A Unified Theory for the Drag and Dispersion over Urban Roughness Elements

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Abstract

In view of the rapid urbanization across the world, urban climate and pollutant transport are important research topics nowadays. While parameterizations are commonly adopted in city- or meso-scale meteorological models to handle different land surfaces, our understanding of how buildings affecting aerodynamic resistance and vertical fluxes is rather limited. This study is thus conceived, using mathematical modeling, to examine how building morphology modifies the drag against prevailing flows and the dispersion of gaseous pollutants over urban roughness elements. We are especially interested in the parameters that could represent the ventilation and pollutant removal of street canyons.

As a pilot attempt, idealized urban street canyons (streets flanked by buildings of equal height) are employed as the spatial domain. The prevailing flows are perpendicular to the street axis in order to consider the worst scenario of ventilation and pollutant removal. A range of building-height-to-street-width (aspect) ratios ($0.08 \leq h/b \leq 2.5$), covering the characteristic regimes of isolated roughness, wake interference, and skimming flow, are tested. Both Reynolds-averaged Navier-Stokes (RANS) k-ε turbulence model (2D spatial domain) and large-eddy simulation (LES; 3D spatial domain) are used.

Using friction factor f to measure the resistance against fluid flows is a common engineering practice (e.g. Moody chart for pipes). The aspect ratio governs the form drag against the flows over street canyons so does the friction factor (Figure 1a). Modeling results consistently suggest that dense buildings impose a higher resistance on the flows. The aerodynamic resistance increases with increasing street width. The friction factors calculated by the RANS model and the LES in the regimes of isolated roughness and wake interference (wide streets) are comparable with each other. However, a larger discrepancy is observed in the skimming flow regime (narrow streets) that is likely attributed to the dominated intermittent transport processes across the roof of street canyons.

An area source of uniform pollutant concentration Φ is placed on the ground level of the first street canyon measuring from the upstream inflow. The street canyon ventilation, which is measured by the air exchange rate (ACH), is proportional to the friction factor (Figure 1b). In particular, their LES-calculated values are closely dependent on each other in which the correlation coefficient is up to 0.93. The RANS-calculated counterparts are less correlated that is likely caused by the single-length scale adopted. On the other hand, it seems that friction factor is not a reliable parameter to estimate the pollutant exchange rate (PCH) because the correlation coefficients are merely over 0.5 (Figure 1c). We believe that this uncertainty is mainly due to the pollutant re-entrainment in the wake interference regime.

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For the pollutant transport in the urban boundary layer over the street canyons in the streamwise direction, we assume that the plume dispersion exhibits a Gaussian shape in which the vertical dispersion coefficient is expressed in the form of $\sigma_z = m\overline{x}^n$ where $\overline{x}$ is the downwind distance measuring from the pollutant source, and m and n are empirical constants. As depicted in Figure 1d, our LES results show that in flows with a small resistance (skimming flow regime), m (n) increases (decreases) monotonically with increasing friction factor. Further increasing the street width results in a higher resistance but m and n converge asymptotically, suggesting a more uniform pollutant distribution in the downstream.

Based on the favorable results reported above, we thus propose that friction factor could be used to estimate the aspect ratios and ventilation of street canyons, as well as the pollutant dispersion over urban areas. However, mainly due to the unexpected pollutant re-entrainment, friction factor cannot be applied in pollutant removal estimate at the moment. Additional investigations are currently undertaken to look into that regard.

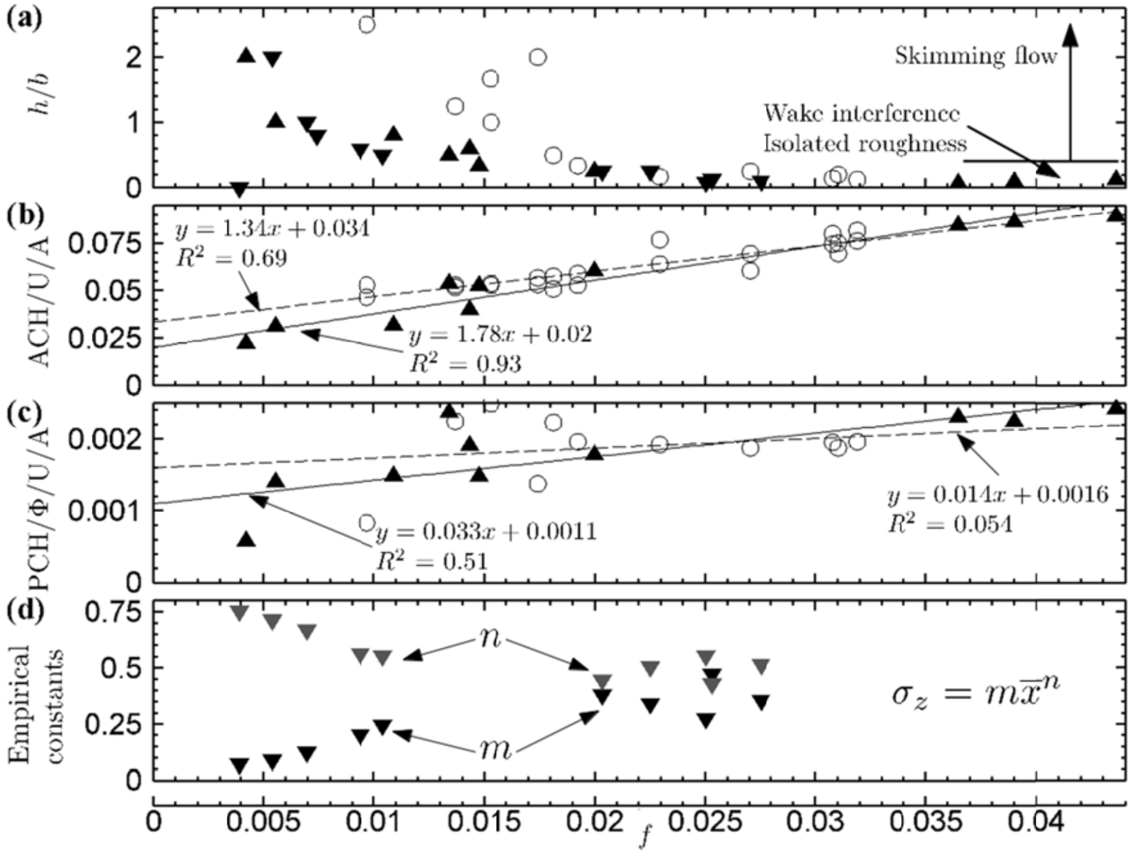

Figure 1. (a) Building-height-to-street-width (aspect) ratio h/b, (b) air exchange rate ACH, (c) pollutant exchange rate PCH, and (d) empirical constants m and n for idealized urban street canyons expressed as functions of the friction factor f measuring the aerodynamic resistance. Large-eddy simulation (LES) using one street canyon (▲); LES using several repeated street canyons (▼); and Reynolds-averaged Navier-Stokes (RANS) k-ε turbulence model (○). Solid and dashed lines are the linear regressions for the LES and RANS data, respectively. Here, R^2 is the correlation coefficient, Φ the (uniform) pollutant concentration on the street-level area source. σ_z the vertical dispersion coefficient for the pollutant plume, and $\overline{x}$ the distance measuring from the pollutant source in the streamwise direction.