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Wind tunnel measurements of buoyant flows in street canyons

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ABSTRACT

At day-times building façades and ground surfaces are heated by solar radiation. Due to the increased surface temperatures, buoyancy is induced which changes the flow field around buildings significantly. Wind tunnel measurements were conducted to study the influence of buoyancy on the flow in a scaled urban street canyon with heated surfaces. Particle image velocimetry was used to measure the flow field in a section of the street canyon. The two wall and the bottom surfaces of the street canyon were heated either individually or all together. A wide range of Froude numbers between 0.65 and 17.3 was covered with surfaces temperatures raised up to 70 °C–130 °C and freestream velocities between 0.68 m/s and 2.32 m/s. The velocity and turbulent kinetic energy (TKE) fields were analysed, and for some cases also the air temperatures inside the street canyon were measured. For most cases one main vortex is formed in the centre of the street canyon. This main vortex is strengthened, and the TKE inside the street canyon increased by, heating of (in order of importance) the ground, the leeward wall, and all three surfaces for low freestream velocities. For windward wall heating a second counter-rotating vortex is formed due to buoyancy and the flow direction close to the windward wall changes from a downward to an upward motion. The centres of the main and secondary vortex change their position for different windward wall temperatures with increasing freestream velocities. For low Froude numbers the air exchange rate is increased due to buoyancy.

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1. Introduction

Today about 50% of the population lives in urban areas. This proportion will rise to 70% within the next 40 [1]. With increasing urbanisation the understanding of the urban microclimate is of great importance. The urban microclimate influences the human comfort of the pedestrians and has an impact on the health of the residents. The ventilation and removal of pollutants from urban areas is strongly depending on the wind flow structures. Minimizing the energy demand of buildings in urban areas has also a great energy-saving potential [2]. The energy demand is amongst others influenced by the temperature in the street canyon and the convective heat flux at the building façades and therefore by the flow field around the buildings. In street canyons buoyancy plays a very important role. During the day the building façades are heated by solar radiation. The heated walls induce buoyancy, what significantly affects the flow field in street canyons (e.g. [3,4]). For a hot summer day with calm winds and high façade temperatures buoyancy has an important impact on the convective heat fluxes at the building facades and thus on the removal of heat from the building and from the street canyon. Some experimental studies have been conducted to analyse buoyant flow fields inside street canyons. Kovar-Panskus et al. [4] investigated the flow field in a street canyon by means of wind tunnel measurements. Maximum windward wall temperatures of 120 °C were used in combination with wind speeds of 0.5–1 m/s (Froude numbers: 0.27–2.03; see Equation (2) for the definition of the Froude number). Kovar-Panskus et al. [4] found only a very weak secondary vortex that was induced by buoyancy close to the ground of the canyon. Liu et al. [5] conducted water tank measurements of flows inside a non-symmetrical street canyon with bottom heating. Instantaneous flow field measured with PIV (Particle Image Velocimetry) were analysed. The study indicated that the bottom heating can strengthen the intensity of the main vortex in the centre of the street canyon and that the flow was completely driven by buoyancy for low ambient wind speeds. Garbero et al. [6] performed wind tunnel measurements of street canyons with different aspect ratios and heated windward and leeward walls (Froude number: about

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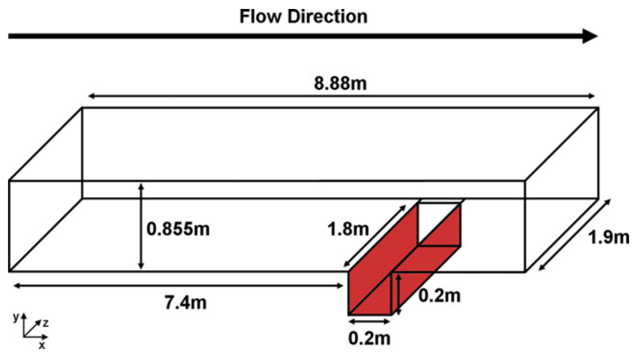

Fig. 1. Dimensions of the wind tunnel model.

60). Only for the narrow street canyon with windward wall heating they found a significant influence of buoyancy on the vortex structure. Uehara et al. [7] conducted experiments in a wind tunnel with thermal stratification. The vortices in the street canyons were weaker for stable than for unstable stratifications. For cases with very stable stratification the wind speeds inside the street canyons almost dropped to zero. Field measurements have been carried out by Louka et al. [8] in a street canyon in Nantes (France). The flow field was visualized with non-buoyant balloons. They observed a strong upwards motion close to those walls which were heated by the sun. In contrast to the CFD (Computational Fluid Dynamics) simulation predictions, the effects of buoyancy were only present in a thin layer close to the walls. Besides the experimental studies, also a number of CFD studies of buoyant flows in urban street canyons can be found in literature (e.g. [3,9]), showing mostly a stronger effect of buoyancy when compared to the experiments. Several wind tunnel studies of flows in street canyons under isothermal conditions have been conducted and reported in literature (e.g. [10–14]). For wind directions normal to the street canyon axis one main vortex in the centre of a street canyon and small corner vortices are formed. The wind velocity magnitudes inside the street canyon are strongly decreased compared to the freestream velocities.

The aim of this study is to investigate experimentally by PIV the influence of wall and ground heating on the flow field inside a street canyon. To characterise the flow field a method to track the centres of the vortices inside the street canyon for different freestream velocities and surface temperatures is proposed in this paper. The dimensions of the street canyon were chosen to be similar to the dimension of the model used by Kovar-Panskus et al. [4] for their experiments. Compared to the study by Kovar-Panskus et al. [4] not only the windward wall but also the leeward wall and the ground were heated and higher surface temperatures were achieved. Compared to the other experimental studies on buoyant flows in street canyons mentioned above, the actual experimental setup allows for a wider range of configurations (windward wall, leeward wall and ground heating and all surface heated) and related flow fields and has the advantage that all flow fields were

Table 1
Surface temperatures and freestream velocities with corresponding Reynolds and Froude numbers.

	70 °C	90 °C	110 °C	130 °C
0.68 m/s (Re = 9000)	1.49	1.04	0.80	0.65
1.07 m/s (Re = 14200)	3.68	2.58	1.99	1.62
1.45 m/s (Re = 19200)	6.75	4.74	3.65	2.97
1.86 m/s (Re = 24600)	11.11	7.79	6.00	4.88
2.32 m/s (Re = 30700)	17.29	12.13	9.34	7.59

measured under the same conditions in the same wind tunnel. Further a PIV measurement system with a high spatial resolution was used. Therefore the measured flow fields are better resolved compared to the experimental studies found in literature, allowing to also resolve smaller flow structures (e.g. corner vortices). Besides the characterisation of the flow field another purpose of this study is to provide detailed data of flow fields that can be used for future validations of CFD simulations.

The structure of the paper is as follows. In section 2 similarity criteria are discussed. In section 3 the experimental setup and the different studied cases are presented. The results are given in section 4. First the velocity and TKE fields are studied together with the trajectories of the vortex centres and then temperature field for specific cases are analysed.

2. Similarity criteria

Because scaled street canyon models have to be used in the wind tunnel, some criteria have to be fulfilled to get a similar flow field compared to a full-scale street canyon with a similar geometry. A first similarity criterion is the Reynolds number:

$$\mathrm{Re} = \frac{U_{FS}H}{\nu} \tag{1}$$

where U_{FS} is the freestream velocity, H the street canyon height and ν the kinematic viscosity.

Due to the high scaling factors, it is not possible to reach the same Reynolds number in the wind tunnel as can be found in full-scale. For flows around bluff bodies this is not required. The Reynolds number needs to be above a critical Reynolds number to guarantee Reynolds independent flow. Different values for the critical Reynolds number are proposed in literature for flows in atmospheric boundary layers (e.g. [7,15–18]). For the scaled street canyons studied here, the critical Reynolds number is about 13000 (see section 4.2), while the flow fields studied have Reynolds numbers between 9000 and 30700 (using the kinematic viscosity at a temperature of 23 °C).

To characterise the flow in terms of buoyancy the Froude number was used in this study:

$$\mathrm{Fr} = \frac{U_{FS}^2}{gH\dfrac{T_w - T_{ref}}{T_{ref}}} \tag{2}$$

where U_{FS} is the freestream velocity, T_w is the surface temperature of the heated wall, T_{ref} a reference temperature (here the temperature of the freestream) and g is the gravitational acceleration.

Small Froude numbers correspond to buoyant flows and high Froude numbers to forced convective flows. To be in a similar range of Froude numbers in the wind tunnel compared to full-scale, very high surface temperatures are needed. In wind tunnels, full Reynolds similarity cannot be realized for highly scaled building models. However, we measured in the Reynolds independent turbulent flow regime, above the critical Reynolds number, which is model geometry dependant. Here it can be assumed that the flow structure is similar also for higher full-scale wind speeds. Because in the wind tunnel the Reynolds numbers are much lower than in full-scale it is not possible to relate the wind speed in the wind tunnel to a realistic full-scale wind speed. As an example, for a scaling factor of 100 and a the highest freestream wind tunnel velocity used in this study (2.32 m/sec), Reynolds number similarity would correspond to a very low full-scale wind speed of 0.0232 m/s. Due to the missing relation between the wind tunnel wind speed and a realistic full-scale wind speed, it is also not

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