Journal of Wind Engineering & Industrial Aerodynamics 175 (2018) 328–341

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

A parametric study of the effect of roof height and morphology on air pollution dispersion in street canyons

H. Wen [1], L. Malki-Epshtein *

Department of Civil, Environmental and Geomatic Engineering, University College London (UCL), Gower Street, London WC1E 6BT, United Kingdom

ARTICLE INFO

Keywords:
CFD
Air quality
Street canyons
Urban pollution
Airflow

ABSTRACT

We investigate the effect of conventional pitched roofs on ventilation and pollution in street canyons using Computational Fluid Dynamics and a parametric approach. We studied parallel street canyons with several street morphologies, created by assigning a set of streets with pitched roofs, and varying their pitch and arrangement for three different height-to-width aspect ratios. The distribution of flow properties and pollution concentrations within the street canyons are examined and the effect of different parameter combinations is assessed. We find the relationship between these properties and the street morphology to be complex and case specific.

For most morphologies, the pitched roofs lead to higher average pollution concentrations, and in some cases to pollution hotspots near emission sources especially on the leeward side. The pitched roofs are rarely beneficial to ventilation of the street canyons, but a few roof arrangements lead to reduced concentrations on the windward side. Roof slope is shown to significantly relate to both average pollution concentrations and their distribution inside the street; in some street geometries more than others. The results have implications for pedestrian and residential pollution exposure, and for conservation of building facades on historical buildings.

1. Introduction

Street canyons, where long narrow streets are bordered by a continuous row of buildings on both sides, are a typical urban geometry in many European cities. These streets are known to suffer from poor ventilation, especially when the buildings are tall and the streets are narrow, leading to accumulation of pollution and heat in the streets. As air quality in urban environments deteriorates and the consequences of this on the health of pedestrians, drivers and residents are apparent, there is a growing recognition that we need to understand the impact of street and building geometries on air quality.

The fundamental flow regimes and pollutant dispersion principles in street canyons are generally well-understood. The pioneering study of Oke (1988), identified that when the background wind is perpendicular to the street, this results in three fundamental flow regimes between buildings depending on the aspect ratio of the building height to the street width: H/W. When the street is narrow ($H/W > 0.7$), the resulting flow regime is skimming flow, which is characterized by recirculating airflow within the street and is adverse for ventilation. Meroney et al. (1996) studied pollutant dispersion from line sources and highlighted the difference in dispersion regimes in open country and in urban settings. Sini et al. (1996) modelled thermal effects on airflow and pollutant dispersion in street canyons, and Kastner-Klein and Plate (1999) tested the significance of several street geometries in affecting street canyon flow. At a more detailed level, the dispersion around buildings is governed by a complex interaction between the atmospheric flow and the flow around buildings (Tominaga and Stathopoulos, 2013).

Many previous experimental and numerical studies are based on idealized building and street morphologies, which are rarely seen in the real world. In particular, there have been many studies assuming flat-roof buildings throughout the length of the street, for example, Uehara et al. (2000), Gu et al. (2011), Wen et al. (2013), Guillas et al. (2014) and Gromke and Blocken (2015). Karra et al. (2017) model a series of consecutive street canyons in a water channel in the laboratory and visualise with PLIF and PIV both the velocities and the release of dye from the center of the street.

Roofs are usually designed to have slopes to avoid accumulation of rain water and snow. The detailed construction of a roof is determined by locally available materials, structural factors, usage of the roof space, walkability, aesthetic architectural factors and local custom. These factors will then determine the shape of the roof and its pitch. The slope of a pitched roof is usually defined by the run divided by the rise, as

* Corresponding author.
E-mail address: l.malki-epshtein@ucl.ac.uk (L. Malki-Epshtein).
[1] Present address: Wind Power Research and Development Centre, Zhejiang University, 5-102 Jianhua Park, Hangzhou China.

https://doi.org/10.1016/j.jweia.2018.02.006
Received 13 November 2017; Received in revised form 1 February 2018; Accepted 14 February 2018

illustrated in Fig. 1 below. It is conventionally expressed as a ratio with 12 in the denominator. According to the ratio, pitched roofs can be classified into non-perfect flat roof (ratio less than 2:12), low-slope roof (2:12 to 4:12), conventional roof (4:12 to 9:12) and steep-slope roof (>9:12) (Schmid, 2014). Pitched roofs on large buildings usually have low rises, considering the cost of materials, labour and space usage (Reid, 2000). Conventional roofs are more commonly seen on residential buildings rather than large commercial or public buildings; steep-slope roof is a typical design in northern regions to prevent accumulation of snow (Reid, 2000).

Roof structure has been found to have a significant aerodynamic impact on airflow and pollutant dispersion around a building in a number of studies. Since pitched roofs are commonly found in European cities, they have been more regularly studied than other roof types. Rafailidis (1997) carried out an experimental study to compare flat roofs with 12:12 pitched roofs. From his measurements, he concluded that: "*street canyon re-aeration is influenced mainly by vertical dispersion of the pollutants (enhanced by vertical turbulence) and their subsequent advective removal horizontally by the oncoming wind*". He found that although the pitched roofs led to weaker horizontal advection at roof height than flat roofs, they significantly increased turbulence intensity above roof height (H) and up to the height of 3H. Thus, Rafailidis (1997) claimed that pitched roofs can be an effective means to increase wind-driven natural ventilation at the street opening. Leitl and Meroney (1997), Theodoridis and Moussiopoulos (2000), and Xie et al. (2005) used CFD models to reproduce Rafailidis' experiment and validated their models based on the concentrations measured by Rafailidis. All of them calculated pollution concentrations on the building walls, finding them to be higher on the windward side than on the leeward side. This result was contradictory to the typical pollutant distribution found in street canyons. However, the use of CFD modelling allowed full exploration of the flow patterns, and revealed that in this particular scenario, where the effective aspect ratio of the street was high, two counter-rotating vortices were formed below the roof-top level, which therefore led to these unexpected results.

Louka et al. (1998) conducted field measurements between two long farm buildings with 9.6:12 pitched roofs. They found that the pitched roofs greatly affected eddy size distribution in the street canyon as well as air exchange between the street and the atmosphere. In addition, their measurements suggested that the typical single vortex flow pattern did not exist in their case. Kastner-Klein et al. (2004) carried out a few experimental studies of flat roofs and 8:12 pitched roofs in urban street canyons. They found that the presence of this pitched roof on the leeward building generated unique flow patterns on the mid-vertical plane of the street: no vortex was formed on the mid-vertical plane; instead, air flowed from the windward side to the leeward side and from the bottom upwards. This observation indicated that the flow structure in the street was three-dimensional and there existed strong air flow along the length of the street.

There are a limited number of studies in the literature of street canyons with various roof shapes. Llaguno-munitxa et al. (2017) studied different roof shapes such as pitched, dome and terraced roofs and demonstrated the flow patterns around the buildings with these roofs. Yassin (2011) tested several roofs with different shapes and slopes and found that both factors had an important effect on flow field and pollutant distribution. Takano and Moonen (2013) focused their efforts on the roof slope of slanted roofs (pitched only on one side). They found that increasing the roof slope resulted in the transition from single-vortex flow regime in the street canyon to a double-vortex flow regime and found that the critical angle for the transition was around 18° for a downward slanted roof. Most previous studies demonstrated the importance of roof slope due to its aerodynamic effects on airflow, however only a limited set of roof slopes have been studied before. These were limited mainly to steep slopes with rise-to-run ratios ranging from 8:12 to 12:12, which are less common in street canyons in real urban settings. Huang et al. (2009) analysed urban morphological arrangements of slanted roofs and pointed out that a slanted roof on the leeward building had much stronger aerodynamic impacts than the same roof geometry on the windward building.

Thus, both roof geometry and the arrangement of the roofs on both sides of the street canyon play a key role in affecting the airflow, but most previous work has only focused on either the geometry or the morphology. The interaction between them is not yet clear, and in particular it is unclear how the airflows are affected by these factors, for a wide range of street aspect ratios.

In this study we conduct a parametric study of urban street canyons with pitched roofs using Computational Fluid Dynamics (CFD). The study considers a set of realistic roof slopes, positions those is several arrangements to create different street morphologies and attempts this for three different street canyon aspect ratios. The paper is structured as follows. Section 2 introduces the numerical modelling methods and settings, and describes the selected street canyon configurations for a total of thirty-nine cases, which are generated by systematically varying three geometric parameters. Section 3 describes the modelled results inside the streets, focusing on flow patterns, flow properties and the distribution of pollution concentration; the results for different cases are analysed to examine the impacts of the three parameters. Section 4 summarises the main findings. The paper concludes by discussing under which conditions, pitched roofs are beneficial or detrimental for street ventilation and pollutant removal and discusses their significance for urban planning.

2. Numerical model

The CFD modelling was carried out in ANSYS FLUENT 12.0. To reduce computational cost, all the CFD models were based on steady-state assumption and full-scale two-dimensional geometry. The background wind was set to be perpendicular to the streets, and the pollutant concentration in the background wind was set to zero. The typical street canyon flow case used for validation of the model is presented in Section 2.1. The full details of the numerical methods and CFD settings are introduced in Sections 2.2 and 2.3. Section 2.4 gives a full description of the CFD models employed in this parametric study.

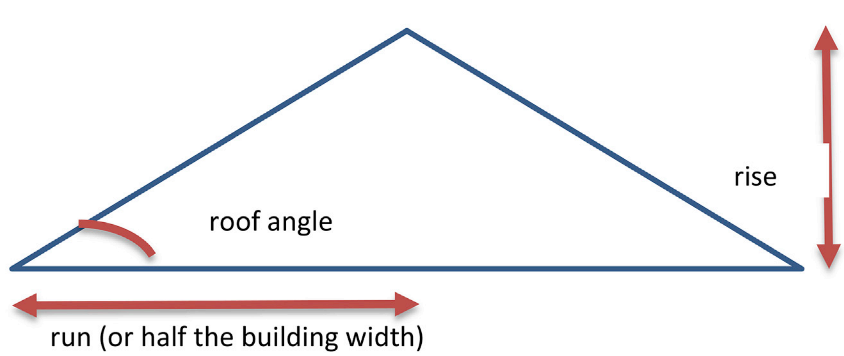

Fig. 1. A typical pitched roof.