Building and Environment 94 (2015) 166–182

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

City breathability in medium density urban-like geometries evaluated through the pollutant transport rate and the net escape velocity

Jian Hang [a], Qun Wang [a], Xieyuan Chen [a], Mats Sandberg [b], Wei Zhu [a], Riccardo Buccolieri [c,*], Silvana Di Sabatino [d]

[a] Department of Atmospheric Sciences, School of Environmental Science and Engineering of Sun Yat-Sen University, Guangzhou, PR China
[b] Laboratory of Ventilation and Air Quality, University of Gävle, SE-80176 Gävle, Sweden
[c] Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, S.P. 6 Lecce-Monteroni, 73100 Lecce, Italy
[d] Department of Physics and Astronomy, ALMA MATER STUDIORUM - University of Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form
3 August 2015
Accepted 4 August 2015
Available online 8 August 2015

Keywords:
Urban canopy layer
Pollutant transport rate
Contribution ratio
Net escape velocity
Computational fluid dynamics

ABSTRACT

This paper investigates pollutant removal at pedestrian level in urban canopy layer (UCL) models of medium packing density ($\lambda_p = \lambda_f = 0.25$) using computational fluid dynamics (CFD) simulations. Urban size, building height variations, wind direction and uniform wall heating are investigated. The standard and RNG $k-\varepsilon$ turbulence models, validated against wind tunnel data, are used. The contribution of mean flows and turbulent diffusion in removing pollutants at pedestrian level is quantified by three indicators: the net escape velocity (*NEV*), the pollutant transport rate (*PTR*) across UCL boundaries and their contribution ratios (*CR*).

Results show that under parallel approaching wind, after a wind-adjustment region, a fully-developed region develops. Longer urban models attain smaller *NEV* due to pollutant accumulation. Specifically, for street-scale models (~100 m), most pollutants are removed out across leeward street openings and the dilution by horizontal mean flows contributes mostly to *NEV*. For neighbourhood-scale models (~1 km), both horizontal mean flows and turbulent diffusion contribute more to *NEV* than vertical mean flows which instead produce significant pollutant re-entry across street roofs. In contrast to uniform height, building height variations increase the contribution of vertical mean flows, but only slightly influence *NEV*. Finally, flow conditions with parallel wind and uniform wall heating attain larger *NEV* than oblique wind and isothermal condition.

The paper proves that by analysing the values of the three indicators it is possible to form maps of urban breathability according to prevailing wind conditions and known urban morphology that can be of easy use for planning purposes.

1. Introduction

The increase of vehicle emissions in cities and the ongoing urbanization worldwide continue to deteriorate urban air quality within the urban canopy layer (UCL) [1,2] which produces adverse effect to the health of people indoor and outdoor [3,4]. Besides reducing pollutant emissions, improving urban ventilation through use of architectural modifications may help street-level pollutant dilution [5–14].

Flow and pollutant dispersion within and above urban areas are commonly classified into four length scales, i.e. street-scale (~100 m), neighbourhood-scale (~1 km), city-scale (~10 km) and meso-scale (~1000 km) [15–18]. The former three scales are microscale (~100 m–10 km) for which the flow below building rooftops are explicitly solved. At this scale, due to pollutant accumulation effect, urban air quality depends upon their neighbourhoods and city-scale characteristics [15,16]. Meso-scale modelling is usually employed to investigate regional pollutant transport in which urban areas are treated as roughness elements thus providing boundary conditions for smaller scale studies [17]. Within this framework flow and pollutant dispersion from street-scale to neighbourhood-scale have been widely investigated often coupling wind tunnel/field experiments with computational fluid dynamics (CFD) simulations [5–14,19–23,25–39,43–45]. CFD modelling has

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[*] Corresponding author.
E-mail address: riccardo.buccolieri@unisalento.it (R. Buccolieri).

http://dx.doi.org/10.1016/j.buildenv.2015.08.002
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been rarely applied to city-scale (~10 km) because it still requires too high computational costs to simulate urban airflows through thousands of buildings [18].

Street-scale and neighbourhood-scale studies usually disregard the larger-scale boundaries and emphasize the local parameters. For two-dimensional (2D) street canyon models, four flow regimes dependent on street aspect ratios (building height/street width, H/W) are reported [19–23], i.e. the isolated roughness flow regime ($H/W < 0.3$), the wake interference flow regime ($0.3 < H/W < 0.67$), the skimming flow regime with one main vortex ($0.67 < H/W < 1.67$), and multi-vortex flow regime ($H/W > 1.67$). For three-dimensional (3D) urban models, major urban morphological parameters are the building planar area index λ_p (i.e. the ratio between the planar area of buildings viewed from above and the total floor area) and the frontal area index λ_f (i.e. the ratio of the frontal area of buildings to the total floor area) [24]. 3D spare urban areas (for example $\lambda_f = 0.0625$) are more effective in removing pollutant [13], but have a lower efficiency of land utilization. Densely built-up urban areas usually results in poor ventilation conditions [7,9–14]. The most typical parameters of real urban areas are $\lambda_p = \lambda_f = 0.25$ [24]. As building packing densities are fixed, some other urban parameters are significant, including urban forms [8,10,11], urban size and building height variations [7,8,12,29], ambient wind directions [5,8,14,26–29] etc. Thermal effect is another key factor. Field measurements showed temperature difference between air and building surfaces can reach up to 12–14 °C [31,32]. If Richardson number (Froude number) is relatively large (small), the buoyancy force induced by air-wall temperature difference can affect or even dominate urban airflows [31–40]. On the other hand, Giovannini et al. [46] showed using temperature data recorded in urban street canyons that when solar radiation is weak or absent, the temperature field remains mostly homogeneous.

In this context, fixing the medium building packing density ($\lambda_f = \lambda_p = 0.25$), we aim to quantify how urban sizes, building height variations, ambient wind directions and wall heating affect the capacity of removing pollutants at pedestrian level. To this purpose, pollutant transport rate (*PTR*) and its ratio (i.e. contribution ratio) (*CR*) [7] are applied to evaluate the relative contribution in pollutant removal by mean flows and turbulent diffusion across UCL boundaries. A new concept, the net escape velocity [41], is used to quantify the net capacity of pollutant dilution at pedestrian level.

2. CFD methodology and case studies

Ansys FLUENT was used to solve the steady-state flow field [42] by employing the RNG and the standard $k-\varepsilon$ model. We are aware that deficiencies of the steady RANS approach with the standard $k-\varepsilon$ model include the stagnation point anomaly with overestimation of turbulence kinetic energy near the frontal corner and the resulting underestimation of the size of separation and recirculation regions on the roof and the side faces, as well as the underestimation of turbulence kinetic energy in the wake resulting in an overestimation of the size of the cavity zone and wake. These limitations can be explicitly resolved by Large Eddy Simulation (LES). There are however still challenges facing LES such as the development of advanced sub-grid scale models,

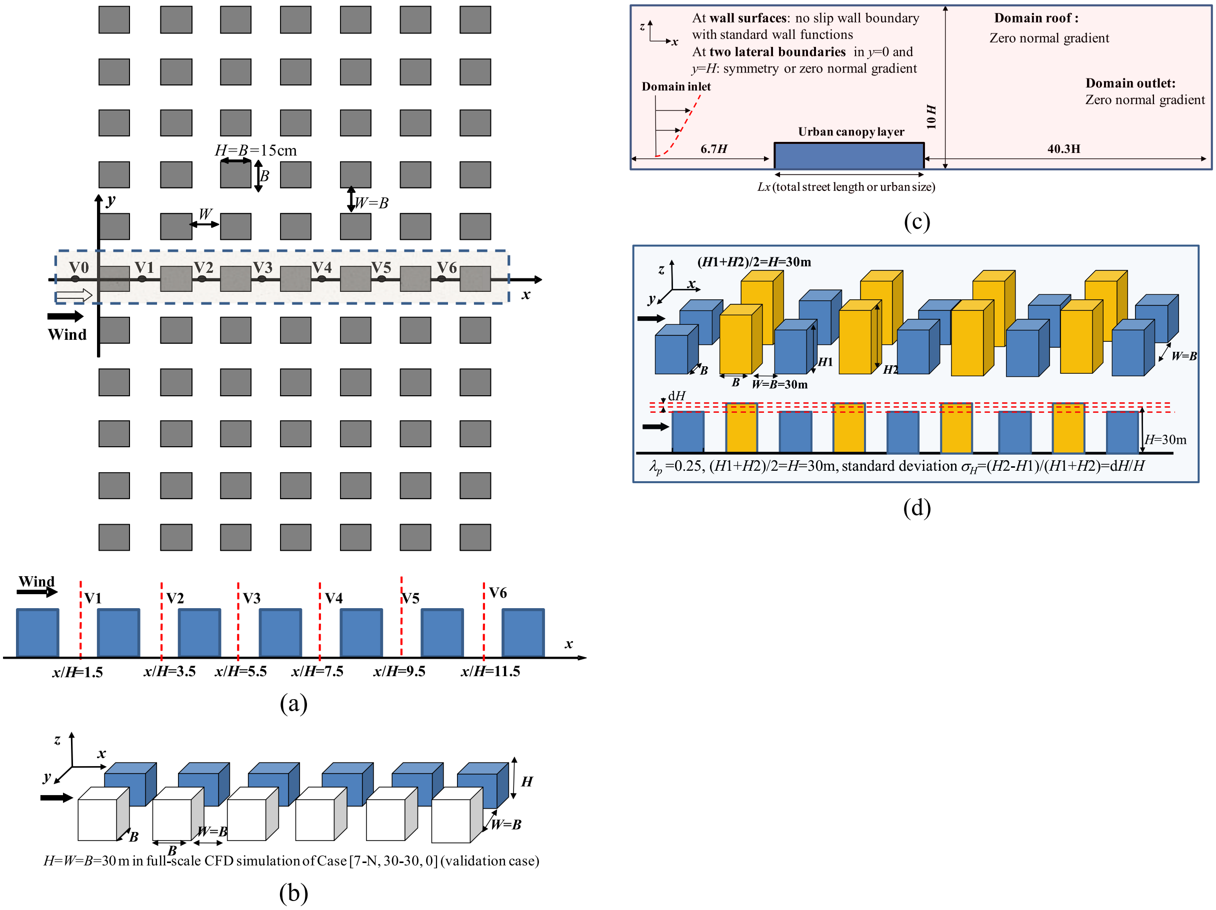

Fig. 1. (a) Array used in the wind tunnel experiments, (b) model in the CFD validation case, (c) computational domain in Group I (see Table 1), (d) model with regular building height variations.