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A wind tunnel study on three-dimensional buoyant flows in street canyons with different roof shapes and building lengths

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ABSTRACT

Higher temperatures are measured in urban areas compared to surrounding rural areas due to the urban heat island effect. One of the most efficient ways of removing heat from urban areas is wind-driven ventilation. Building configurations have a strong impact on the wind flow patterns and therefore on the heat removal from urban areas. Buoyancy can promote heat removal by inducing three-dimensional flow structures. This prevents the formation of standing vortices in street canyons, which are formed for forced convective flow regimes and trap heat inside the street canyons. A wind tunnel study is conducted for street canyons in an urban area. The wind tunnel floor is heated to different temperatures to induce buoyancy. The flow structures are measured with PIV (Particle Image Velocimetry) on horizontal and vertical planes within the street canyon and the air temperatures are measured with an approach based on infrared thermography. The flows entering the street canyon through the lateral sides are measured on a horizontal PIV plane. These lateral flows can be found for buoyancy driven flows and are important, since they prevent the formation of standing vortices. To improve the heat removal in forced convective flows, different roof shapes and heights are studied and the lengths of the street canyon buildings are varied. The results show that lateral flows can be found for street canyons with non-uniform building heights and that the air temperatures are decreased in such street canyons due to the improved ventilation.

1. Introduction

It is well known that the air and surface temperatures in urban areas are higher compared to surrounding rural areas due to the urban heat island effect [24]. In addition to the heat island effect at city-scale, also local heat islands at the urban neighbourhood scale can be found in cities [4]. The urban and local heat island intensities are expected to further increase due to the continuous growth of cities [32] and climate change. This will lead to even harsher urban climates in the future. The high temperatures in urban environments have a strong impact on space cooling demands of buildings [28] and the thermal comfort [30] and health [26] of inhabitants of urban areas.

For a wide range of applications, it is important to understand the urban microclimate and therefore a large number of urban microclimate studies can be found in literature. Overviews of such studies are given for example by Refs. [8,22] and [23]. To study the urban climate mostly numerical simulations (e.g. CFD: Computational Fluid Dynamics) or laboratory experiments (e.g. wind tunnel measurements) are conducted. Also a number of detailed field measurement campaigns can be found in literature (e.g. Refs. [9,27] and [7]). In a large number of studies, urban street canyons are used as a representation of urban environments. Common assumptions are that the flows in urban street canyons are isothermal and that the street canyon buildings have uniform heights and flat roofs. Further often (infinitely) long street canyons are studied focusing on quasi two-dimensional flows within the street canyons. In reality, flows in urban environments are buoyant for critical weather conditions with high air and surface temperatures and low wind speeds. Buoyant flows are in urban areas mostly three-dimensional and therefore studies in which the flow fields are modelled to be two-dimensional might lead to misleading results. Also non-uniform building heights and varying roof shapes can lead to fully three-dimensional flows.

A number of experimental and numerical studies on the impact of buoyancy on urban flows have been conducted [18] studied buoyant street canyon flows with windward wall heating in a wind tunnel and found a weak secondary vortex that was induced by buoyancy close to the ground of the canyon [19] conducted water tank measurements of buoyant flows in a street canyon with bottom heating. The study

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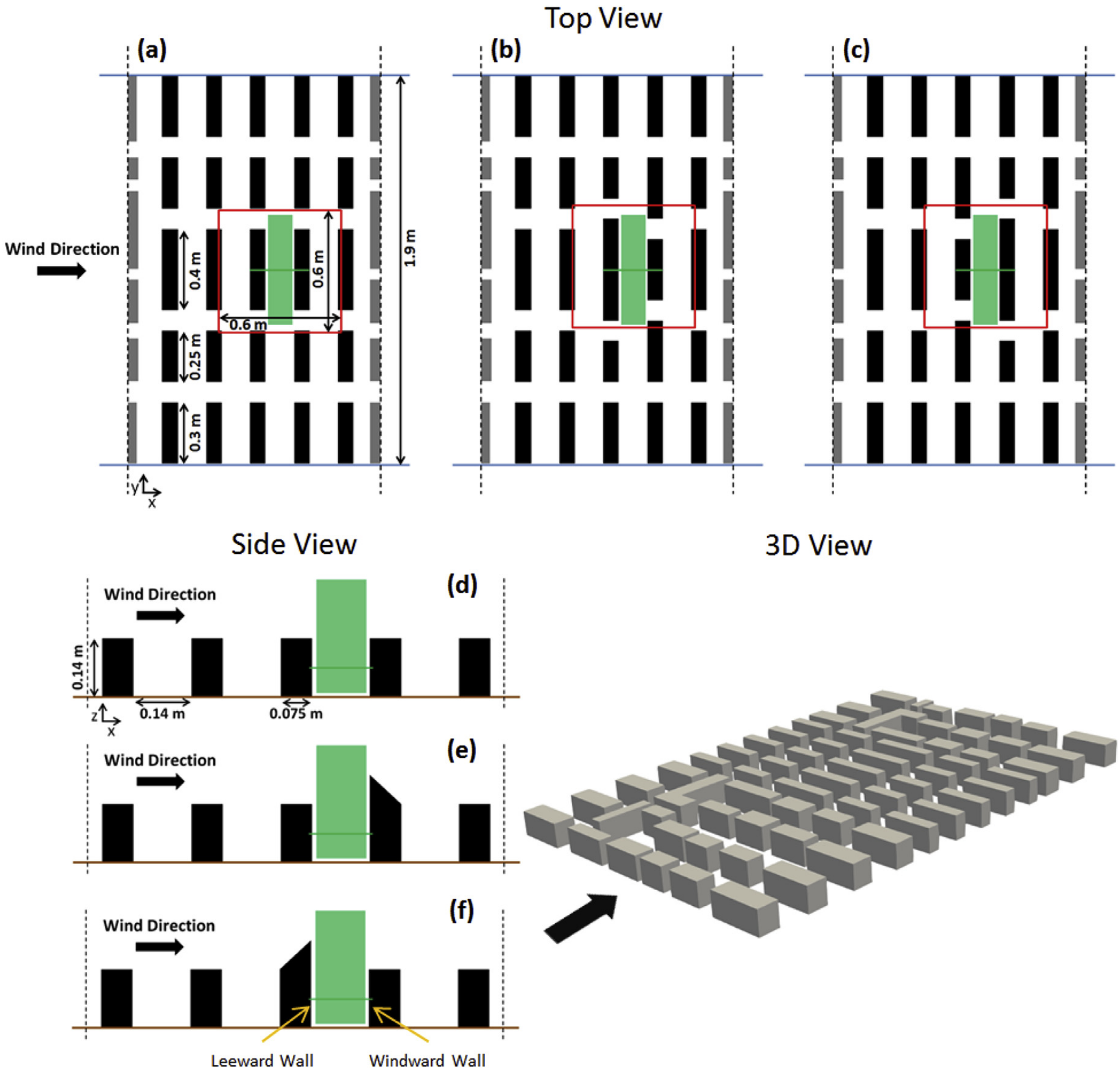

Fig. 1. Sketches of the different street canyon configurations. The positions of the horizontal PIV planes are given as green surfaces and the positions of the vertical PIV planes are given as green lines in the top view. For the areas within the red lines (top view), the wind tunnel floor is heated. In the side view the positions of the vertical PIV planes are given as green surfaces and the horizontal PIV planes are given as green lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

indicated that bottom heating can strengthen the intensity of the main vortex in a street canyon. Another wind tunnel study for quasi-two-dimensional flows in urban street canyons was conducted by Ref. [1]. They heated the different street canyon surfaces individually and found a strong impact of buoyancy on the vortex structures inside the studied street canyon. Similar studies have also been conducted using two-dimensional CFD simulations [34] and [20] studied buoyant flows in street canyons with different aspect ratios and found similarly to [1] a strong influence of buoyancy on the vortex structures [21] found additionally that the flows in street canyons are dependent on the number of street canyons in the neighbourhood. For all these studies, the flow in urban street canyons was modelled as quasi-two-dimensional with a wind direction normal to the street canyon axis. Therefore flows in lateral directions were not modelled in CFD or blocked in laboratory measurements. In real urban environments street canyons have a finite length and lateral flows can be important especially for buoyancy-driven flows [17] studied these lateral flows in an array of buildings with CFD and found an increase in lateral wind velocities due to buoyancy [11] did not block the lateral flows for their wind tunnel measurements on buoyant flows in a street canyon. They did not focus

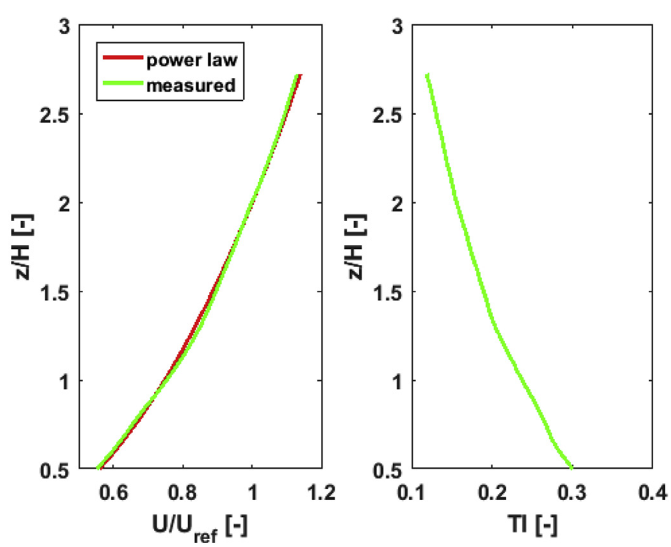

Fig. 2. Boundary layer profiles of normalized wind speed and turbulence intensity.