STREET CANYON VENTILATION AND POLLUTION DISPERSION MODELLING

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Abstract:
Owing to the rapid urbanization in recent years, air quality has become a major public concern because of its adverse effect on stakeholders' health. Despite there are many innovative researches focusing on air pollutant transport over the decades, our understanding of air pollutant removal mechanism from urban areas is rather limited. In this paper, the relations among air exchange rate (ACH), pollutant exchange rate (PCH) and friction factor (*f*) are proposed to evaluate the performance of ventilation and pollution removal of street canyons of different building-height-to-street-width (aspect) ratios (ARs) and building shapes using computational fluid dynamics (CFD). Hypothetical urban areas were simplified to idealized computational domains consisting of two-dimensional (2D) street canyons and the Reynolds-averaged Navier-Stokes (RANS) equations with the Renormalization Group (RNG) *k*-*ϵ* turbulence model were adopted for the numerical simulations. It is found that the turbulent component of ACH contributed over 60% to ventilation performance and is linearly proportional to the square root of friction factor ($ACH'' \propto f^{1/2}$) among various types of building shapes. Although a well-defined relation was shown between ACH and *f*, the relation of pollutant transport (or heat transfer) against *f* is not yet concluded because of their diversified behaviours for different building types.

Key words: *Air quality, computational fluid dynamics (CFD), city ventilation, pollutant transport, turbulence model.*

INTRODUCTION

Air pollution problems have aroused considerable public concerns in recent years. In Hong Kong, Environmental Protection Ordinance, such as The Statutory Ban against Idling of Motor Vehicle Engines, a study to review the Air Quality Objectives (AQOs) in Hong Kong, and the latest Indoor Air Quality (IAQ) awareness campaign, has received tremendous attention in the community. In fact, air pollutants, such as ozone (O_3) and particulate matter (PM), can cause serious illness to our respiratory system. Studies of air quality are therefore absolutely paramount to safeguard the health of urban inhabitants.

Air (ACH) and pollutant (PCH) exchange rates are two major indicators comparing the air quality in urban areas. Despite the numerous valuable researches related to air pollutant transport over the decades, our understanding of the removal mechanism of air pollutants from a street canyon to the urban atmospheric boundary layer (UABL) aloft is limited. ACH and PCH (together with average pollutant concentration Θ and pollutant retention time τ as well) were originally suggested by Liu et al. (2005) based on large-eddy simulation (LES) to compare the air quality in a street canyon. In view of the vast computational resource required, Li et al. (2005) used Reynolds-averaged Navier-Stokes (RANS) *k*-*ϵ* turbulence model instead to estimate ACH. Afterwards, the RANS approach was extended to include PCH by Cheng et al. (2008).

In this paper, idealized street canyons of different building-height-to-street-width (aspect) ratios (ARs) and building shapes were used to fabricate hypothetical urban areas with various surface roughness. The simulations were then performed by the commercial computational fluid dynamics (CFD) code FLUENT (FLUENT, 2008). The relations among ACH, PCH, and *f* were calculated based on the CFD results and were used to evaluate the performance of ventilation and pollution removal of idealized street canyons.

METHODOLOGY

In this study, the commercial CFD code, FLUENT, is used to investigate the relations among *ACH, PCH*, and *f*. RANS equations with the Renormalization Group (RNG) *k*-*ϵ* turbulence model were adopted for the numerical simulations.

Isothermal and incompressible flows were assumed in the simulations with the continuity equation

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \qquad (1)$$

and the momentum conservation equation in steady state

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial}{\partial x_j} \overline{u_i'' u_j''} \tag{2}$$

where i and j are the conventional tensor notation denoting the streamwise x and vertical z directions, the overbars and double primes denote the ensemble-averaged values and unresolved turbulent quantities, respectively. The variables x_i are the Cartesian coordinates, u_i are the velocity components and $\bar{p}$ is the kinematic pressure.

The Reynolds stress tensors R_{ij} (= $-\overline{u_i'' u_j''}$) are modelled by the Boussinesq hypothesis

$$-\overline{u_i'' u_j''} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ik} k \tag{3}$$

where ν_t (= $C_\mu k^2/\varepsilon$) is the kinematic turbulent viscosity, C_μ (= 0.0845) is a model constant, δ_{ik} is the Kronecker delta, k is the turbulence kinetic energy (TKE) and ε is the TKE dissipation rate. The transport equations for TKE

$$\bar{u}_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\alpha_k \nu_{eff} \frac{\partial k}{\partial x_i} \right) + P_k - \varepsilon \tag{4}$$

and TKE dissipation

$$\bar{u}_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\alpha_\varepsilon \nu_{eff} \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} P_k - \left[C_{2\varepsilon} + \frac{C_\mu \eta (1 - \eta/\eta_0)}{1 + \beta \eta^3} \right] \frac{\varepsilon^2}{k} \tag{5}$$

where P_k (= $\nu_t \left(\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right) \times \left(\partial \bar{u}_i / \partial x_j \right)$) is the TKE production, ν_{eff} (= ν + ν_t) is the effective kinematic viscosity, α_k and α_ε are the inverse effective Prandtl numbers for k and ϵ, respectively, η (= Sk/ε), η_0 (= 4.38) and β (= 0.012) are the RNG modifiers, and S (= $(2S_{ij}S_{ij})^{1/2}$) is the modulus of the mean rate of strain tensor.

The aerodynamic resistance is measured by friction factor f that is defined as

$$f = \frac{\Delta p \, D_h / L}{U^2/2} \tag{6}$$

where L is the channel length, U is the mean flow speed, D_h is the hydraulic diameter and Δp is the drop in kinematic pressure over the distance L.

The ventilation performance is measured by ACH that is defined as

$$ACH = \overline{ACH} + ACH'' = \frac{1}{\Gamma_{\text{roof}}} \left(\int_{\Gamma_{\text{roof}}} w_+ \big|_{\Gamma_{\text{roof}}} d\Gamma + \int_{\Gamma_{\text{roof}}} w_+'' \big|_{\Gamma_{\text{roof}}} d\Gamma \right) \tag{7}$$

where w is the vertical velocity component, Γ_{roof} is the roof area just above the street canyon and the subscript + signifies that only the upward flows are considered in Equation (7).

The pollutant removal performance is measured by *PCH* that is defined as

$$PCH = \overline{PCH} + PCH'' = \frac{1}{\Gamma_{\mathrm{roof}}}\left(\int_{\Gamma_{\mathrm{roof}}} \overline{w}\,\overline{\phi}\Big|_{\Gamma_{\mathrm{roof}}} d\Gamma + \int_{\Gamma_{\mathrm{roof}}} \overline{w''\phi''}\Big|_{\Gamma_{\mathrm{roof}}} d\Gamma \right) \tag{8}$$

where ϕ is the pollutant concentration.

The computational domain (Figure 1), parameters (Figure 2) and the eight types of idealized building models (Figure 3) used in the CFD are simplified to fabricate hypothetical urban roughness elements.

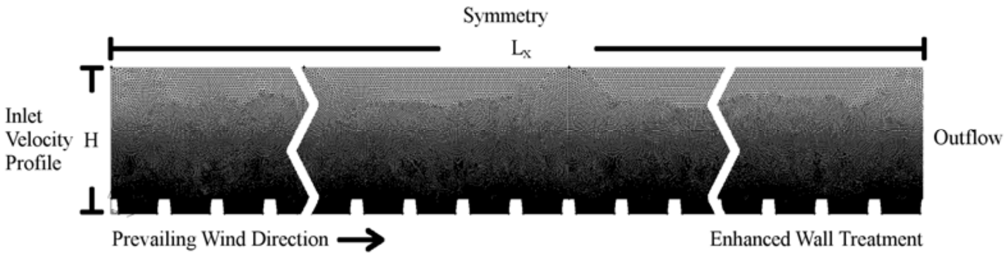

Figure 1. Computational domain.

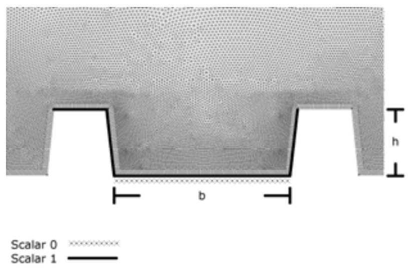

Figure 2. Scalar 0: Ground-level pollutant and Scalar 1: Heat.

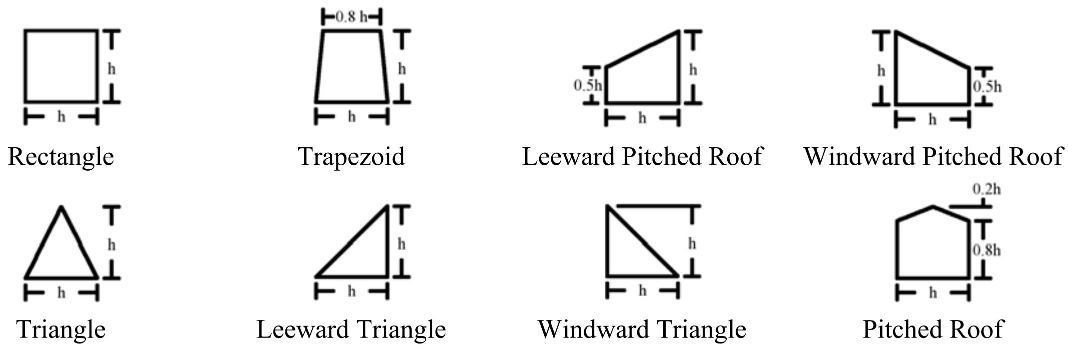

Figure 3. Idealized building shapes.

A total of 144 different types of idealized street canyons were built for the simulations and their configurations were tabulated in Table 1.

Table 1. Configurations of idealized street canyons.

Aspect Ratio *(h/b)*	*b/h*	Number of Street Canyons	L_x/h
0.05	20.00	15.00	315.00
0.08	12.50	25.00	337.50
0.11	9.09	30.00	302.73
0.14	7.14	40.00	325.71
0.17	5.88	45.00	309.71
0.20	5.00	50.00	300.00
0.23	4.35	60.00	320.87
0.26	3.85	65.00	315.00
0.29	3.45	70.00	311.38
0.32	3.13	75.00	309.38
0.35	2.86	80.00	308.57
0.38	2.63	85.00	308.68
0.50	2.00	100.00	300.00
0.75	1.33	130.00	303.33
1.25	0.80	170.00	306.00
2.00	0.50	200.00	300.00
3.00	0.33	230.00	306.67
5.00	0.20	250.00	300.00

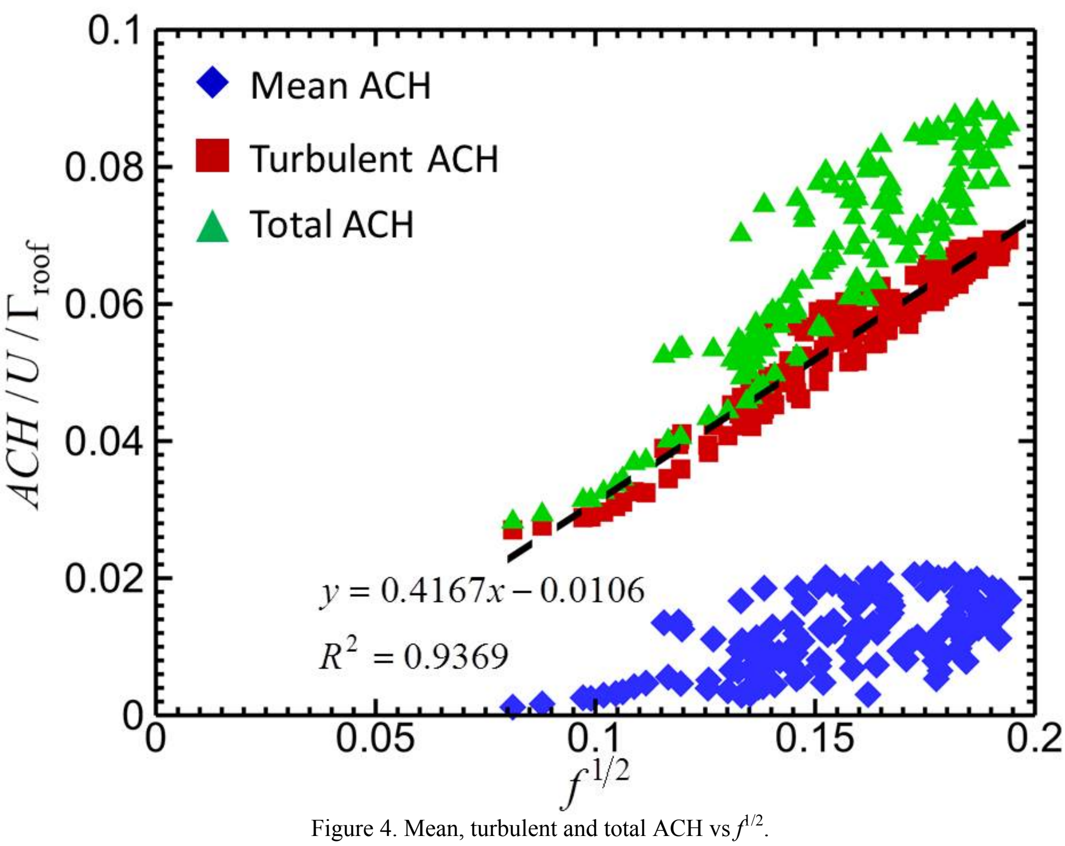

Figure 4. Mean, turbulent and total ACH vs $f^{1/2}$.

RESULTS AND DISCUSSION

The dimensionless ACH of the idealized street canyons were plotted against the square root of friction factor *f* (Figure 4). It is found that the turbulent ACH is linearly proportional to the square root of *f* with the correlation coefficient $R^2 = 0.9369$. It is also noted that the turbulent ACH dominates the ventilation over the street canyons (at least 60% of overall contribution). Therefore, the friction factor *f* could serve as an independent parameter to estimate the minimum ventilation performance of urban areas.

However, the dimensionless PCH against $f^{1/2}$ (Figure 5) exhibit behaviour quite different from its dimensionless ACH counterpart. Although both the ground-level pollutant transport and heat transfer are substantially affected by the turbulent component similar to the mechanism of ACH, the ground-level pollutant transport and the heat transfer are different functions of the friction factor. The ground-level pollutant transport increases with increasing friction factor. On the contrary, the heat transfer decreases with increasing friction factor. A conclusion has not been drawn yet because of this discrepancy in the behaviour of transport processes.

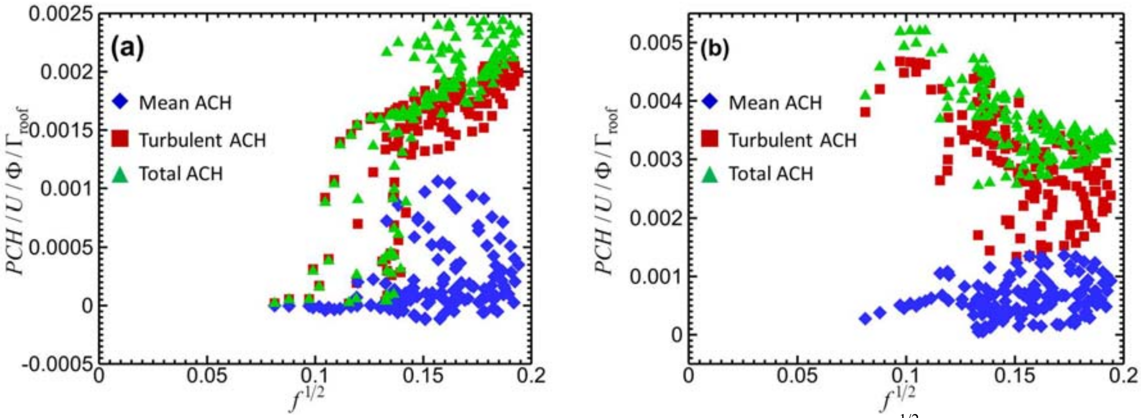

Figure 5. (a) Ground-level pollutant transport and (b) heat transfer vs $f^{1/2}$.

CONCLUSIONS

Idealized street canyons representing hypothetical urban areas were examined with CFD in this paper. Eight different types of building geometry together with configurations of 18 aspect ratios were used to construct a total of 144 idealized street canyons of a range of friction factors. ACH and PCH were calculated with respect to various friction factors that were used to estimate the ventilation efficiency and pollutants removal performance. It is found that both ACH and PCH were dominated by their turbulent components. In particular, the turbulent ACH is found to be linearly proportional to the square root of friction factor ($ACH'' \propto f^{1/2}$) in which the correlation coefficient is up to 0.9369. However, due to the diversified behaviour of PCHs, no conclusion has been drawn in the aspect of PCH against friction factor. In view of the dominance of ACH in street-level ventilation performance and its linearity toward the independent variable, friction factor, regardless of building geometries. Friction factor is therefore suggested to be used as a parameter to evaluate ventilation performance in urban areas.

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