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Effect of short–time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer

Fabio Murena [1], Benedetto Mele [2]

[1] Department of Chemical, Materials and Production Engineering University of Naples "Federico II", Italy
[2] Department of Aerospace Engineering University of Naples "Federico II", Italy

ABSTRACT

2D URANS CFD simulations were conducted to study the effect of short–time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer (ABL). A street canyon with a height–to–width ratio (aspect ratio) of three was considered as a case study. The study is of practical interest since it illustrates a skimming flow regime, the regime where pollutants are less effectively exchanged between the canyon and the above atmosphere, typically found in many urban areas in Mediterranean countries. Short–time variations of wind velocity magnitude were simulated assuming a sinusoidal function with average magnitude = 4 m s^{-1}; amplitude ±2 m s^{-1} and period from 1 to 40 s, and subsequently with short–time averaged (0.1 s, 1 s and 10 s) real world data measured with an ultrasonic anemometer (50 Hz). Mass transfer rate between the canyon and the ABL was evaluated as the rate of reduction of spatially averaged concentration of a passive pollutant, carbon monoxide (CO), in the street canyon. Results show that mass transfer rate increases with the frequency of short–time variations. In CFD studies pertaining to pollutant dispersion in street canyons, wind hourly average velocity is usually assumed as a reference value to simulate real world cases. Our results show that this input data must be completed with additional information about the extent of variation in wind intensity and its frequency in the hour.

Keywords: *Street canyon, mass transfer, modeling, CFD, short–time variations*

Corresponding Author:
Fabio Murena
☎ : +39-081-7682277
🖷 : +39-081-2391800
✉ : murena@unina.it

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1. Introduction

Accurate evaluation of the mass transfer rate between urban roads and the atmospheric boundary layer (ABL), together with evaluation of vehicular emission rates, is crucial for reliable assessment of air quality (concentration of pollutants at street level) in urban areas. However, although mass transfer from such roads to the ABL has been studied more than two decades, complete knowledge of the phenomenon has yet to be achieved.

Starting from the first papers on this topic, real urban roads were idealized as a single road of infinite length delimited by buildings of the same constant height on both sides of the road and with wind direction perpendicular to the street axis. This geometry is that of a cavity termed "ideal street canyon". The building height–to–street–width aspect ratio (AR) was assumed as the key geometrical parameter defining the building geometry and the flow patterns.

Oke (1987) characterized the flows in street canyons into three regimes, namely isolated roughness (AR<0.3, wide street), wake interference (0.3≤ AR ≤0.7), and skimming flow (0.7<AR, tall buildings or narrow streets). CFD studies were conducted from the 1990s onwards (Sini et al., 1996) to obtain the flow field inside the canyon and information about pollutant dispersion inside the canyon and mass exchange with the ABL.

Reliable evaluation of mass transfer between the canyon and the ABL is essential for the prediction of concentration levels inside the street canyon. Indeed, it has been studied by several authors: Bentham and Britter (2003) developed a model to characterize in–canopy velocity and to evaluate average exchange velocity between in–canopy and above–canopy flows; Barlow et al. (2004) measured the mass transfer coefficient observing naphthalene sublimation in a lab–scale array of street canyons for H/W=0.25, 0.6, 1 and 2. Hamlyn and Britter (2005) simulated the processes of flow and exchange within obstacle arrays using the CFD code FLUENT and discussed the transfer of mass between the canopy and the air above it in terms of the exchange velocity. Salizzoni et al. (2009) studied the mass exchange between a street canyon and the external atmospheric flow by means of wind tunnel experiments. They developed a two–box model and evaluated a mass transfer velocity. Murena et al. (2011) in a 2D CFD study, developed a box model for deep street canyons. In this case an overall mass transfer velocity was defined to quantify the overall mass transfer process from the bottom volume of the canyon to the ABL.

In recent years the large eddy simulation (LES) approach has been frequently applied to this topic. Chung and Liu (2013) in a LES study on a 2D idealized canyon evaluated ventilation and pollutant removal, determining the following parameters: air exchange rate (ACH) and pollutant exchange rate (PCH).

The mass exchange between the air in the street canyon and the atmosphere above takes place through the shear layer which forms between the cavity and the ABL (Caton et al., 2003). Although published studies generally make reference to an external velocity to characterize the mass transfer rate, many authors agree with the evidence that turbulent transport dominates the mass exchange. It is widely considered that the instantaneous (turbulent) contribution to mass transfer velocity is higher than the mean (advective) contribution. However, the latter is not negligible. The advective contribution may be considerable when the building height is not uniform (Hamlyn and Britter, 2005). Caton et al. (2003) observed that mass transfer depends both on an external reference velocity and on the structure of the incoming turbulence. Further, by contrast, Salizzoni et al. (2009) observed that mass transfer appears to be entirely governed by the fluctuating component of the turbulent flow and unaffected by the magnitude of the mean recirculating flow within the canyon.

Results of LES show that in all three regimes (i.e. isolated roughness, wake interference and skimming flow) street canyon ventilation is dominated by turbulent transport (Chung and Liu, 2013). Indeed, roof–level turbulence mainly governs the ventilation performance of street canyons, contributing up to 80–90% to the total air exchange rate (Chung and Liu, 2013). The flow in the ABL above in correspondence of the canyon cavity is also characterized by strong unsteadiness (Castro et al., 2006; Takimoto et al., 2011) generating intermittent coherent turbulent structures which penetrate the street canyon, affecting mass transfer. Michioka and Sato (2012) observed in LES on a two–dimensional street canyon with an aspect ratio of one that coherent structures of low–momentum fluid, generated close to the plane of the roof, contributed to pollutant removal. An LES model of the transport and dispersion of passive scalars in a 2D street canyon was developed for H/W=1/3, 1/2, 2/3, 1/1, 3/2, and 2/1 (Cai et al., 2008). Results of simulations were validated against several datasets of wind tunnel experiments.

In all the studies reported above, average wind velocity in the ABL is assumed constant with time. To compare results of simulations with real world data it is common to make reference to hourly average wind speed data. The choice of one hour as the averaging time originates from ambient air quality regulations adopted in many countries (EC, 2008; U.S. EPA, 2013) where one hour is the shortest averaging time during which pollutant concentrations have to be measured.

Short–time resolution of wind data (direction and intensity) can be obtained by using an ultrasonic anemometer with a measurement frequency generally in the range 10–50 Hz. Xie (2011) reports 30 s and 60 s averaged time wind data collected by an ultrasonic anemometer showing how wind magnitude and direction can vary in a time interval of one hour by ±36% and ±22° respectively (but larger variations can be frequently observed). The paper by Xie (2011) shows how wind magnitude and direction can fluctuate around the hourly average or follow an increasing or decreasing trend in some fractions of the hour. However, it is evident that real wind deviates from the one–hour average both in magnitude and in direction.

Some measurements with a 50 Hz triaxial ultrasonic anemometer were carried out at roof top level in the centre of Naples (Spano, 2011). Wind variations were extremely fast and generally random around a time–averaged value. In some cases a trend with time (increasing or decreasing) was observed. An example of ultrasonic anemometer measurements of the horizontal wind magnitude (Spano, 2011) at roof top level is reported in the Supporting Material (SM).

The effect of short–time wind variations on the mass exchange between the urban canopy or a single street canyon and the ABL has been rarely considered. Xie (2011) used 30– and 60 s averaged wind data measured at 190 m above street level by an ultrasonic anemometer (10 Hz resolution) to simulate real wind conditions in an LES simulation of the Marylebone Road. Since it was a 3D simulation both wind intensity and direction variations were considered. A comparison of 3–min averaged concentration at a selected site showed fairly good agreement between simulation results and real data when 30– and 60 s averaged real wind data were adopted in place of steady wind conditions (Xie, 2011).

In this paper the results of 2D URANS CFD simulations in an ideal deep street canyon assuming a time–dependent inflow wind velocity are reported. The time dependence of inflow wind velocity was first described assuming a sinusoidal function with average value v=4 m s^{-1} and amplitude ±2 m s^{-1}. The time period was varied from 1 to 40 s. Then real world data measured with an ultrasonic anemometer placed at the roof top level in the centre of Naples were time–averaged (0.1 s, 1 s and 10 s) and used to simulate wind velocity in the ABL.

The correct choice of the turbulence simulation method is a critical issue in CFD (see for instance Spalart, 2000). LES calculations at high Reynolds numbers (i.e. >10^{6}) require strong, sometimes prohibitive, computational effort. In fact, increasing the Reynolds number the mesh size required for an accurate LES calculation becomes almost comparable to the mesh size required for a Direct Numerical Simulation (see for instance Pope, 2000). On the other hand, RANS–URANS pros and cons are also well known. That said, in the last two decades RANS–URANS have been successfully applied in complex external flows (see for instance Durbin, 1995; Iaccarino et al., 2003; Do et al., 2010, Catalano and Tognaccini, 2010) and in wash–out simulations (Murena et al., 2011; van Hoff and Blocken, 2013), demonstrating that accurate URANS calculation is able to recover reasonable results. One of the cases where URANS methods are particularly effective at providing time–accurate prediction is when the unsteadiness is externally imposed, provided that the external imposed time scale is far enough from the time scale of turbulent fluctuations. This is the main reason why we chose such methodology together with the consideration that the large number of simulations required in the present study were difficult to perform by LES methods. That said, in order to validate the URANS calculations, an LES simulation was also performed in one of the cases studied and compared with URANS result in terms of street canyon wash–out time.

Geometry and boundary conditions of simulations were selected in order to study a case of practical interest. Indeed, the aspect ratio was set at 3, which is typical of many urban areas in Mediterranean countries governed by a skimming flow regime, where pollutants are less effectively exchanged between the canyon and the above atmosphere. Average wind velocity was set at 4 m s^{-1}, a value very frequently occurring in the Mediterranean area.

The aim of this study was to obtain information on to what extent mass transfer rate between urban street canyons and the ABL depends on short–time wind variations. These results could be used to enhance the performance of operational models like STREET (Johnson et al., 1973) and OSPM (Hertel and Berkowicz, 1989), both of which assume that mass transfer velocity is proportional to a characteristic velocity in the ABL.

2. Methodology

2.1. Computational domain and boundary conditions

2D RANS and URANS CFD simulations were carried out with the commercial flow solver FLUENT widely used in industry and applied research. The computational domain, mesh and boundary conditions are shown in supporting material. An ideal 2D street canyon with dimensions H=18 m and W=6 m (AR=3) was considered. The inflow and outflow length and the vertical size of the domain were set to ensure that the turbulent flow was fully developed at the leading edge of the street canyon.

The computational mesh was a structured mesh comprising 256×256 quadrilateral cells inside the street canyon zone while upstream, downstream and along direction Y it numbered 256