Street-canyon ventilation and pollution removal estimate

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Abstract

The correlations 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 in this paper. Hypothetical urban areas were simplified to computational domains consisting of idealized two-dimensional (2D) street canyons and the Reynolds-averaged Navier-Stokes (RANS) equations with the Renormalization Group (RNG) k-ϵ turbulence model were adopted in the mathematical modelling. It is found that the turbulent components of *ACH* and *PCH* are closely related to *f* while their mean components are rather extraneous.

1 Introduction

Air quality issues have proliferated among public concerns in recent years around the world. Environmental Protection Ordinance, such as “The Statutory Ban against Idling of Motor Vehicle Engines”, a study to reviews of Hong Kong’s Air Quality Objectives (AQOs), and the latest Indoor Air Quality (IAQ) awareness campaign in Hong Kong received tremendous amount of publicity. In fact, air pollutants, such as ozone and particulate matter, can cause serious illness to our respiration system. Therefore, air quality studies are absolutely paramount to protect the health of urban inhabitants nowadays.

ACH and *PCH* are two of the major parameters to assess 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 is limited. Liu et al. (2005) suggested the indicators *ACH*, *PCH*, average pollutant concentration and pollutant retention time to compare the air quality in a street canyon using large-eddy simulation (LES). In view of the vast computational resource required, Li et al. (2005) used RANS k-ϵ turbulence model instead to estimate *ACH* and subsequently Cheng et al. (2008) extended to include *PCH* as well.

In this paper, the configurations of different building types and *AR*s are further investigated. To cope with the diversified building types, the *AR*s are converted into a single dimensionless parameter – friction factor *f*. The RANS RNG k-ϵ turbulence model is utilized to formulate the correlation among ACH, PCH and *f*.

2 Methodology

In this study, the commercial computational fluid dynamics (CFD) code, FLUENT (FLUENT, 2008), is used to investigate the correlation among *ACH*, *PCH* and *f*. The computational methodology is detailed in the following sections.

2.1 Mathematical model

Isothermal and incompressible flows are assumed in the simulation with the continuity equation

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

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 denoting the ensemble-averaged values and unresolved turbulent quantities, respectively. The variables x_i are the Cartesian coordinates, u_i are the velocity components and 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 $\nu_t (= C_\mu k^2/\epsilon)$ is the kinematic turbulent viscosity, C_μ $(= 0.0845)$ is a model constant, δ_{ik} is the Kronecker delta, k is the turbulent kinetic energy (TKE) and ϵ is the turbulent dissipation rate (TDR).

The transport equations for TKE

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

and TDR

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

where $P_k \left(= \nu_t \left(\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right) \left(\partial \bar{u}_i / \partial x_j \right) \right)$ is the production of TKE, $\nu_{eff} (= \nu + \nu_t)$ is the effective kinematic viscosity, α_k and α_ϵ are the inverse effective Prandtl numbers for k and ϵ, respectively, η $(= S\,k/\epsilon)$, $\eta_0 (= 4.38)$ and $\beta (= 0.012)$ are the RNG modifiers, and $S \left(= \sqrt{2 S_{ij} S_{ij}} \right)$ is the modulus of the mean rate of strain tensor.

2.2 Friction Factor

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.

2.3 Air Exchange Rate

The ventilation performance is measured by *ACH*. It is defined as

$$ACH = \overline{ACH} + ACH'' = \frac{1}{\Gamma_{roof}}\left(\int_{\Gamma_{roof}} \overline{w}_{+}|_{\Gamma_{roof}}\, d\Gamma + \int_{\Gamma_{roof}} w''_{+}|_{\Gamma_{roof}}\, d\Gamma\right) \qquad (7)$$

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

2.4 Pollutant Exchange rate

The pollutant removal performance is measured by *PCH*. It is defined as

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

where ϕ is the pollutant concentration.

2.5 Computational domain and building shapes

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

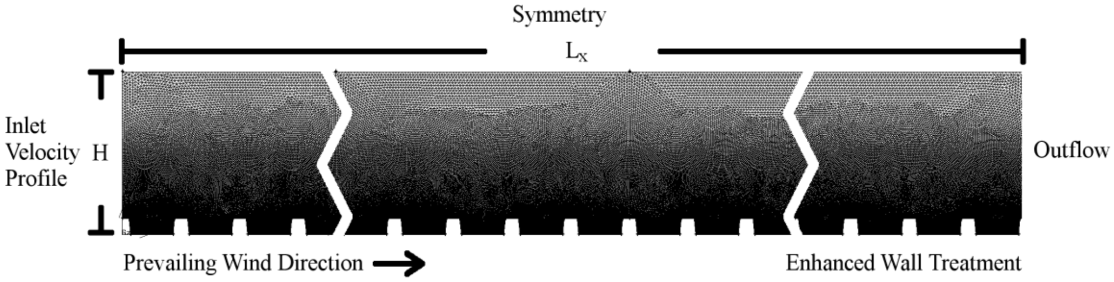

Figure 1: Computational domain.

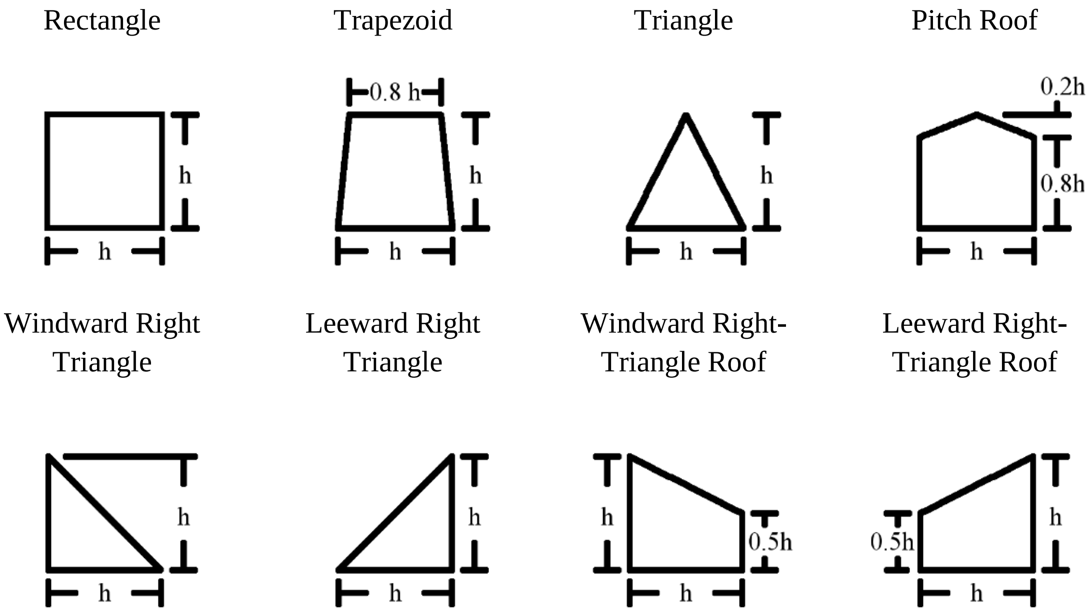

Figure 2: Eight types of street canyons and building types.

3 Major Findings

Figures 3 and 4 summaries the results found in the CFD. Data points with different colour represent the results of all the eight building shapes in the simulation. It is shown that *ACH* and *PCH* are closely related to the friction factor *f*.

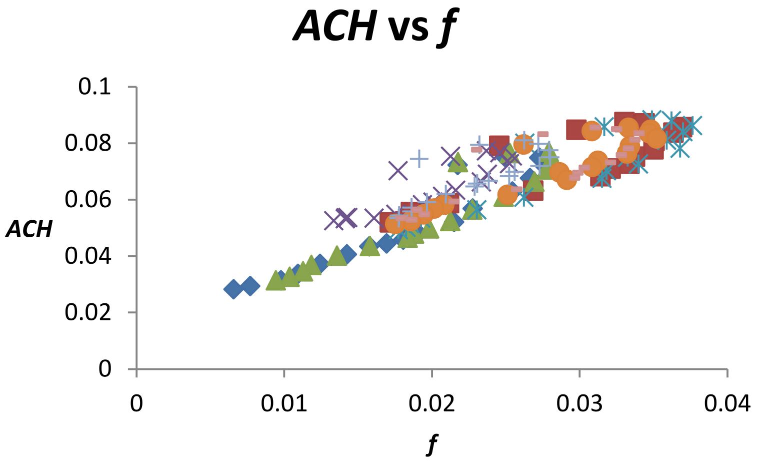

Figure 3: *ACH* plotted as a function of fiction factor *f*

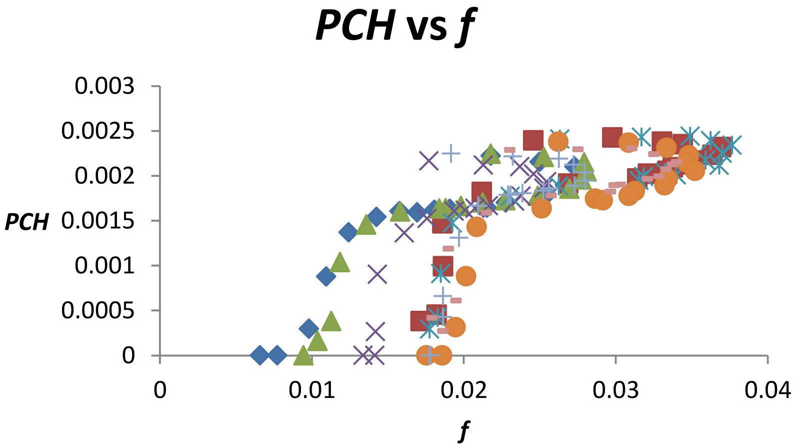

Figure 4: *PCH* plotted as a function of fiction factor *f*

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