w}$ (Figure 3III) induces the fresh air entrainment from the shear layer. Similar to the entrainment in the isolated roughness regime, the disadvantage of fresh air entrainment is the pollutant re-entrainment from the roof level signified by the negative mean pollutant flux $\overline{w}\overline{\Phi}$ (Figure 3IV).The integration of $\overline{w}\overline{\Phi}$ across the roof level $\Gamma_{roof}$ is the $\overline{\mathrm{PRR}}$ that is a negative net value. Therefore, the $\overline{\mathrm{PRR}}$ is indeed the pollutant re-entrainment which carries roof-level pollutant back into the street canyon (Figure 2b). On the windward side, the pollutant cannot be removed quickly because of the shallow fresh air entrainment. Eventually, the negative $\overline{\mathrm{PRR}}$ lowers down the overall pollutant removal in which a trough of PRR is observed in the wake interference regime (Figure 2b). Compare this trend of PRR with the increasing VR with decreasing aspect ratio in this regime, we can draw the conclusion that improved ventilation does not necessarily represent better air pollutant removal performance in street canyons. We should assess the air quality in street canyons by concurrent analyses on both ventilation and pollutant.

### 3.3 Skimming flow regime

The isolated recirculations that completely immersed inside the street canyon (Figure 4VII-IX) characterize the wind flow behaviours in the skimming flow regime (*h/b*≥0.25). Positive and negative mean vertical pollutant fluxes are observed, respectively, on the leeward and windward sides of the street canyon. Small vertical components of $\overline{w}$ and $\overline{w}\overline{\Phi}$ are observed and even negative (i.e. pollutant re-entrainment) in some region. Because of the isolated nature of recirculations, turbulence dominates the ventilation and pollutant removal from the street canyon to the shear layer, which is illustrated in Figure 2b. Roof-level turbulence is mainly generated by the mechanical wind shear and the recirculations in street canyon. Moreover, the size of the upper recirculation is about the street width, therefore, the roof-level turbulence will not change much under the same prevalent wind speed that explains the broad flat VR in skimming flow regime. However, increasing $\mathrm{VR}'$ and *h*/*b* suggests the increasing turbulence levels along the roof level of street canyon. The PRR (dominated by $\mathrm{PRR}'$) reduces almost 50% for *h*/*b*≥1. Here, the negative $\overline{\mathrm{PRR}}$ (pollutant re-entrainment) is initiated by the (upper) recirculation on the windward side calculated in this range (Figure 2b). Whereas, the reduced VR is not the major reason for the suppressed PRR. In fact, for *h*/*b*≥1, more than one recirculations are generated in the vertical direction inside the street canyon. The transport processes between them are governed by the relatively weaker turbulent transport. Hence, most pollutant emitted at ground level cannot be carried upward to the roof level but accumulate in the near-ground region in the lower part of the street canyon.

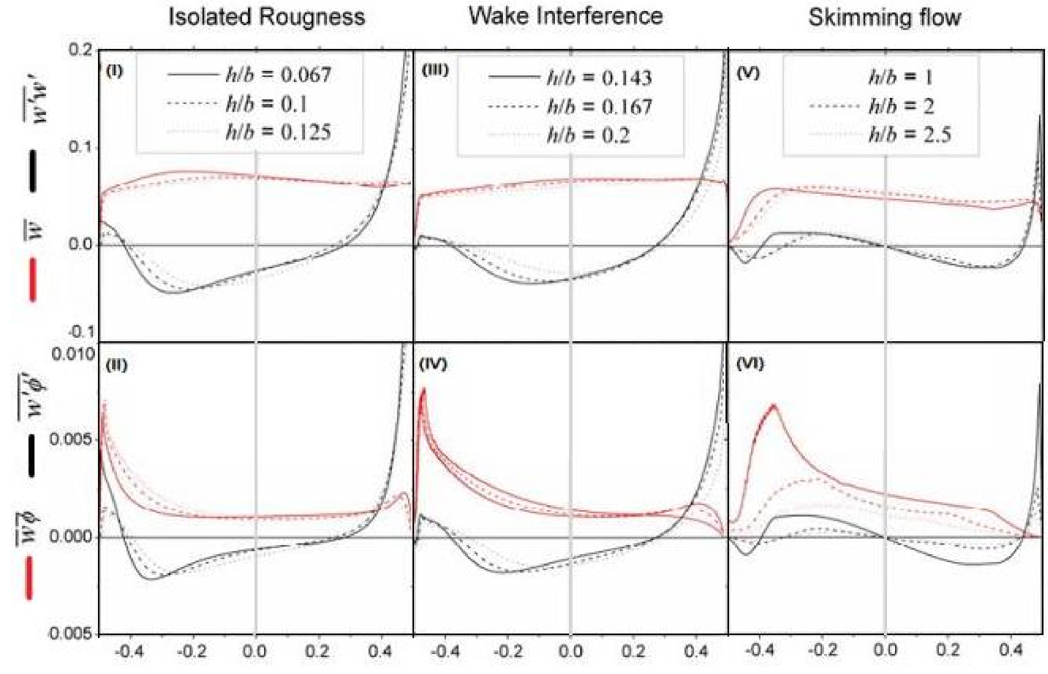

Figure 3. Profiles of roof-level mean vertical wind velocity $\overline{w}$, fluctuating vertical wind velocity $\overline{w'w'}$, mean vertical pollutant flux $\overline{w}\overline{\phi}$ and fluctuating vertical pollutant flux $\overline{w'\phi'}$ against aspect ratios. Dark lines for mean components and red lines for fluctuating components.

## 4 CONCLUSIONS

A series of CFD parametric tests were performed in idealized 2D street canyons of different aspect ratios to elucidate the mechanisms of ventilation and pollutant removal, especially the characteristics of pollutant re-entrainment. The results show that turbulence dominates the ventilation and pollutant removal. A range of characteristic VR and PRR in different flow regimes demonstrates the importance of turbulent transport in urban street canyons. In the isolated roughness regimes ($h/b \le 0.125$), the wider street enhances both VR and PRR. The small aspect ratio improves the free-stream air entrainment down to ground level together with mild pollutant re-entrainment on the windward side of the street canyon. However, the re-entrained pollutant is removed from the street canyon quickly by the entraining free-stream air and eventually the adverse impact is insignificant. The wake interference regime is determined in $0.125 \le h/b \le 0.25$ where the fresh air can entrain below the roof level of street canyons but cannot touch down to the ground of the street. In this regime, the VR increases monotonically with decreasing aspect ratio while the $\overline{\mathrm{PRR}}$ shows a trough. This phenomenon is due to the pollutant re-entrainment instead of poor ventilation. As shown in the CFD results, the roof-level pollutant follows the mean flow then re-entrains back into the street canyon. This finding demonstrates that better ventilation does not necessarily lead to more effective pollutant removal performance for street canyons in urban area. The flow regime changes to skimming flow after $0.25 \ge h/b$ where $\mathrm{PRR}'$ dominates the pollutant removal. For the range of aspect ratios tested, the most remarkable pollutant removal is observed in the range of $0.8 \le h/b \le 1$. The PRR decreases with increasing $h/b$ thereafter. Pollutant re-entrainment for $h/b \ge 1$ only partially explains the deteriorating air quality in street canyons. The major reason for the reduced pollutant removal performance is the counter-rotating recirculations vertically aligned in the street canyon in which the pollutant transport is weak and eventually leads to poorer street canyon air quality.

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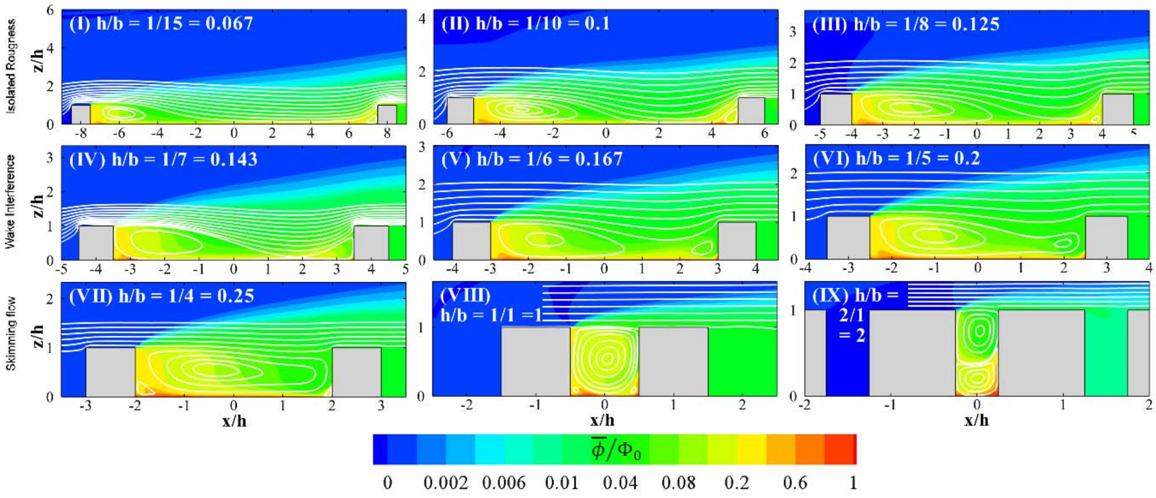

Figure 4. Stream function (lines) in different flow regimes with the pollutant concentration distribution (colour contours) for ground-level uniform area source.