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The pollutant removal capacity of an urban street canyon and its link to the breathability and exchange velocity

A. Kubilay[a,b] , M. K.-A. Neophytou[a,c,]*, S. Matsentides[c], M. Loizou[c], J. Carmeliet[a,b]

[a]*Chair of Building Physics, Swiss Federal Institute of Technology ETHZ, Zurich, Switzerland*

[b]*Laboratory for Multiscale Studies in Built Environment, Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland*

[c]Environmental Fluid Mechanics Laboratory, Department of Civil and Environmental Engineering, University of Cyprus, Nicosia, Cyprus

Abstract

The rate of removal of pollutants within simplified urban street canyons is investigated using air flow fields obtained from Particle Image Velocimetry (PIV) experiments and Computational Fluid Dynamics (CFD) simulations of the resulting pollutant dispersion. In particular, the link between the pollutant removal capacity and the air-flow exchange velocity, a characteristic velocity widely used to characterize this pollutant removal capacity, is examined. First, velocity fields through a series of homogeneous urban street canyons with flat roofs are obtained using ensemble-averaged PIV measurements as obtained within water channel experiments. The experimental results for the fully-developed street canyon air velocity field are used to drive numerical simulations of turbulent pollutant dispersion from a pollutant release source located within the street canyon. The rate of removal of pollutant from the canyon is deduced from the numerical simulations and analyzed in terms of mean convective and turbulent exchange mechanisms. It is found that rate of pollutant removal as expressed through a pollutant-exchange velocity is dominated by the turbulent pollutant diffusion in the street canyon case. It is found that the air-exchange velocity cannot be used as a representative measure for pollutant removal, since it does not take into account all physics involved in the removal process. It is only a measure for the convective pollutant flux when the pollutants are uniformly distributed in the control volume.

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Keywords: Water-channel measurements; Particle image velocimetry (PIV); Computational fluid dynamics (CFD); Pollutant removal; Breathability; Exchange velocity

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* Corresponding author. Tel.: +357-2289-2266; fax: +357-2289-5323.
E-mail address: neophytou@ucy.ac.cy

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1. Introduction

There has been substantial discussion in the literature on the capacity of the urban air flow to remove pollutants produced within street canyons (e.g. emissions from traffic or buildings). Different concepts have been used and discussed in order to characterize this capacity, such as the “exchange velocity” [1, 2], and the “mean age of air” [2, 3], adopted from indoor ventilation studies. The concept of “breathability” was introduced and defined as the capacity to remove pollutants produced within a city [4-6] and has been linked to the air-exchange velocity, which is derived from the air flow velocity field in and above a street canyon. However, no theoretical nor experimental evidence is given that the rate of pollutant removal can be directly related to air-exchange velocity. Aim of this paper is to analyze critically this link based on a combined experimental / computational approach.

In order to investigate the link between the rate of pollutant removal and the air-exchange velocity, the air flow characteristics within urban street canyons is briefly reviewed. The flow and pollutant dispersion within and above an urban street canyon is substantially determined by the presence of a shear layer generated at the rooftop level as well as the recirculation flows within the canyon. Different shear layer thickness can be observed depending on the packing density of the canyons and additional roughness arising mainly at the roof surfaces. The nature of the shear layer at the rooftop level, its level of unsteadiness and thickness, determines the mean convective and turbulent fluxes through that level. The turbulent fluctuations within the shear layer are governed by coherent turbulent structures, which interact with each other across a wide range of spatial and temporal scales [7]. Such turbulent structures within shear layers can have a significant influence on pollutant and heat removal mechanisms in the built environment [8]. Furthermore, the flow structures can also be different within street canyons depending on the geometry of the canyon e.g. on its aspect ratio, resulting in single or multiple recirculation regions within the street canyon.

In this paper, pollutant dispersion and its removal from a street canyon is investigated in order to identify the different pollutant-removal mechanisms. In particular, the link between the pollutant removal capacity and the air-exchange velocity is investigated. To achieve this, existing experimental measurements of the turbulent air velocity field in and above street canyons (Neophytou et al. [6]) are used in order to drive numerical simulations to compute the pollutant dispersion using the unsteady scalar transport equation. In this way, possible discrepancies associated with the RANS models within the shear layer near the critical street canyon rooftop region are avoided. Section 2 presents the methodology used in the present study, giving specifications of the water-channel measurements and the numerical model for the pollutant dispersion. Furthermore, the results of pollutant dispersion in an idealized homogeneous street canyon with an aspect ratio 1 are presented in Section 3. Finally, section 4 provides a general discussion of the results while section 5 provides the concluding remarks of this research work.

2. Methodology

2.1. Water-channel measurements

The flow measurements were conducted in a water channel instrumented with a particle image velocimetry (PIV) system [6]. The measurements were conducted in the fully-developed region following a series of idealized street canyons; the configuration was formed using six rectangular building arrays and therefore forming five consecutive street canyons spanning the entire width of the water channel, representing a 2-D problem. The measurements were performed in and above the last canyon. The Reynolds number based on the building height ranged between 19 000 and 25 000 ensuring a fully turbulent regime. Fig. 1(a) and (b) show the measured fields of flow speed and turbulence kinetic energy per unit mass, respectively, in the configuration with street canyons of aspect ratio 1. The building height H and the street canyon width W equal 0.06 m, while the bulk velocity U_b equals 0.29 m/s. Fig. 1(c) shows the vertical profiles of the Reynolds stress components along three different horizontal positions in the canyon, whereas Fig. 1(d) shows the approach profiles of streamwise velocity and turbulence kinetic energy. Flow speed within the street canyon is considerably lower compared to the free flow, the maximum speed being 0.13 m/s. The main recirculation region stays within the street canyon and does not extend above the rooftop level. The interaction between the flow in and above the street canyon shows a pattern of a skimming flow regime [9] with an