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On the effect of gable roof on natural ventilation in two-dimensional urban canyons

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ABSTRACT

Flow regimes occurring in urban canyons are strongly influenced by the geometrical shape of the buildings; however, fluid dynamic investigations are typically carried out using parallelepiped obstacles. The present study is focused on assessing the effect of gable roofs on the flow regimes characterizing urban canyons (skimming flow, wake interference, isolated roughness) and the implications in terms of integral parameters (air exchange rate and friction factor), which are useful in practical applications. Numerical simulations are performed by means of RANS modeling of idealized two dimensional urban canyons between series of identical gable roof buildings with pitch ranging from 0° up to 40°, and wind direction perpendicular to the canyon axis. Simulations performed for different canyon aspect ratios show the key role played by the roof pitch in enhancing turbulence and in increasing ventilation, in particular for narrow canyons. Furthermore, turbulence-driven ventilation is observed to be related to the square root of the friction coefficient by a single linear relation, despite of the roof pitch. These results may have an impact on design and planning strategies aimed at enhancing natural ventilation and promoting efficient pollutant and heat dispersion in urban areas.

1. Introduction

The fluid dynamic interaction between street canyons and the wind in the overlaying boundary layer plays a fundamental role in the determination of the living standard in the urban environment since it contributes to mitigate the degradation of air quality at the street level caused by vehicular emissions by promoting the removal of polluted air from the canyon and its substitution with fresh air. Therefore, the assessment of air ventilation in street canyons is an important tool in urban planning and air quality control in high-density cities (Fernando et al., 2001; Ng, 2009; Yazid et al., 2014).

Most of laboratory (Ahmad et al., 2005; Di Bernardino et al., 2015a, 2015b; Neophytou et al., 2014) and numerical (Ho et al., 2015; Hunter et al., 1992, 1990) studies on the fluid dynamics of the Urban Canyons (UCs) focused on the dependence on the spacing and height of buildings. They represented the buildings by its simplest geometrical schematization, parallelepiped obstacles, without going in further geometrical details, thus reproducing only the case of flat roof buildings. Also some field experiments focused on the same build shape (Zajic et al., 2010). However, other roof shapes are widespread in cities. Particularly in the regions of high rain or snowfall, most of the buildings have pitched roofs and, in some areas, building codes prescribe a minimum slope.

The shape of the obstacles, and in particular the presence of a pitched roof, causes deep modifications in the urban roughness sublayer. Specifically, Rafailidis (1997) compared, by means of laboratory experiments, two dimensional street canyons between buildings with flat and gable roof (45° slope) considering two different canyon aspect ratios and proposing the idea that roof shape plays a predominant role in controlling natural wind ventilation in the upper part of the urban canyons. Afterwards, several experimental (Kastner-Klein and Plate, 1999) and numerical simulations (Huang et al., 2009; Takano and Moonen, 2013; Xie et al., 2005; Yassin, 2011), mainly focused on air quality, indicated that the shape of adjacent buildings could be an effective element to reduce pollution within street canyons. Recently, Ozmen et al. (2016) investigated the effect of differently pitched gable roof on an isolated building. Actually, despite these works suggest the importance of the roof shape, there is no systematic study of Rafailidis intuition in the basic case of a regular array of gable roof buildings forming a series of urban canyons.

The present paper aims at filling this gap with a parametric analysis of the dependence of the flow field in the urban roughness sublayer, and canyon ventilation, on the roof slope and aspect ratio: in particular, the roof slope was gradually varied between 0° and 40°, in order to both cover a wide range of real building's roof pitches and unveil its influence on the ventilation in the urban canyon. Actually, literature

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works (Oke, 1988; Hunter et al., 1990; Zajic, 2010) showed that, in addition to canyon aspect ratio, also the length of the buildings, L, plays an important role in tuning the transition between the different flow regimes. However, in order to focus on a limited number of parameters, we chose to analyze the ideal case of the infinite-length urban canyon. As global descriptors of the fluid dynamics of the urban canyon, we refer to air exchange rate, representing the rate of air removal from a street canyon measured at the roof ridge level (Liu et al., 2005), and friction factor, which was considered to be a good predictor of the turbulent air exchange rate (Liu et al., 2015). In the following, after the description of the simulation methods (Section 2), we firstly compare the results (Section 3) with literature experimental data for model validation. Secondly, we present and analyze flow maps occurring in the different regimes characteristic of the UC and successively investigate how their occurrence affects global indexes, such as pressure coefficients, friction factor and air exchange coefficient. Discussion is carried out in Section 4, to then draw the conclusions (Section 5).

2. Methods

We simulated fully-developed steady turbulent flow over idealized two-dimensional canyons between an array of dual-pitched roof buildings, all with the same eave height, H, and square cross-section (building width D=H), while the width of the canyon, W, was varied between 0.4 and 12 H (hence the aspect ratio of the canyons, H/W, ranged from 0.08 up to 2.5). A uniform, indefinite succession of buildings was simulated by imposing periodic boundary conditions (BC) in the streamwise direction.

For each canyon width, the roof slope α was varied between 0° and 40° at 10° steps, covering a wide range of pitches adopted in real buildings. Analyzed configurations, although idealized, correspond to geometrical parameters ranging from isolated buildings to dense cities, hence spanning over the three characteristic flow regimes (isolated roughness, wake interference, skimming flow) described by Oke (1988) in case of flat roof buildings.

For all the range of pitches considered, the simulation domain (sketched in Fig. 1) is three canyons (L=3W+3D) long in the streamwise direction, and 15 H high (which fairly corresponds to 6 times the overall building height for the highest roof pitch, 40°). This fulfils the condition reported for flow simulation around buildings in the best practice guidelines (Franke et al., 2011; Tominaga et al., 2008), which require a vertical domain exceeding 6 overall building heights, in order to avoid unrealistic flow acceleration.

Wind direction is perpendicular to the canyon axis. For all the examined configurations the same Reynolds number, based on the building height and vertically averaged velocity, V, is imposed (Re=HV/ν=43,000). The pressure gradient between inlet and outlet is adjusted in order to assure the required flow rate. Snyder (1981) assumes a Reynolds number (based on the velocity of the unperturbed profile at the building height) greater than 15,000 for the flow to be independent on Reynolds number. Here, due to the periodic BC, we do not have an unperturbed velocity profile, however the chosen Re grants the fulfillment of the requirement and hence the independence.

Simulations were performed using the open source CFD library OpenFOAM 2.3. Reynolds Averaged Navier-Stokes model (RANS) with two equation k-ε closure (Launder and Spalding, 1974) was set up. Since we are investigating the ideal case of infinite length buildings, the problem is two-dimensional, thus a 2-D formulation of RANS equations is used. We used simpleFoam, a steady state solver for incompressible turbulent flow, which applies the SIMPLE algorithm (Patankar and Spalding, 1972), and second order schemes for discretization. A threshold of 10^{-6} for scaled residuals was adopted as a convergence criterion (Franke et al., 2011).

As above mentioned, a periodic regular building arrangement was simulated. Therefore cyclic boundary conditions were imposed at the inlet and outlet for all the variables except for pressure, whose gradient is adjusted to obtain the required mean velocity at the inlet. The upper boundary of the computational domain was considered a symmetry plane. At ground and building surfaces no slip condition was set. Neumann zero gradient conditions was imposed for pressure, whilst for turbulent quantities (kinetic energy, energy dissipation rate and turbulent viscosity) wall functions were applied.

In agreement with the above mentioned best practice guidelines, the mesh consists of hexahedral cells in order to introduce smaller truncation errors (Fig. 1, right panel). The grid is stretched in x and z direction, keeping the stretching ratio between neighboring cells below 1.3. The inner region of the street canyons is discretized with 40 cells whose size is doubled, both in x and z directions, compared to the cells adjacent to the walls. For the analyzed cases, the number of cells ranges from 12,300 (for H/W=2.5) up to 106,000 (for H/W=0.08).

3. Results

3.1. Model validation

OpenFOAM has been extensively and successfully used to perform RANS simulations of the wind in urban environment (Franke et al., 2012; Hertwig et al., 2012); moreover, a similar OpenFOAM configuration was already proven to properly reproduce a two-dimensional periodic array of flat roof buildings (Takano and Moonen, 2013).

Model validation was here performed on the basis of experimental

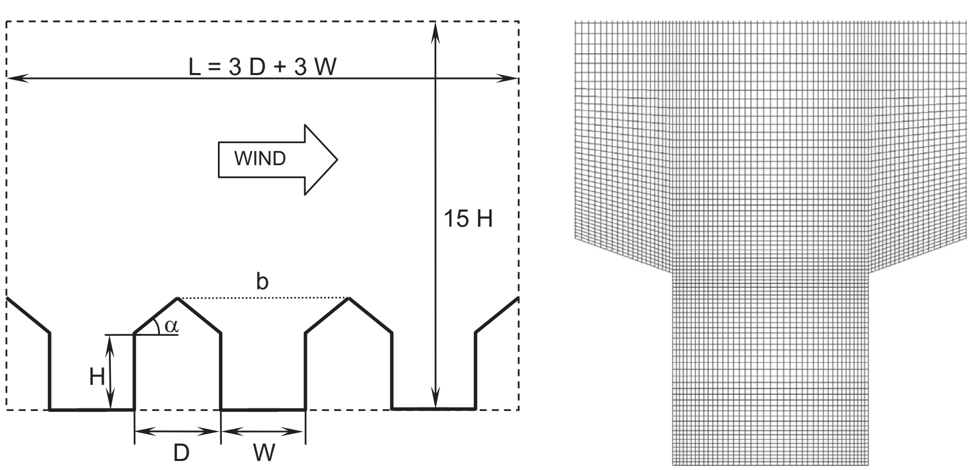

Fig. 1. Sketch of the computational domain: H is the eave height, D the width of the building, α the roof slope, W the canyon width, L=3 (D+W) the streamwise dimension of the domain, and b the line connecting the ridges (left panel). Inset of the mesh used for H/W=1 and α=20° (right panel).