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The influence of building geometry on street canyon air flow: Validation of large eddy simulations against wind tunnel experiments

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the effect of roof and façade geometry on the mean wind flow and turbulence in street canyons, as well as the ability of numerical simulation techniques in capturing the flow features. Numerical experiments, using the large eddy simulation FLUENT code, have been conducted under neutral stability conditions to test 5 building geometries: i) flat roof, ii) pitched roof, iii) round roof, iv) terraced building and v) building with balconies. Wind tunnel experiments were also conducted for the first three geometries. The simulation and experimental setups were closely matched and both featured configurations consisting of seven building arrays. The results from the physical and numerical experiments concur that (i) in-canyon vortex dynamics and over-canopy flow conditions, are strongly dependent on the geometric features of the buildings, and (ii) pitched and round roof geometries increase in-canyon mean and turbulent velocities, as well as the depth of the shear layer. The findings provide novel insight on the sensitivity of the flow and turbulence fields, as well as the simulation quality, to urban topography, inflow conditions, and the Reynolds number. They also underline the influence on the flow of small-scale features such as balconies, which are often ignored in prior literature.

1. Introduction

As of 2015, more than half of the world's population is living in towns or cities. The number of urban dwellers rose from 729 million in 1950 to 3.9 billion in 2014. By 2050, two out of three humans are expected to be living in urbanized areas (WHO, 2014). The global tendency towards urbanization deteriorates the urban air quality and increases the Urban Heat Island (UHI) intensity, thus amplifying the risk of exposure of citizens to discomfort and health hazards and leading to higher energy demands for cooling (Fernando, 2010; Li and Bou-Zeid, 2013; Li et al., 2014; Oke, 1973).

Air flow plays an important role in determining the urban micro-climate and pollutant dispersion (Britter and Hanna, 2003). Regular arrays of cubic buildings have been widely investigated to understand the effect of morphological parameters, such as the plan area density λ_T λ_T and the frontal area density λ_F on the street canyon air flow dynamics (Grimmond et al., 1998). These parameters have been utilized to describe urban areas as well as to define many empirical urban boundary layer formulas. Using the alternative but related parameters, Oke (1988) distinguished 3 different urban flow regimes, depending on the street width (S) to building height (H) ratios: i) *the isolated roughness flow* for low urban roughness levels generated by large spacing between buildings ($S/H \gtrsim 3$) such that the wake of one building does not influence the next building downwind, ii) *the wake interference flow* where building wakes start to influence the subsequent downwind structures ($1/5 \lesssim S/H \lesssim 3$), and the iii) *skimming flow* for dense streets where the flow is deviated above the buildings with little penetration into the canyon ($S/H \lesssim 1.5$). This last regime is very common in urban environments and is typically associated with adverse air quality since the streets are poorly ventilated. Hosker (1987) noted that when S/H is between 1.4 and 2.4, the wake of one building interferes with the next one downstream, and that when the separation is smaller than 1.4, different vortices are generated within the canyon which depend on the aspect ratio.

The principal steady flow features in a canyon oriented perpendicular to the approach flow are now well known from various published studies (e.g. Hunter et al., 1990; Kastner-Klein et al., 2004; Kovar-Panskus et al., 2002). Variations on the different flow regimes have also been reported for example by Counehan (1971), Raupach et al. (1980). Counter rotating flow recirculations were observed for narrower street

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canyons by Liu et al. (2004), Sini et al. (1996). Although to a lesser extent, the influence of the building length (in the stream wise direction, *W)* to height ratio, as well as the influence of the angle of attack of the wind flow relative to the main street axis, have also been researched. The angle of attack for example was found to influence the formation of a mean recirculating flow in the street canyon (Yamartino and Wiegand, 1986). Modelling of street canyon pollution was the major topic of the European Research network named "Optimization of Modelling Methods for Traffic Pollution in Streets", with the short acronym TRAPOS (Berkowicz, 2001). Within this network, the influence of traffic movement on turbulence and dispersion of pollutants, the thermal effects on flow modification within street canyons, the sensitivity of the flow and turbulence characteristics to the architecture of the street, the implementation of pollution models for Environmental Impact Assessment studies, and dispersion and transformation processes of traffic-emitted particles were researched.

Most of these previous numerical and wind tunnel studies, developed to model street canyon flow and pollutant dispersion, have been devoted to the exploration of idealized building configurations, i.e. buildings of rectangular shapes and flat roofs. The influence of more complex building geometries, such as variable building heights within the street canyon or variable roof geometries, have more recently been researched but only to a limited extend. Assimakopoulos et al. (2003) studied the microscale model MIMO to take into account pollution dispersion in the vicinity of buildings; different aspect ratios were studied by changing the building height, and both street geometry and building height were reported to influence the interaction between air flow inside and above the street canyons. Baik et al. (1999) developed similar building height variation studies in a water channel as well as with numerical simulations using Reynolds-averaged Navier Stokes (RANS) simulations. They reported that, for the step-up notch geometry, a vortex is observed in the canyon, while for the step-down notch, two counter rotating vortices were observed. Rafailidis (1997), Rafailidis and Schatzmann (1996) initiated the investigation of the influence of pitched roof building arrays on street flow and pollutant dispersion to conclude that altering the roof geometry can have a bigger impact on urban air quality than modifying canyon aspect ratios. Theodoridis and Moussiopoulos (2000) compared flat and pitched roofs and reported that more complex vortex systems were developed for the pitched roof geometries and that when a pitched roof is added to a $S/H=1$ building configuration, a secondary strong vortex is developed at the roof level. Xie et al. (2005) studied pitched roofs in combination with flat roofs in different configurations to conclude that in-canyon vortex dynamics and the characteristics of pollutant dispersion are strongly dependent on roof shapes and ambient building structures. Kastner-Klein and Plate (1999) showed results that give evidence that roof shape can be an important factor in determining the vorticity dynamics in the canyon and the intensity of pollutant transport towards the downwind side of the canyon. Kastner-Klein et al. (2004) performed wind tunnel studies of wedge-shaped, flat, and pitched roofs, and tested them in various combinations to highlight that roof geometry appears to have a strong influence on the vortex dynamics and therefore also on the canyon ventilation mechanism. Huang et al. (2009) revealed that inclined roofs affect in-canyon vortex dynamics and the pollutant distribution. Yassin (2011) found that roof slopes are important for street canyon air flow and pollutant concentration. Kellnerova et al. (2012) developed wind tunnel measurements using the PIV technique to compare the flow features generated by the presence of flat and pitched roofs. They also reported that given the presence of the sharp crease of the pitched roof, behind the roof top, an intense vortex is generated. Takano and Moonen (2013) studied the critical roof angles that generated a mean recirculating flow in the street canyon. The number of vortices generated within the street canyon was found to be dependent on the roof angle.

As described above, slanted and pitched roofs have been quite extensively studied in prior literature; however, this is not the case for round roof geometries. Dezső-Weidinger et al. (2003) performed wind tunnel studies of an array of linear buildings with a round roof geometry. However, given that the main focus of that study was the exploration of a new PIV/PTV measuring technique, the flow physics obtained from the study were not extensively reported. More recently, Huang et al. (2014) studied the influence of 5 different building roof geometries, the vaulted roof, the trapezoidal roof, the slanted roof, the upward wedged roof and the downward wedged roofs, as well as three different roof-height to building-height ratios for the upstream building roof. They reported that the shape and height of an upstream roof have significant influence on flow pattern and pollutant distribution in an urban canyon. However, their studies used the RANS approach with a k-ε model, which hindered detailed analyses and validation of higher-order turbulence statistics.

Similarly, the influence of smaller roughness scale geometrical features, such as the presence of terraces in building cornices or balconies, on street canyon flow statistics have not yet been studied in detail. Therefore, the understanding as to which extent small roughness scale elements influence the street canyon air flow characteristics is yet to be fully developed. Salizzoni et al. (2008) conducted wind tunnel experiments to investigate this question over a series of street canyons and for various street canyon aspect ratios; they reported that the tested small-scale roughness elements (2D roughness elements that were added to the top of the building arrays) only influence the dynamics in the skimming flow regime, and only if they are sufficiently large to interact with the eddies generated by the building that have a scale $\sim H$. However, further research on different geometrical characteristics is necessary to understand the influence of smaller roughness scale elements such as façade or urban elements on the in-canyon and above-canyon flow conditions. Zajic et al. (2011), based on data acquired from an atmospheric measurement campaign developed in Oklahoma City during summer 2003 and which therefore would include such small features, reported on the dependence of turbulence quantities on incoming wind direction and time of the day. However, as they noted, the complexity of the flow configurations causes the flows to be largely site dependent. This limits the ability to understand the fundamental features of the flow, which as they state "is best obtained using laboratory and numerical investigations based on idealized geometries" (Zajic et al., 2011). Savory et al. (2013) also pointed out the limitations when operating on overly detailed or "realistic" setups as they called it, given that the results become too site specific. On the other hand, an over simplification can also prove limiting. The balance we strike in this paper is to analyse the flow in the last canyon of a six-identical-canyons configuration. Many urban neighbourhoods have very homogeneous building heights and roof shapes, and the flow over such areas can be seen to be "in equilibrium" with the underlying surface (i.e. flow profiles are self-similar). This implies that the inflow to each canyon (except the few ones on the edges) is similar and is determined by the homogeneous topographic features of the neighbourhood.

This choice is consequential since the influence of the upstream building geometries, as well as the inflow conditions, have been shown to be quite important when studying the mean and turbulent statistics within the urban street canyon. Brown et al. (2000) developed wind tunnel studies of a street canyon configuration composed of a seven-building array, and described the relevance of the upstream building configuration given the variability of the flow features from canyon #1 to canyon #6. They reported that only after canyon #3 or #4 can the flow be considered in equilibrium. Salizzoni et al. (2011) also studied the effect of upstream array building configurations by varying the width of the canyons upstream while maintaining the square geometry of the test canyon. They reported that momentum transfer is due to coupling between the instabilities generated in the shear layer above the canyons and turbulent structures in the ABL. Therefore, if the building arrays are widely spaced, it is likely that the levels of intensity and scales of turbulence in the ABL will be reduced. Savory et al. (2013) described