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A theory of ventilation estimate over hypothetical urban areas

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HIGHLIGHTS

- Ventilation and pollutant removal over hypothetical urban areas are examined by CFD.
- Street canyons consisting of different building shapes are employed.
- Ventilation and pollutant removal are dominated by turbulent transport processes.
- Turbulent air exchange rate is proportional to the square root of friction factor.
- Aerodynamic resistance can serve as an estimate to urban ventilation efficiency.

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ABSTRACT

Urban roughness is a major factor governing the flows and scalar transport in the atmospheric boundary layer (ABL) but our understanding is rather limited. The ventilation and pollutant removal of hypothetical urban areas consisting of various types of street canyons are examined using computational fluid dynamics (CFD). The aerodynamic resistance, ventilation efficiency, and pollutant removal are measured by the friction factor f, air exchange rate (ACH), and pollutant exchange rate (PCH), respectively. Two source configurations of passive tracer, ground-level-only (Tracer 0) and all-solid-boundary (Tracer 1) are employed to contrast their transport behavior. It is found that the ventilation and pollutant removal are largely attributed to their turbulent components (over 60%). Moreover, with a consistent support from analytical solution and CFD results, the turbulent ACH is a linear function of the square root of the friction factor ($\mathrm{ACH}' \propto f^{1/2}$) regardless of building geometry. Tracer 0 and Tracer 1 exhibit diversified removal behavior as functions of friction factor so analytical parameterizations have not yet been developed. In view of the large portion of aged air removal by turbulence, it is proposed that the aerodynamic resistance can serve as an estimate to the minimum ventilation efficiency of urban areas.

1. Introduction

Urban air quality has received considerable public attention because of the adverse health impact on the dense population in urban areas [1–3]. However, our understanding of the relation among building morphology, city ventilation, and pollutant removal from street level is very limited [4,5]. In the urban climate community, a massive effort has been sought to examine the flows [6–8], drag [9–11], accidental release [12–14], scalar removal [15–17], and pollutant retention [18,19] over rough land or building surfaces for decades. Roughness elements modify the near-wall flow structures, leading to increases in aerodynamic resistance and boundary layer depth, together with the associated heat and mass transfer [20]. Apparently, there is a lack of systematic studies on how urban roughness affects street-level ventilation and pollutant removal.

Different roughness elements, such as sand grain [21], sand paper [22], grooves [23], or mesh screen [24], have been tested for flow modification over rough surfaces. One of the approaches relating the flows and the geometrical factor is the roughness density [25] but the changes in turbulence structure depend on the geometry of individual roughness elements [26]. Although the flows over rough and smooth surfaces share the same similarity [27,28], the conventional smooth-surface scaling is inapplicable to its rough-surface counterpart [29,30]. Roughness height is commonly used to describe the logarithmic velocity profile but is unable to characterize the flows near roughness elements [31], nor the more complicated ventilation behavior over urban areas. It is therefore hard to formulate a mathematical relation between urban morphology and city ventilation at the moment.

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Estimation of the aerodynamic resistance over roughness elements has long been an essential component in engineering [32,33]. It is well known that, at high Reynolds number (say over 6×10^4), the augmentation of heat transfer over grooved structures is proportional to the friction factor [34–36]. While the geometrical factor alone is insufficient to parameterize the flows, an analogous approach is attempted in this study to examine the relation between urban morphology and street-level transport processes in order to provide the essential flow details in a compact manner [37]. As a pilot attempt, idealized street canyons of various cross sections are used constructing hypothetical urban areas of different roughness. Momentum conservation shows that the roof-level characteristic vertical velocity scale is closely related to the aerodynamic resistance. The analytical derivation is verified by computational fluid dynamics (CFD) results and their agreement is favorable. The problem background is outlined in this section. The mathematical models and the computing issues are described in Section 2. The theoretical solution is detailed in Section 3 and the CFD results are reported in Section 4. Finally, the conclusion and the practical significance is discussed in Section 5.

2. Methodology

Mathematical modeling, which facilitates the large-scale sensitivity tests required, is adopted. The computing issues and the numerical methodology are detailed below.

2.1. Mathematical model

Incompressible and isothermal flows in steady-state conditions are assumed. They are described by the continuity equation

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

supplemented by the Reynolds-averaged Navier–Stokes (RANS) equations

$$\overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial}{\partial x_j} \overline{u'_i u'_j} \quad . \tag{2}$$

These equations are commonly used to calculate atmospheric contaminant dispersion [38–40]. The tensor notation is used in Eqs. (1) and (2) in which the summation convention on repeated indices (i, j = 1, 2) is employed. The vector x_i contains the Cartesian coordinates in the streamwise (x) and vertical (z) directions. The overbars $\overline{\bullet}$ and primes $\bullet'$ denote, respectively, the ensemble-averaged and unresolved turbulent quantities. The vector components $\overline{u}_i$ represent the velocity components in the streamwise ($\overline{u}$) and vertical ($\overline{w}$) directions, and $\overline{p}$ is the kinematic pressure. The last term on the right-hand side of Eq. (2) is the Reynolds stress

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

that accounts for turbulent transport using the Eddy-viscosity model. Here ν_t (= $C_\mu k^2/\epsilon$) is the kinematic turbulent viscosity, δ_{ij} the Kronecker delta, and C_μ (= 0.09) a modeling constant. Closure is obtained by the Renormalization Group (RNG) k-ϵ turbulence model with enhanced wall treatment because it has shown to be more accurate for modeling recirculating flows [41]. The transport equations for the turbulence kinetic energy (TKE) k

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

Table 1
Configuration of street canyons constructed by building models of different aspect ratios h/b.

Aspect ratio h/b	b/h	Pitch $b/h+1$	Number of street canyons	L_x/h
0.05	20	21	15	315
0.08	12.5	13.5	25	337.5
0.11	9.1	10.1	30	303
0.14	7.1	8.1	40	324
0.17	5.9	6.9	45	310.5
0.2	5	6	50	300
0.23	4.3	5.3	60	318
0.26	3.8	4.8	65	312
0.29	3.4	4.4	70	308
0.32	3.1	4.1	75	307.5
0.34	2.9	3.9	80	312
0.38	2.6	3.6	85	306
0.5	2	3	100	300
0.77	1.3	2.3	130	299
1.25	0.8	1.8	170	306
2	0.5	1.5	200	300
3.33	0.3	1.3	230	299
5	0.2	1.2	250	300

and the TKE dissipation rate ϵ

$$\overline{u}_i \frac{\partial \epsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\alpha_\epsilon \nu_t \frac{\partial \epsilon}{\partial x_i} \right) + C_{1\epsilon} P_k \frac{\epsilon}{k} - \left[C_{2\epsilon} + \frac{C_\nu \eta \left(1 - \eta/\eta_0\right)}{1 + \beta \eta^3} \right] \frac{\epsilon^2}{k} \tag{5}$$

are solved to close Eq. (3), where P_k (= $-\overline{u'_i u'_j} \times \partial \overline{u}_i / \partial x_j$) is the TKE production due to mechanical shear and η is used to handle the large strain rate. In Eqs. (4) and (5), α_k (= 1.393) and α_ϵ (= 1.393) are the inverse effective Prandtl numbers for the TKE and the TKE dissipation rate, respectively. The empirical modeling constants used in this paper are η_0 (=4.38), β (=0.012), C_ν (=0.0845), $C_{1\epsilon}$ (=1.42), and $C_{2\epsilon}$ (=1.68). The pollutant transport is calculated by the conservation of a passive and inert tracer

$$\overline{u}_i \frac{\partial \overline{\phi}}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\kappa_t \frac{\partial \overline{\phi}}{\partial x_i} \right) \tag{6}$$

where ϕ is the tracer concentration, κ_t (= ν_t/Sc_t) the turbulent mass diffusivity, and Sc_t is the turbulent Schmidt number, which is chosen to be equal to 0.72 in this study.

2.2. Computational domain and boundary conditions

The two-dimensional (2D) CFD domain comprises a number of identical street canyons placed in the urban boundary layer (UBL). Eight types of idealized building models, including (1) rectangle, (2) trapezoid, (3) triangle, (4) pitched roof, (5) windward triangle, (6) leeward triangle, (7) windward pitched roof, and (8) leeward pitched roof, are used in the CFD sensitivity tests (Fig. 1). The building width d is set equal to the building height h and the aspect ratio h/b is controlled by the building separation b. The length of one periodic unit is thus l (= $b + h$) and the pitch is equal to l/h (= b/h + 1). Because various building separations are employed, the number of street canyons is a function of the aspect ratio (Table 1). The above combination of building models and aspect ratios lead to 144 different configurations. Only the flows and pollutant transport of the central street canyon is investigated. The street canyons placed either upstream or downstream of the central one are used to facilitate fully developed flows. The streamwise domain extent is in the range of $299h \le L_x \le 337.5h$. The change in the velocity profile is negligible and the change in TKE is less than 5% before the central sample street canyons. In an open channel, the boundary layer thickness is comparable to the flow depth [42]. Hence, the UBL depth is kept constant equal to the vertical domain extent H = $10h$.