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Preliminary study of the parameterisation of street-level ventilation in idealised two-dimensional simulations

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ABSTRACT

In this paper, the flows over idealised two-dimensional (2D) urban street canyons of different building-height-to-street-width (aspect) ratios (ARs) and urban boundary layer (UBL) depths are numerically examined. We attempt to utilise the friction factor f and the air-exchange rate (ACH) to parameterise the aerodynamic resistance and the street-level ventilation performance over urban areas. The aerodynamic resistance is controlled systematically by both the AR and the UBL depth. The AR varies between 0.083 and 1 while the UBL depth between 6h and 1,200h (where h is the building height) so the three characteristic flow regimes are included. Based on the current study, it is found that atmospheric turbulence contributes most to street-level ventilation because the turbulent component of ACH (ACH″) dominates the transport process (at least 70% of the total ACH). Moreover, the collective effect of AR and UBL depth on ACH is reflected by the friction factor. A linear relation between the turbulent ACH and the square root of the friction factor (ACH″ $\propto f^{1/2}$) is revealed in which the correlation coefficient is over 0.9. Extrapolation of ACH″ on predicting the ventilation efficiency covers at least 70% of the total ACH, indicating that using friction factor alone is sufficient to describe the aerodynamic resistance over urban areas of different surface roughness and UBL depth, and to estimate the street-level ventilation performance as well.

1. Introduction

Urban air pollution has received considerable concern owing to its adverse health impact on the public. In particular, heavy vehicular emission is the major source of air pollutants degrading air quality and living standard of urban environment [1,2]. Wind flow over urban areas plays an important role in city ventilation and pollutant dispersion, especially, in the lowest part of (velocity) urban boundary layer (UBL), a zone of reduced mean velocity but enhanced atmospheric turbulence is developed due to urban rough surfaces [3]. The enhanced atmospheric turbulence in turn helps remove aged air and bring in fresh air between the streets and the overlying UBL in order to improve the street-level air quality.

Idealised street canyon, which constitutes the basic units of a city, is commonly adopted in urban air pollution research because of its simplicity. Vast majority of studies have been performed to examine how the key morphological feature of street canyons could influence the UBL flows and the city ventilation behaviour. It was revealed that the flows and city ventilation are affected by a number of morphological quantities, for example, building configuration [4–6], street intersection [7], building-height-to-street-width (aspect) ratios (ARs $= h/b$ where h is the building height and b is the street width) [8–12], packing density [13,14], uneven building layout [15,16], roof shape [17–19]. Apart from ground surface features, atmospheric condition is another factor governing city ventilation performance. Approaching wind direction [20], wind speed [21,22], buoyancy effect [23,24] and traffic induced turbulence [25], to name just a few, have been extensively studied.

In view of the broad spectrum of spatio-temporal scales, parameterisation is commonly adopted to characterise the effect of ground surface roughness on flow features at an affordable computation load. Among various practical approaches, aerodynamic resistance handles the near-wall flow impingement induced by morphological effect. Results of correlating flow resistance over hypothetical urban areas with city ventilation and pollutant removal were first reported by Chung and Liu [26]. Large-

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Nomenclature

ACH	air-exchange rate
$\overline{\text{ACH}}$	mean air-exchange rate
ACH″	turbulent air-exchange rate
$\text{ACH}''_{\text{est}}$	estimated value of turbulent ACH calculated by the estimator
$\text{ACH}_{\text{total}}$	extrapolated value of total ACH calculated by the extrapolation
AR	aspect ratio ($=h/b$)
b	street width (m)
C_μ	empirical modelling constant (=0.0845)
$C_{1\varepsilon}$	empirical modelling constant (=1.42)
$C_{2\varepsilon}$	empirical modelling constant (=1.68)
f	friction factor
h	building height (m)
H	domain height (m)
i, j	indices for tensor notation and the usual summation convention on repeated indices
k	turbulent kinetic energy TKE (m^2 s^{-2})
l	length of a unit of street canyon (m)
PCH	pollutant-exchange rate
$\overline{p}$	kinematic pressure
ΔP_x	background kinematic pressure gradient
ΔP	drop in kinematic pressure
P_k	TKE production ($=\nu_t(\partial\overline{u}_i/\partial x_j + \partial\overline{u}_j/\partial x_i) \times (\partial\overline{u}_i/\partial x_j)$)
Re	Reynolds number ($=U_f h/\nu$)
UBL	urban boundary layer
$\overline{u}_i$	velocity tensor
U_f	free-stream velocity (m s^{-1})
U_m	average wind speed (m s^{-1})
u_*	friction velocity (m s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ν_t	kinematic turbulent viscosity ($=C_\mu k^2/\varepsilon$, m^2 s^{-1})
ν_{eff}	effective kinematic viscosity (m^2 s^{-1})
$\overline{w}$	mean vertical velocity component (m s^{-1})
$\overline{w''w''}$	covariance of vertical velocity (m s^{-1})
x_i	Cartesian coordinates (streamwise x and vertical z directions)
α	wind exponent in power law (=0.25)
α_k, α_ε	inverse effective Prandtl numbers for TKE (=1.393)
δ_{ij}	Kronecker delta
η_0	empirical modelling constant (=4.38)
β	empirical modelling constant (=0.012)
τ_w	wall shear stress (kg m^{-1} s^{-2})
ρ	air density (kg m^{-3})
ε	TKE dissipation rate (m^2 s^{-3})

eddy simulation (LES) was performed to examine the relation between flow resistance and street-level ventilation for idealised two-dimensional (2D) street canyons of different ARs using friction factor f, air-exchange rate (ACH) and pollutant-exchange rate (PCH). It was found that f increases with decreasing ARs (wider building separation) until AR = 0.1 in the isolated roughness regime and decreases thereafter. On the other hand, Wong and Liu [27] investigated how urban roughness affects the vertical dispersion coefficient of pollutant plume in the UBL using LES. The results showed that the plume dispersion strongly depends on f. The vertical dispersion coefficient increases with increasing friction factor in the skimming flow regime (lower resistance) and is more uniform in the regimes of wake interference and isolated roughness (higher resistance). Based on numerical results using RANS k-ε turbulence model, Liu et al. [28] carried out computational fluid dynamics (CFD) sensitivity tests for eight types of idealised building models with various ARs and partitioned the total ACH into its mean and turbulent components. They revealed that the ventilation mechanism over hypothetical urban areas is dominated by turbulent transport. In addition, both analytical solution and CFD results showed that the dimensionless turbulent ACH exhibits a linear behaviour with (the square root of) f regardless of the building shape and flow regime. Recently, Ho and Liu [29] conducted a preliminary set of wind-tunnel measurements to study the ventilation behaviour over idealised urban surfaces. A similar correlation between dimensionless turbulent ACH and (the square root of) f is demonstrated in the experiments of reduced-scale physical modelling.

The aforementioned studies have collectively suggested the crucial roles of building geometry and roughness elements in ventilation over urban areas. Apparently, the friction factor could be used as a quick estimate to street-level ventilation performance regardless of building shapes, ARs and flow regimes. Although numerous combinations of idealised surface have been studied, the impact of random surfaces, such as building height or orientation variability, on flows and ventilation has not been investigated systematically yet. Besides, the influence of UBL depth on city ventilation is another factor that is rarely taken into account in parameterisation. The UBL depth is a spatio-temporal function that ranges from hundreds metres to a few kilometres in diurnal cycle. Moreover, its structure is tightly coupled with the eddy size that alters the vertical turbulent transport and eventually the street-level air quality. Specifically, the scope investigated in this paper covers the following:

- To test the collective effect of different urban configuration and UBL depth on the aerodynamic resistance over rough urban surfaces;
- To estimate the ventilation performance over various urban surfaces in different UBL conditions; and
- To demonstrate the feasibility of using friction factor f and air-exchange rate ACH to quantify the aerodynamic resistance and ventilation performance, respectively, over idealised 2D urban surfaces (but do not intend to serve as a quantitative guideline for street-level ventilation).

The remainder of this paper is structured as follows. The numerical model and boundary conditions (BCs) are described next. The current CFD results are then compared with the previous experimental and modelling data in Section 3. The correlation among surface roughness, UBL depth and ACH is discussed in Section 4. Finally the conclusions are drawn in Section 5.

2. Methodology

In this study, CFD is employed to calculate the flows over idealised 2D street canyons of a range of AR and UBL depth. The commercial CFD code FLUENT [30] is used. The incompressible Reynolds-averaged Navier–Stokes (RANS) equations with the Renormalisation Group (RNG) k–ε turbulence model [31] are adopted in the CFD. Compared with the standard or realizable k–ε turbulence models, the RNG k–ε turbulence model provides an