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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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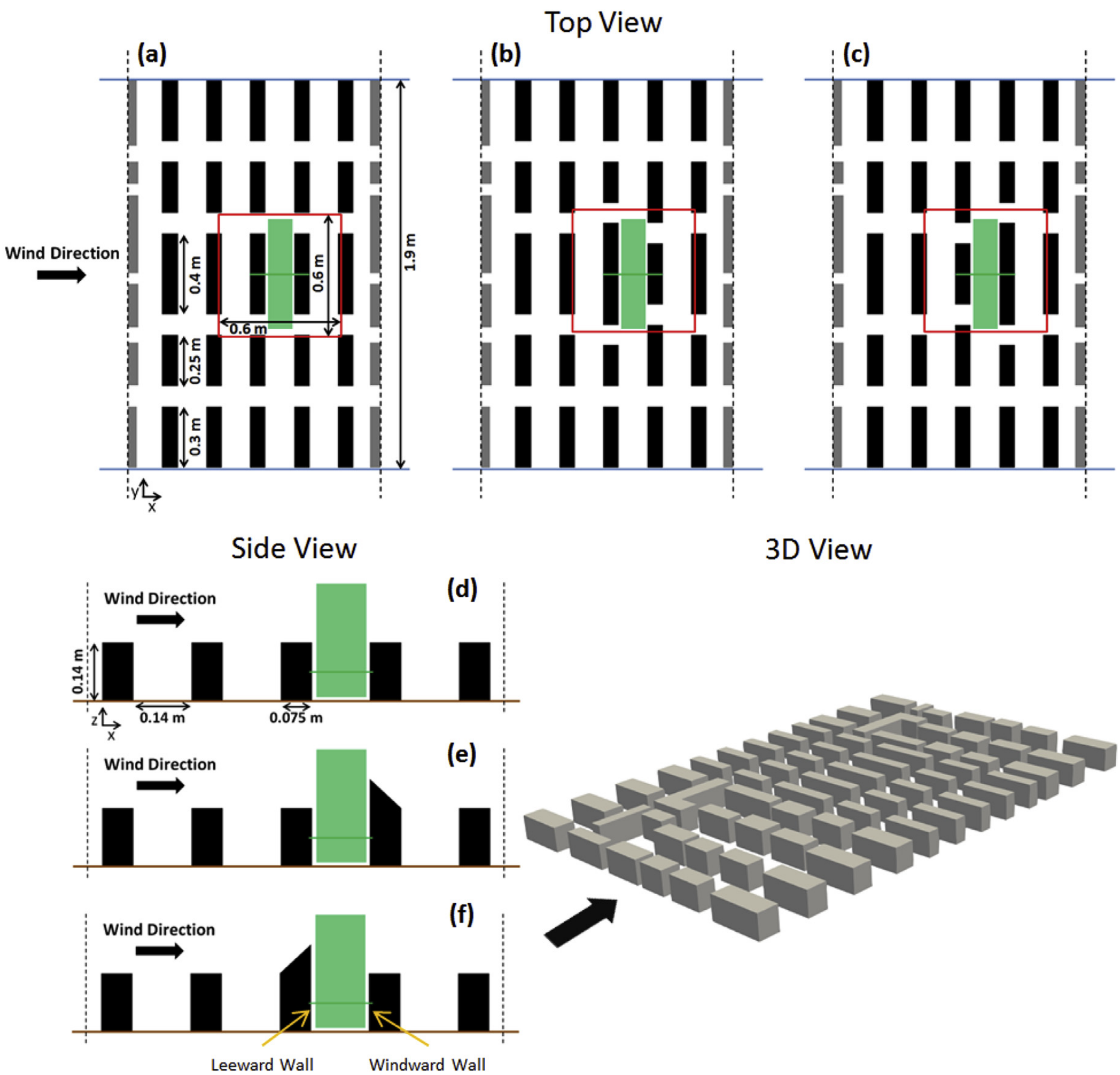

Fig. 1. Sketches of the different street canyon configurations. The positions of the horizontal PIV planes are given as green surfaces and the positions of the vertical PIV planes are given as green lines in the top view. For the areas within the red lines (top view), the wind tunnel floor is heated. 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

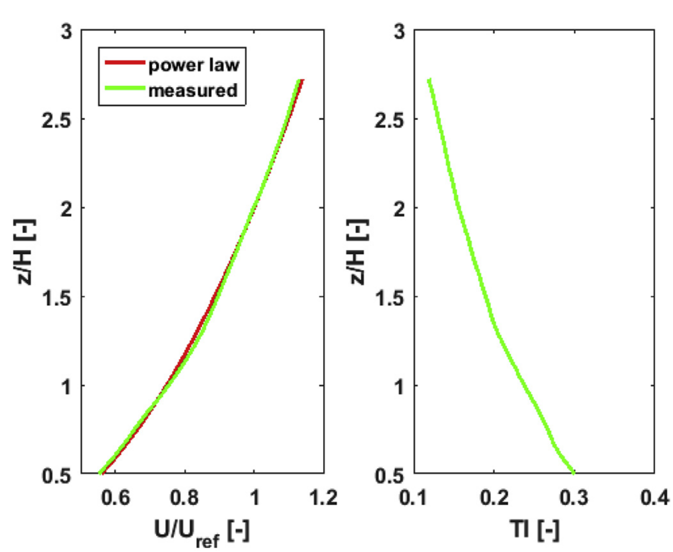

Fig. 2. Boundary layer profiles of normalized wind speed and turbulence intensity.

on the lateral flows and since they studied an isolated street canyon, the flow structures on the lateral sides of the street canyon might differ significantly from flow structures in urban environments [2] and [3] studied the local microclimate for different urban morphologies using CFD. They showed that buoyancy increases the vertical heat exchange and by that improves the heat removal efficiency. In a similar study [5], showed that buoyancy increases the vertical wind speeds in urban areas, which leads to increased lateral wind speeds causing cold air to enter to regions with high air temperatures. This effect was not only found for generic building configurations, but also for a case study simulating the local heat islands in a neighbourhood of the city of Zürich (Switzerland) [4].

The importance of the roof shapes of street canyon buildings has been shown in literature. The wind tunnel measurements of [16] show that pitched roofs produce more turbulence compared to flat roofs, which improves the ventilation of urban street canyons. This effect is more significant for narrow street canyons as shown by Ref. [12] with water tunnel measurements [14] studied a wider range of different roof shapes with two-dimensional CFD simulations and found a strong impact of the roof shapes on the vortex structures in street canyons. Similar conclusions were also drawn by Ref. [29]; who systematically varied the roof slopes of street canyon buildings. All these studies on roof shapes, modelled the flow in street canyons as two-dimensional. However, roofs can potentially induce three-dimensional flow structures, if they for example catch wind from the roof level and divert it into the street canyon. In this case, the air would leave the street canyon through the lateral sides.

The aim of this study is to investigate the three-dimensional flow structures for buoyant and forced convective flows in street canyons. Since three-dimensional flow structures with lateral flows in street

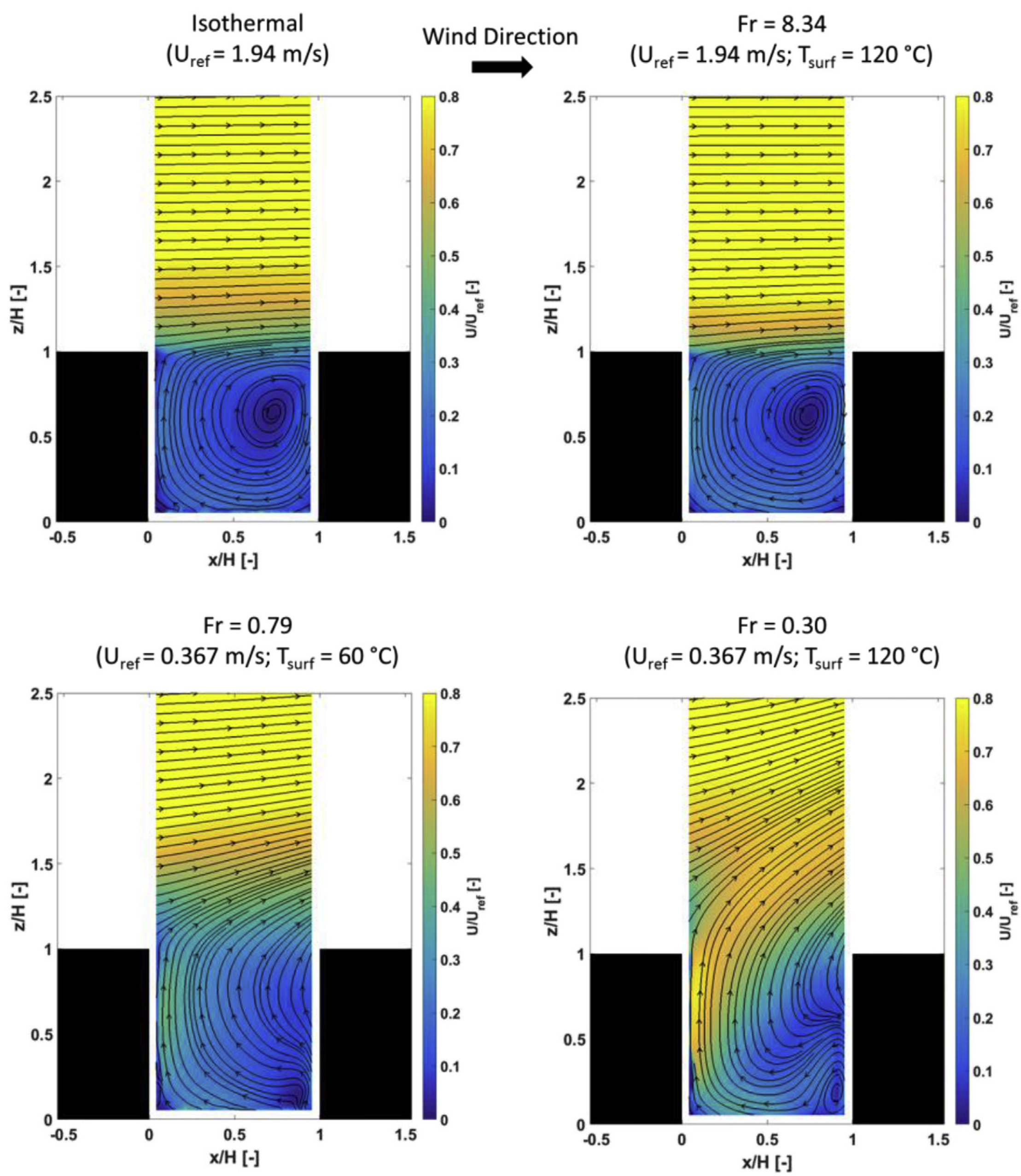

Fig. 3. Normalized (in-plane) wind speeds and streamlines for Case A on the vertical PIV plane. Results are given for isothermal conditions as well as for three different Froude numbers.

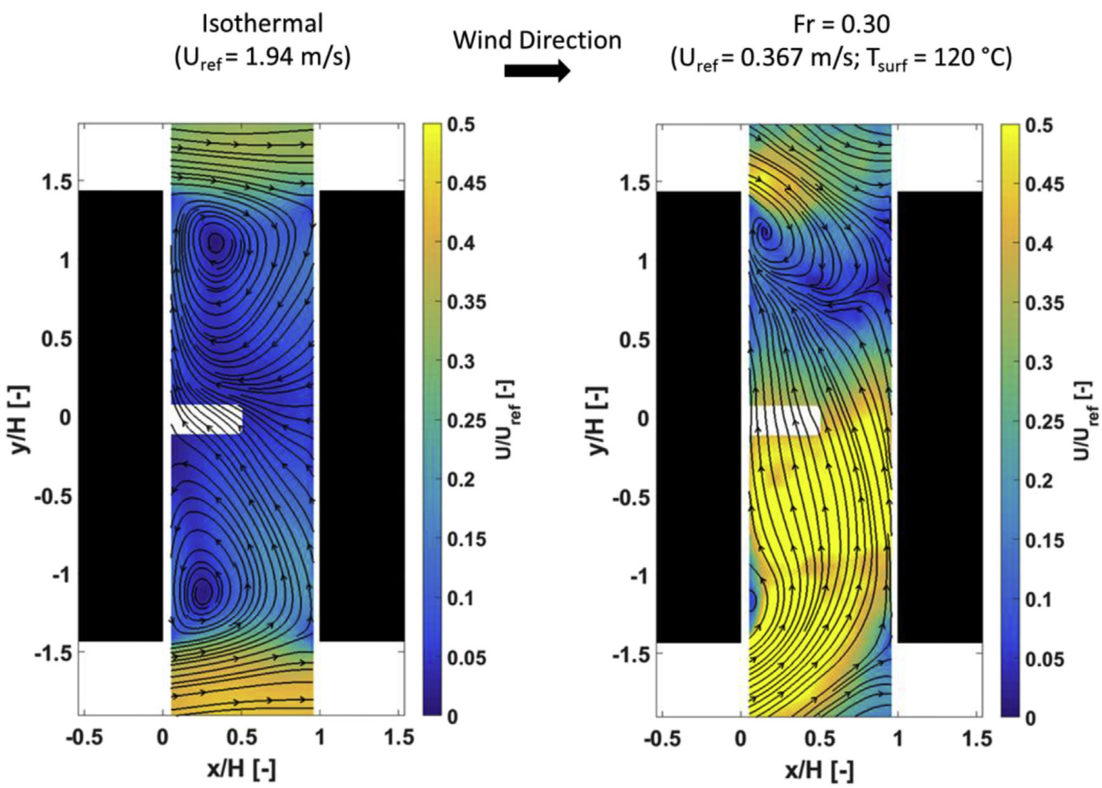

Fig. 4. Normalized (in-plane) wind speeds and streamlines for Case A on the horizontal PIV plane. Results are given for isothermal conditions as well as for the most buoyant conditions.

canyons can promote heat removal, the roof shapes and building lengths are varied to induce lateral flows. The study is conducted in a wind tunnel and the flow fields are measured with PIV (Particle Image Velocimetry). The flow fields are measured on vertical planes as well as horizontal planes to capture the three-dimensional structures of the flows. The wind tunnel floor is heated to induce buoyancy. The measurements are conducted for different mixed and forced convective flow regimes. Velocity and turbulent kinetic energy fields are analysed to study the flow structures. Additionally, the air temperatures in the street canyons are measured indirectly by placing a target made out of felt in the street canyon and taking infrared images of the target. By analysing the flow fields together with the temperature fields, the heat removal potential of the street canyon configurations can be evaluated indirectly. A more direct way of evaluating the heat removal would be beneficial, but this is not possible to evaluate the heat removal directly based on the flow fields measured with planar PIV in this study. Stereoscopic PIV measurements at the surfaces of a control volume surrounding the studied street canyons would be needed together with spatially resolved air temperatures on the same planes to determine directly the heat fluxes.

The structure of the paper is as follows. The details of the model geometries, the wind tunnel and the measurement system are given in Section 2. In Section 3 the results of the wind tunnel measurements are given for the different studied cases. In Section 4 the limitations of this study are discussed and in Section 5 the conclusions from the results of this study are drawn.

2. Experimental setup

2.1. Model geometry and studied cases

The study presented in this paper is conducted for a generic urban area consisting of four street canyons, which are formed by 25 buildings. In total 42 buildings with similar shapes as the street canyon buildings are placed up- and downstream of the four street canyons to develop an urban boundary layer in the wind tunnel. These buildings are part of an urban neighbourhood designed by Ref. [31] for their wind tunnel measurements. In Fig. 1 the different studied street canyon configurations are presented. The street canyon buildings are given in black and the nearest surrounding buildings are given in grey (top view). In the 3D view the geometries of all the buildings placed in the wind tunnel are shown. In Fig. 1 also positions of the PIV planes are given. Further, it is indicated which street canyon surfaces are referred to as windward and leeward walls in the paper. In a square area of 0.6 m × 0.6 m the wind tunnel floor is heated to different temperatures (Fig. 1) to simulate high street surface temperatures caused by absorption of solar radiation. The analysis of this study focuses on the street canyon in the centre of the heated area. In total five different street canyon configurations are studied:

- Case A: Base case, where both street canyon buildings of the studied street canyon have the same length (Fig. 1a) and the same heights with flat roofs (Fig. 1d).
- Case B: Both street canyon buildings have the same length (Fig. 1a). The upstream street canyon building has a flat roof and the downstream building has a wedged roof (Fig. 1e).
- Case C: Both street canyon buildings have the same length (Fig. 1a). The upstream street canyon building has a wedged roof and the downstream building has a flat roof (Fig. 1f).
- Case D: The upstream building of the street canyon is 0.5 m long and the downstream building is 0.3 m long (Fig. 1b). Both street canyon buildings have the same heights and have flat roofs (Fig. 1d).
- Case E: The upstream building of the street canyon is 0.3 m long and the downstream building is 0.5 m long (Fig. 1c). Both street canyon buildings have the same heights and have flat roofs (Fig. 1d).

The wind tunnel models are scaled with a factor of 1:200 and are 0.14 m high (H) (buildings with wedged roofs are 0.21 m high),

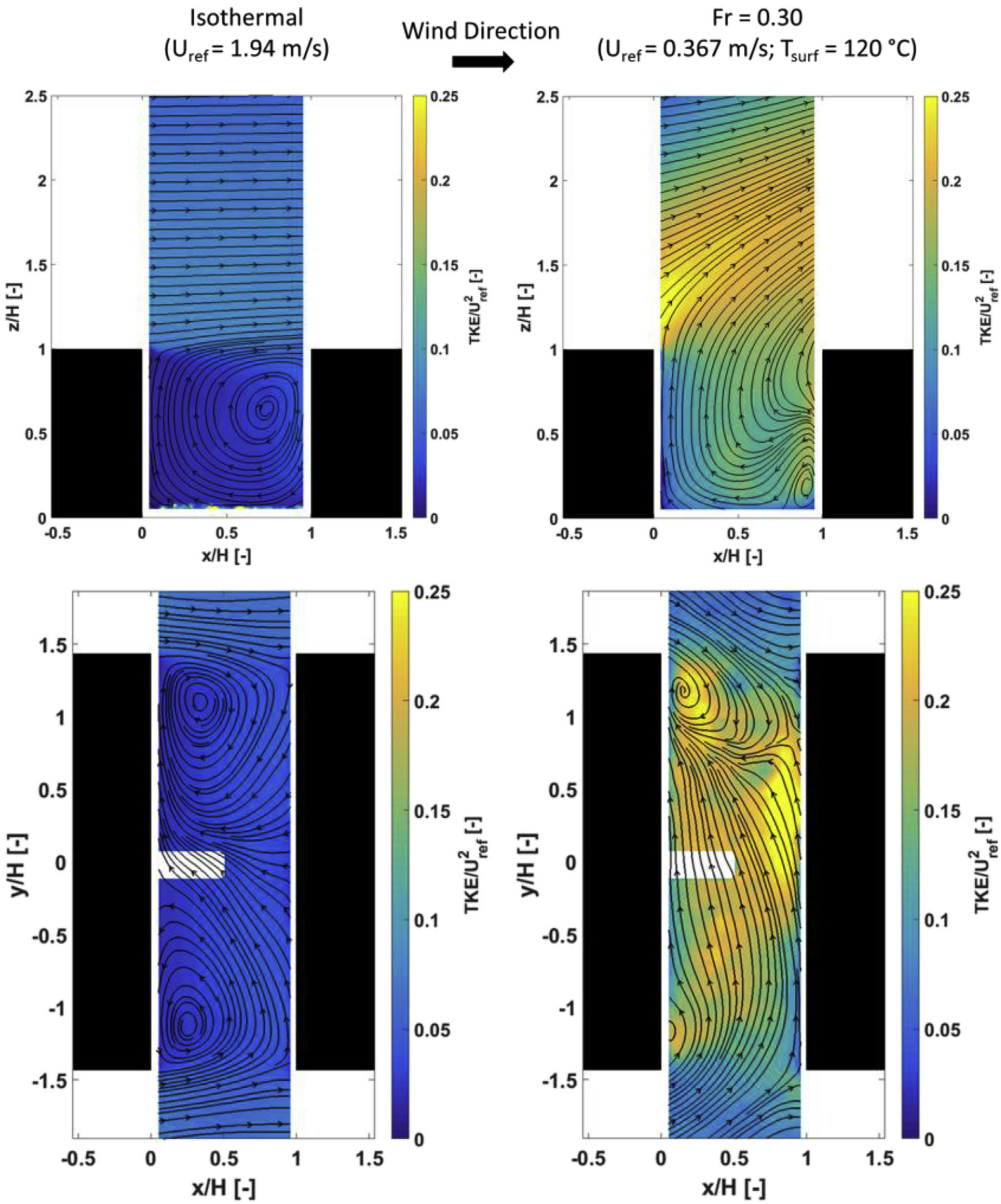

Fig. 5. Normalized turbulent kinetic energies and streamlines for Case A. Results are given for isothermal conditions as well as for the most buoyant conditions on the vertical and horizontal PIV planes.

0.075 m wide (W) and have different lengths. All other dimensions are given in Fig. 1. The wind tunnel models are made out of wood and covered with black paper to limit the laser light reflections for the PIV measurements. The building models, which are placed on the heated part of wind tunnel floor, are insulated with a 0.01 m thick layer of cork to avoid heating up. The heated part of the wind tunnel floor is made out of aluminium plates and is heated with heating mats from below. Due to heat losses at the edges of the heated plates, the temperatures at the edges are 2.8 °C lower compared to the centre for the surface temperature of 120 °C and 1.7 °C for the surface temperature of 60 °C (measured with thermocouples). The non-heated part of the wind tunnel floor is made out of wood. To create a scaled atmospheric boundary layer four Irwin-type spires, a barrier with castellation and roughness elements is installed in the wind tunnel upstream of the modelled urban neighbourhood. These elements have originally been installed by Ref. [31] for their measurements. The simulated atmospheric boundary layer (measured above the roughness elements) is fully developed and has a power law exponent of 0.38 and a turbulence intensity of 30% close to the ground (decreasing in vertical direction) and therefore corresponds to a very rough atmospheric boundary layer [33] (Fig. 2). Such boundary layers can be found in inner-city areas.

2.2. Operating conditions

The wind tunnel tests are conducted for two different wind speeds (0.367 m/s and 1.94 m/s at 2H above the wind tunnel floor). The wind direction is for all cases normal to the axis of the studied street canyon. Isothermal cases as well as the cases with two different ground surface

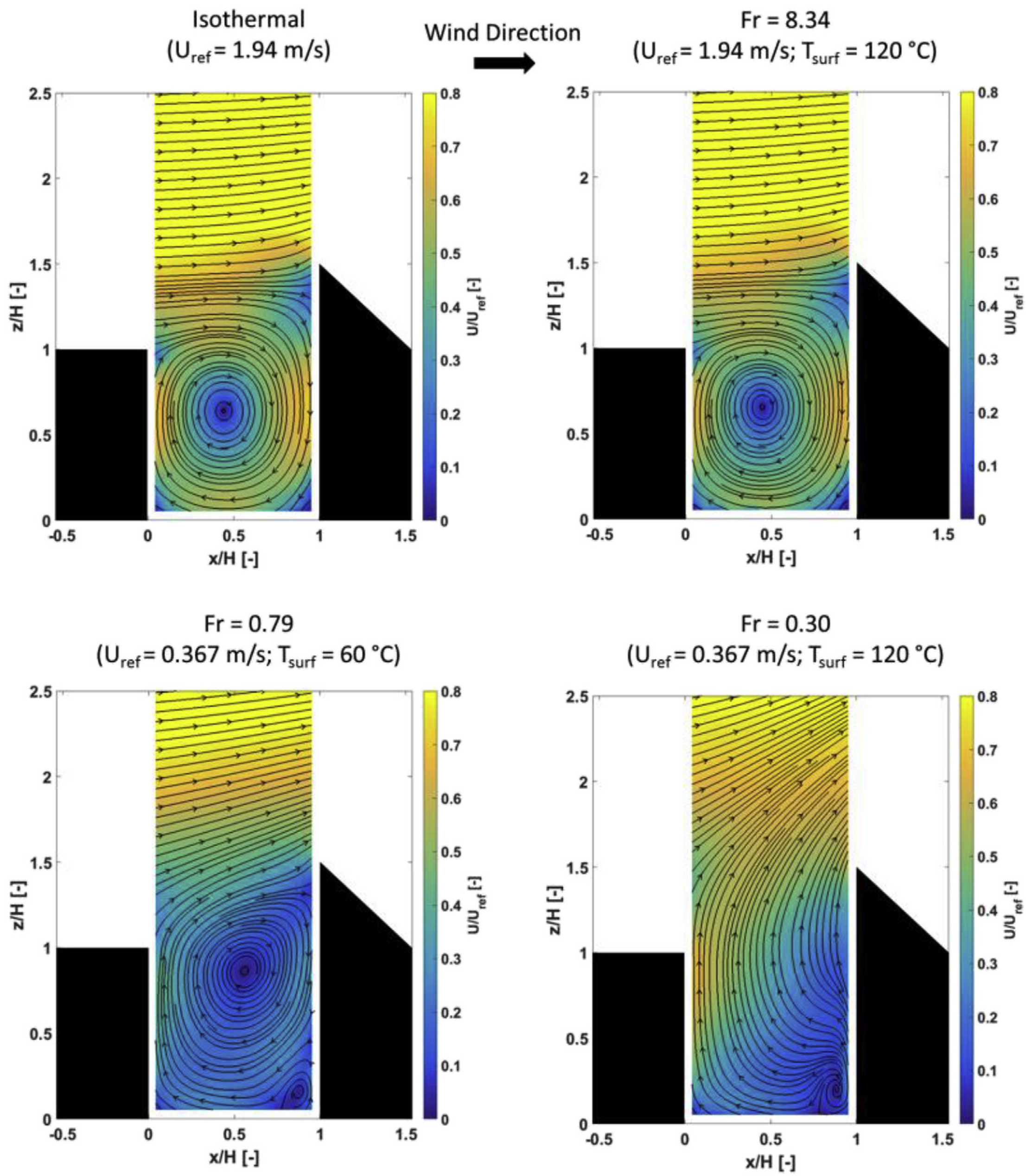

Fig. 6. Normalized (in-plane) wind speeds and streamlines for Case B on the vertical PIV plane. Results are given for isothermal conditions as well as for three different Froude numbers.

temperatures (60 °C and 120 °C) are studied. To characterise the flow in terms of buoyancy the Froude number is used in this study:

$$Fr = \frac{U_{ref}^2}{gH\frac{T_S - T_{ref}}{T_{ref}}} \tag{1}$$

where U_{ref} is the reference velocity, T_S is the surface temperature of the heated ground, T_{ref} a reference temperature (here the temperature of the approach flow) and g is the gravitational acceleration.

Small Froude numbers correspond to buoyant flows, Froude numbers of about one to mixed convective and high Froude numbers to forced convective flows. Therefore the studied street canyon flows are in mixed to forced convective flow regimes with Froude numbers between 0.30 and 21.9. The approach flow temperature is 23 °C for all studied cases.

2.3. Experimental facility and measurement systems

This study is conducted in the closed circuit ETH/Empa atmospheric boundary layer wind tunnel in Dübendorf (Switzerland). The test section is 1.9 m wide and 1.3 m high. The flow fields in the studied street canyons are measured using planar PIV on a vertical plane in the centre of the wind tunnel and on a horizontal plane at 0.5H above the wind tunnel floor (see Fig. 1). For the PIV measurements, the flow is seeded with DEHS (Di-Ethyl-Hexyl-Sebacat) aerosol particles with a diameter of 1 µm. The PIV images are acquired with a 2560 pixels x 2160 pixels sCMOS camera. The camera is equipped with a 50 mm F1.2 Canon lens. The particles are illuminated by a pulsed 200 mJ/pulse Nd:YAG double cavity laser. The recording frequency is 15 Hz and 3000 double frame images are acquired. The laser and camera are installed outside of the wind tunnel, which has windows to have optical access. The image acquisition and PIV vector processing are performed with the software DynamicStudio from Dantec. The velocity vectors are calculated using

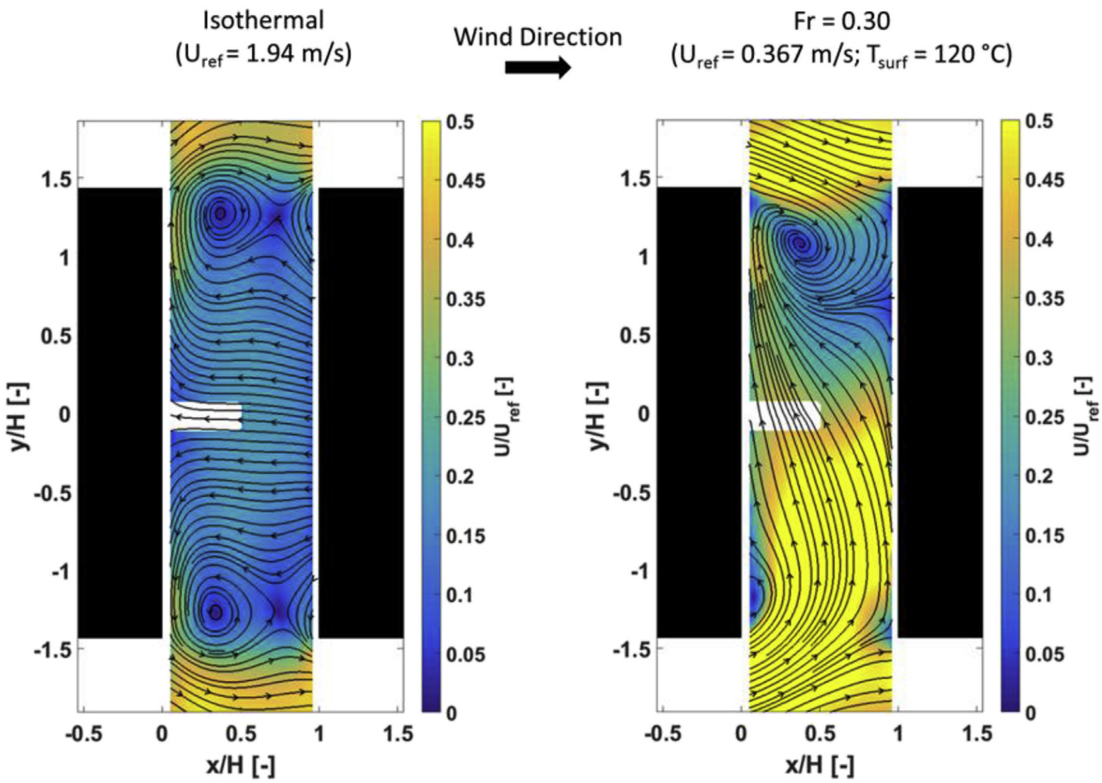

Fig. 7. Normalized (in-plane) wind speeds and streamlines for Case B on the horizontal PIV plane. Results are given for isothermal conditions as well as for the most buoyant conditions.

an iterative cross-correlation algorithm. The final interrogation area is 32 pixels x 32 pixels with a 50% overlap. Best practice guidelines for PIV [10,15,25] are taken into account to reduce the measurement uncertainties. The uncertainties (ε) are estimated to be 2–4% with a confidence interval of 95% using the following equation:

$$\varepsilon = 1.96\frac{\sigma}{\mu\sqrt{N}} \tag{2}$$

where σ is the standard deviation of the velocity, μ is the average of the velocity and N the number of independent samples.

On the same vertical plane on which the flow fields are measured with PIV, the air temperatures are measured using infrared thermography. For this measurement technique a target consisting of a thin black felt sheet is placed in the centre of the studied street canyon. The felt is mounted on a frame made out of wires and is not touching the street canyon surfaces, to prevent heat conduction from the heated ground surface. Due to the convective heat transfer with the air in the street canyon, the felt has approximately the same temperature as the air. The felt temperature is then measured with infrared thermography. This measurement technique is presented in Ref. [6]. A similar measurement technique was also used by Ref. [13] to measure air temperatures during field measurements. The felt has a low thermal conductivity to assure that the felt is only heated by the air and not by heat conduction. For the infrared thermography an Optris PI 640 camera with a resolution of 640 pixels x 480 pixels is used. The camera has an accuracy of 2 °C. At one location of the felt (with maximal distance from the heated wind tunnel floor) the temperature is additionally measured with a Pt 100 sensor (platinum resistance thermometer with a nominal resistance of 100 Ω) to calibrate the infrared camera. 60 infrared images are acquired with a frequency of 1 Hz. The uncertainty of the temperature measurements is estimated to be 5 °C. This rather high uncertainty is caused by the fact that the felt exchanges longwave radiation with the surroundings and heat conduction through the felt cannot be completely avoided. The estimation of the uncertainty is based on a sensitivity test that was conducted before the measurements. For this sensitivity test a small piece of felt was used, which could be shielded from longwave radiation with only a minor effect on the flow field. The temperatures were measured with and without shielding for comparison. The effect of heat conduction on the uncertainty was estimated by locally heating the felt and measuring the effect of the local heating on the surrounding felt temperatures. Additionally, the felt disturbs the flow field, what can lead to different temperature distributions compared to conditions during the PIV measurements, when the felt is not installed. Therefore, the air temperature measurements are only used to qualitatively access the impact of different street canyon configurations on the local air temperatures and not to measure local temperatures with high accuracy. Note that not the absolute values are studied here, but the temperature differences between the different cases.

3. Results

In this section the results of the wind tunnel measurements are given. First the flow fields of the five studied cases are discussed and then the impact on the air temperatures is presented.

3.1. Case A

Case A is the base case and has a commonly studied geometry. It is a street canyon with an aspect ratio (defined as the street canyon building height divided by the street canyon width) of one. Fig. 3 presents the normalized wind speeds in and above the street canyon for different forced and mixed convective conditions. Additionally also the streamlines are given in the figure to visualise the flow structures. As expected, a standing vortex can be found in the street canyon for isothermal conditions. The wind speeds inside the street canyon are strongly reduced compared to the wind speeds in the atmospheric boundary layer. Due to the high velocity gradients a shear layer between the flow above

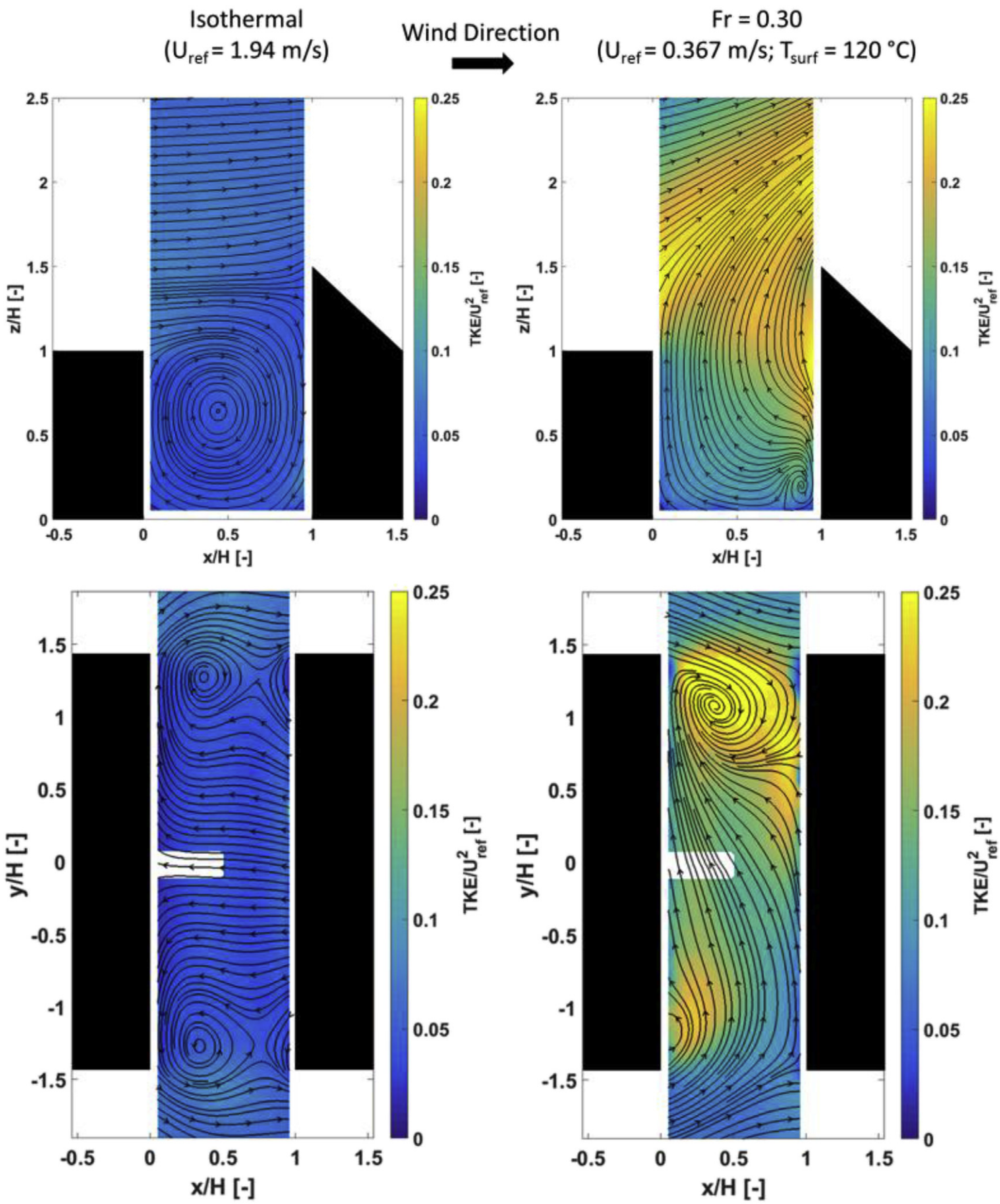

Fig. 8. Normalized turbulent kinetic energies and streamlines for Case B. Results are given for isothermal conditions as well as for the most buoyant conditions on the vertical and horizontal PIV planes.

and inside the street canyon is formed, which decreases the air exchange between the street canyon and the flow above the street canyon. A very limited impact of buoyancy on the flow structures can be found for the case with the high reference velocity (U_{ref} = 1.94 m/s), when the ground surface is heated. For the cases with the lower reference velocity (U_{ref} = 0.367 m/s) a strong change in flow patterns can be found with increasing ground temperatures. The main vortex in the centre of the street canyon disappears and air leaves the street canyon in vertical direction at the roof level. These vertical flows are strengthened with the decrease of the Froude number. These flow structures are also very different from the flow structures that are reported in previous studies, where the street canyons were modelled as quasi-two-dimensional geometries. For example [19] and [1] showed that the main vortex in the street canyon is strengthened with ground heating. In this study the main vortex is disappearing at low Froude numbers, because the air in the centre of the street canyon is accelerated in the vertical direction due to buoyancy and cold air is sucked into the street canyon from the lateral sides. These lateral flows are blocked in the 2D experiments reported in the literature, which leads to very different flow fields.

The lateral flows entering the street canyons are shown in Fig. 4. In this figure the normalized wind speeds are given on the horizontal PIV plane together with the streamlines. In the regions where the wind speeds are not given in the figure (white areas) the flow fields could not be measured due to strong laser light reflections. For the isothermal case the (in-plane) velocities on the horizontal plane are very low (less than 30% of the reference velocity). Vortices at the two corners of the upstream street canyon building are formed. Some air is entering the

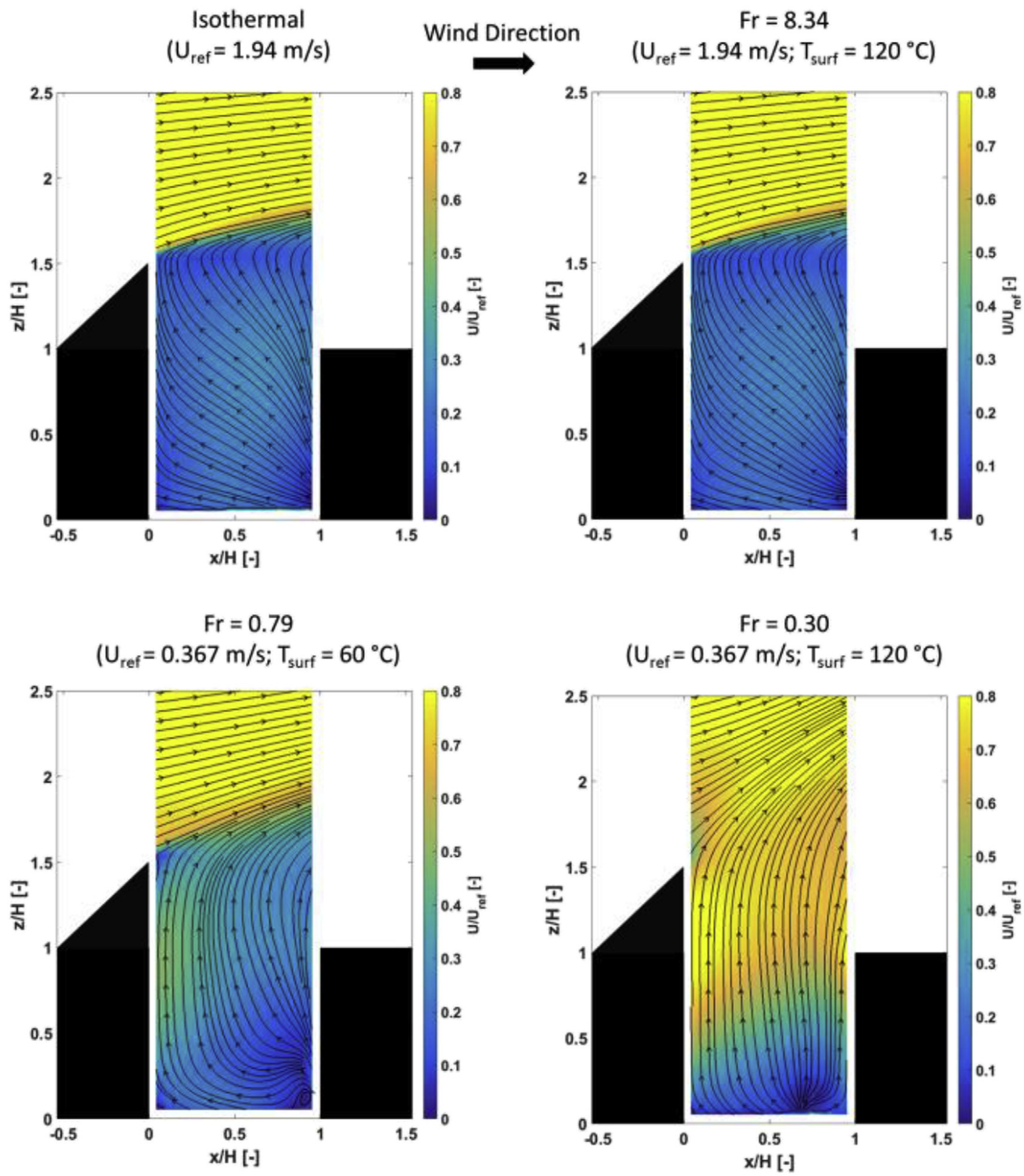

Fig. 9. Normalized (in-plane) wind speeds and streamlines for Case C on the vertical PIV plane. Results are given for isothermal conditions as well as for three different Froude numbers.

street canyon through the lateral sides. The flow structures on the horizontal plane are significantly changed at low Froude numbers. The normalized (in-plane) velocities are in the centre of the street canyon increased by a factor of 5–10 and there is a significant amount of air entering the street canyon through the lateral sides. This air is then leaving the canyon close to the centre of the street canyon through the top as shown in Fig. 3. These flow structures have for example already been found in Ref. [3] with CFD and are confirmed here with wind tunnel measurements. The flow structures on the horizontal plane are not symmetric for the isothermal as well as the buoyant cases. In both cases the wind speeds are lower in the regions around y = 1.5 H compared to the regions around y = −1.5 H. This asymmetry is caused by neighbouring buildings upstream of the street canyons. In the region of y = 1.5 H the flow is blocked by a building upstream of the street canyons, while it is not blocked in the region of y = −1.5 H (see 3D view in Fig. 1).

Buoyancy not only impacts the wind speeds, but also affects the turbulent kinetic energies. Turbulent kinetic energies normalised by the square of the reference velocity (TKE/U_{ref}^2) are given in Fig. 5. To determine the turbulent kinetic energies, all three velocity components would be needed, but only the two in-plane components are measured here with planar PIV. To account for the out-of-plane component, it is assumed here that the third component behaves like the other two:

$$w'^2 = \frac{1}{2}(u'^2 + v'^2) \tag{3}$$

where u', v' and w' are the turbulent fluctuations of the streamwise, vertical and out-of-plane velocity components. With this assumption the turbulent kinetic energy (k) is determined using the following equation:

$$k = \frac{3}{4}(u'^2 + v'^2) \tag{4}$$

Since this assumption does not always hold in urban environments

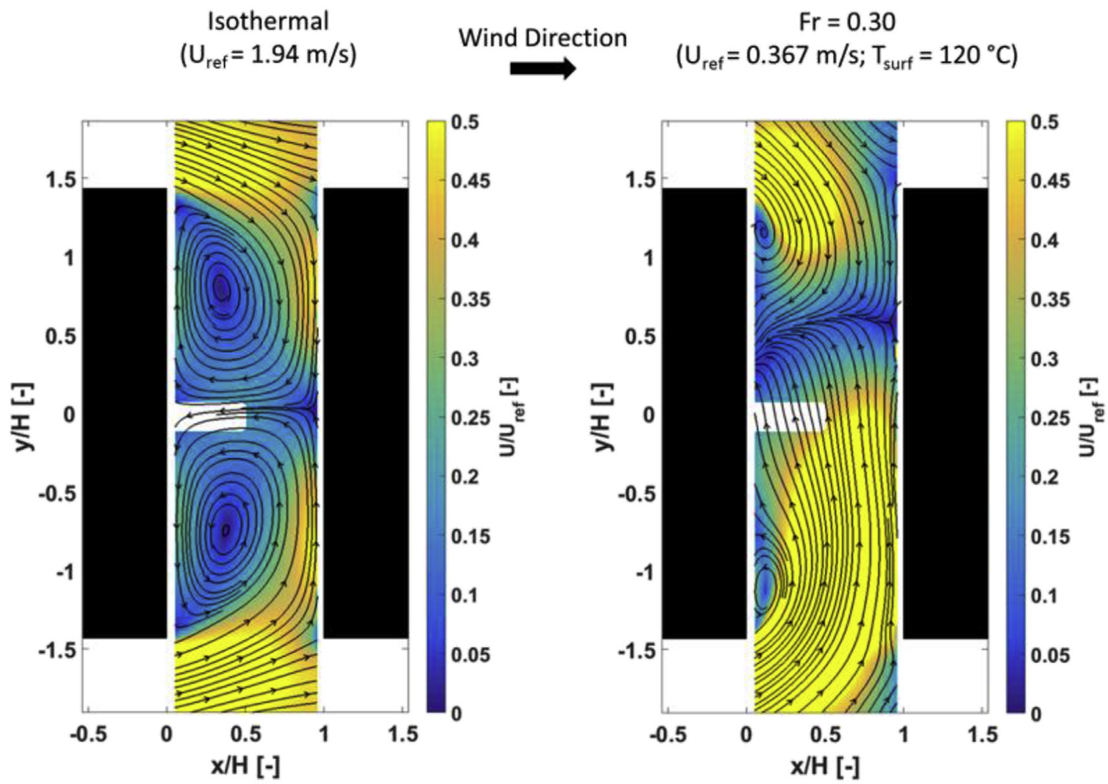

Fig. 10. Normalized (in-plane) wind speeds and streamlines for Case C on the horizontal PIV plane. Results are given for isothermal conditions as well as for the most buoyant conditions.

the turbulent kinetic energies measured at the same locations on the vertical and horizontal planes are not always equal. The results of the measured turbulent kinetic energies show a strong turbulence production due to buoyancy effects. The normalized turbulent kinetic energies are strongly increased inside the street canyon (by a factor of 4–8) as well as above the street canyon (by a factor of 2–2.5). This increased turbulence level can have a positive impact on the removal of heat from the street canyon as shown by Ref. [3] [3] studied heat fluxes in urban areas using CFD. They determined the convective and turbulent heat fluxes separately and found that depending on the flow structures an important part of the heat is removed from urban areas by turbulence. Turbulence further also has an impact on the comfort of pedestrians. High turbulence levels can lead to discomfort.

For the isothermal as well as for the buoyant case the highest turbulent kinetic energies are measured above the street canyon. Turbulence is produced in the ABL, the shear layers at the roof level and due to buoyancy. The turbulence level is lower at the windward compared to the leeward wall.

3.2. Case B

For Case B the downstream street canyon building has a wedged roof and has therefore a 1.5 times higher height compared to all the surrounding buildings having flat roofs. This has an important impact on the flow structures in the studied street canyon. In Fig. 6 the flow fields on the vertical PIV plane are given. As for Case A also in Case B a main vortex can be found in the centre of the street canyon for the forced convective conditions (isothermal and Fr = 8.34). Compared to Case A, the vortex in Case B is stronger and the centre of the vortex is more centred in the street canyon. The velocities close to the building walls and street surface are increased by a factor of 2.5–3. The reason for the stronger vortex is that due to the higher downstream building, air with higher momentum is diverted into the street canyon. Due to the stronger vortex the inertial forces are higher and therefore stronger buoyancy forces are needed for the vortex to disappear. For Case B the vortex can still be found for Fr = 0.79, while for the same Froude number no vortex can be found for Case A. For the lowest Froude number for Case B the vortex disappears, but the vertical velocities in the street canyon are lower compared to Case A.

The velocities on the horizontal PIV plane for Case B are presented in Fig. 7. For the isothermal case the flow structures are significantly different compared to Case A. The vortices at the corners of the upstream street canyon building can still be found, but are smaller. There is also no air entering the street canyon through the lateral sides on the studied horizontal plane. Some air is leaving the street canyon close to the windward side of the downstream street canyon building. In large areas of the street canyon, air is flowing in opposite direction compared to the freestream. For the most buoyant case, the flow structures on the horizontal plane look similar as for Case A. There is (cold) air entering the street canyon from the lateral sides. In Fig. 8 it is shown that also the turbulent kinetic energies increase with a similar magnitude (differences of up to 20%) as for Case A. On the horizontal plane, the area with high turbulent kinetic energies is smaller in Case B compared to Case A and can mainly be found in the vortex centres, while for Case A the turbulence is also increased in the street canyon centre, where there is no vortex. The turbulent kinetic energies are not symmetrically distributed on the horizontal plane. On one lateral side of the street canyon, the turbulent kinetic energies are higher compared to the other

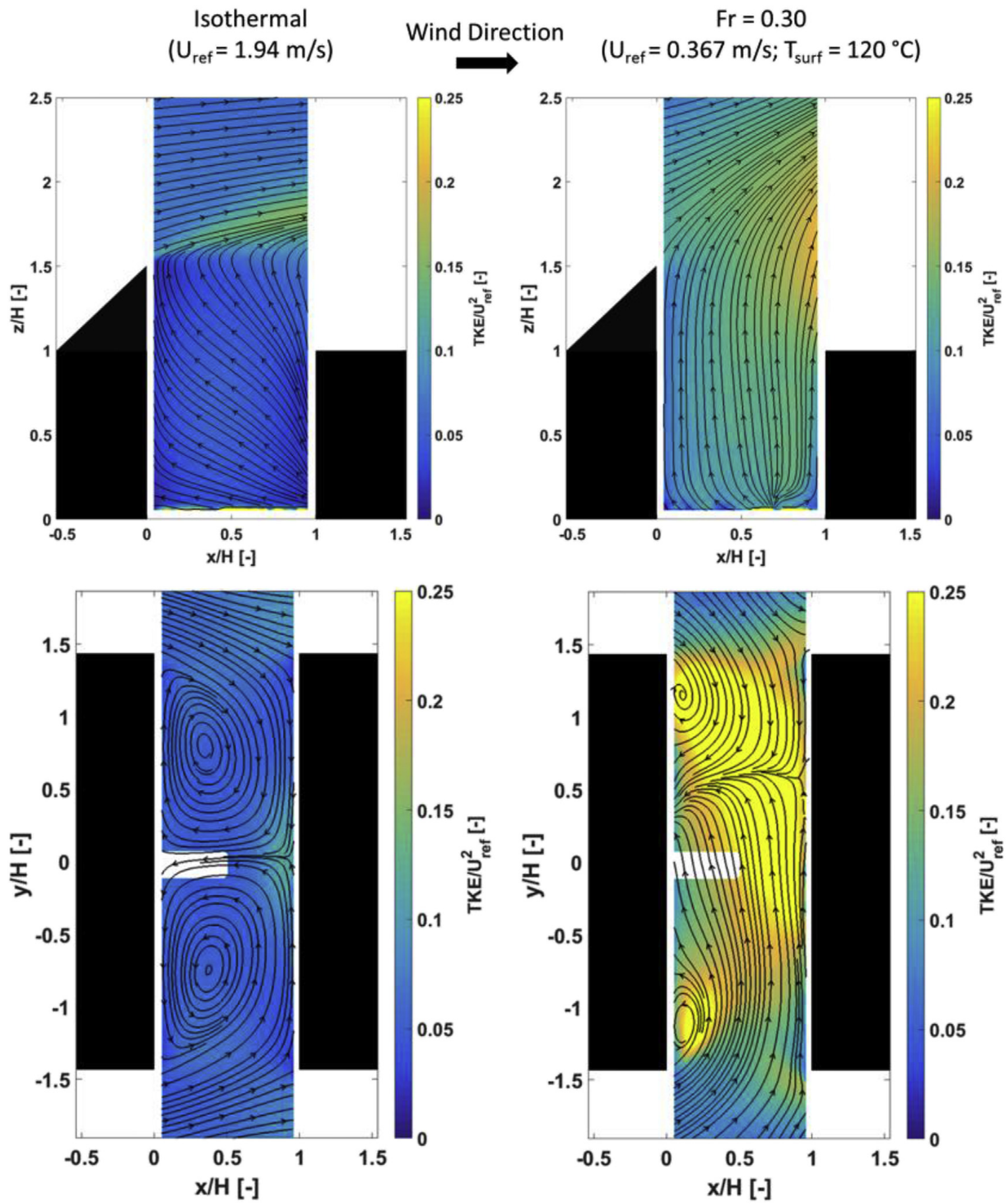

Fig. 11. Normalized turbulent kinetic energies and streamlines for Case C. Results are given for isothermal conditions as well as for the most buoyant conditions on the vertical and horizontal PIV planes.

side. This can have an impact on the heat removal, because turbulence helps to mix the air and remove heat. Therefore the heat removal efficiency is different at different lateral locations of the street canyon. The same asymmetry of the distribution of the turbulent kinetic energy can also be found for the other studied cases.

Based on the analysed results, it can be concluded that the increased height of the downstream street canyon building has an impact on the flow structures inside the street canyon. For forced convective flow regimes the wind speeds are higher in the canyon and stronger buoyancy forces are needed to get mixed convective flows. For flow regimes with strong buoyancy effects the differences between Case B and Case A are lowest, since for these cases the higher downstream building cannot divert air with higher velocities into the street canyon anymore.

3.3. Case C

Similarly to Case B, Case C has a taller building with a wedged roof,

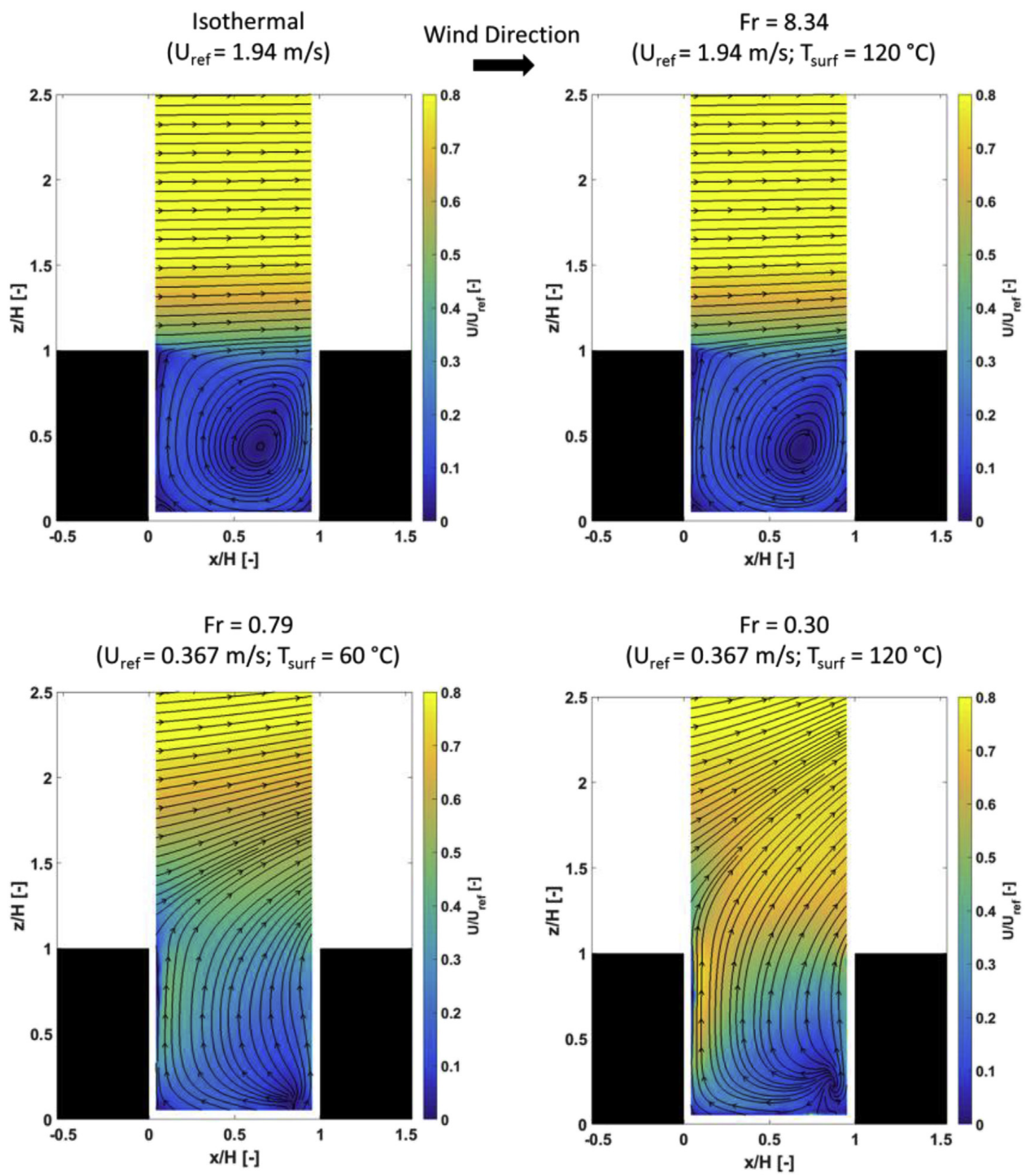

Fig. 12. Normalized (in-plane) wind speeds and streamlines for Case D on the vertical PIV plane. Results are given for isothermal conditions as well as for three different Froude numbers.

but on the upstream side of the street canyon. Fig. 9 shows the wind speeds on the vertical PIV plane for Case C. There is a noticeable difference of the flow field in the street canyon compared to all other studied cases. For none of the studied conditions in Case C a standing vortex can be found in the studied plane. For all conditions in Case C there is air leaving the street canyon through the roof level. Strong velocity gradients can be found close to the top of the wedged roof. Therefore the shear layer between the flow inside the street canyon and the flow above the street canyon is moved from the level of the flat roofs to the level of the top of the wedged roof. Due to this upward shift of the shear layer, the air can leave the street canyon at the heights between the roof heights of the upstream and downstream street canyon buildings. The flow structures on the studied vertical plane are not completely changing with increasing strength of buoyancy. The upward motions are strengthened (by a factor of 1.5–3.5) due to buoyancy and the velocity gradients of the flow over the street canyon and the flow out of the street canyon are decreasing.

Because of the air that leaves the street canyon in the vertical direction for isothermal as well as buoyant conditions, air has to flow from lateral direction to the inside of the street canyon. This can be seen in Fig. 10. Already for the isothermal case the lateral wind speeds close to the windward wall of the street canyon are much higher compared to the other studied cases. The two standing vortices formed at the corners of the upstream street canyon building have each about the diameter of

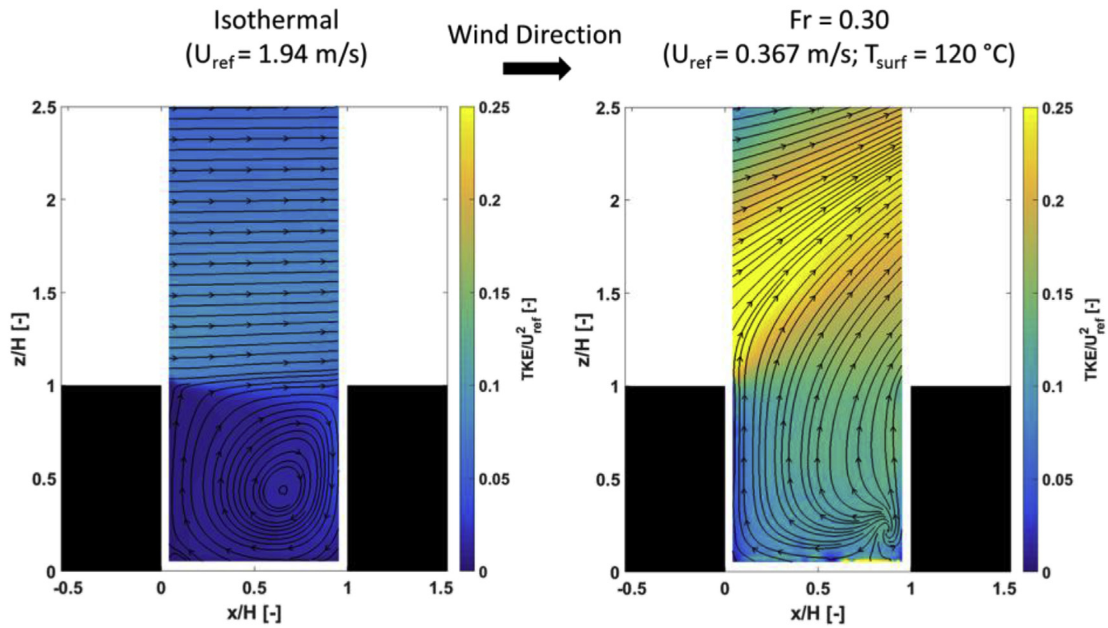

Fig. 13. Normalized turbulent kinetic energies and streamlines for Case D. Results are given for isothermal conditions as well as for the most buoyant conditions on the vertical PIV planes.

half of the street canyon length. These rather strong lateral flows inside the street canyon can help to ventilate the street canyon. Also for Case C the velocities in the lateral directions are increasing due to buoyancy (by a factor of 1.5–2.5), but the increase is relatively small compared to the other studied cases, but they are relatively high for the isothermal conditions (factor of 2–3 higher compared to Case A).

The measured turbulent kinetic energies for Case C are shown in Fig. 11. For Case C the turbulent kinetic energies on the vertical plane are higher in the shear layer region for the isothermal conditions compared to the other studied cases. The increase of turbulent kinetic energies for the buoyant conditions on the other hand is lower compared to the other cases. On the studied horizontal PIV plane, the turbulent kinetic energy increase is similar to the other studied cases. In general the turbulent kinetic energies are low in the lower half of the street canyon. No large gradients of the turbulent kinetic energies can be found on the vertical plane. On the horizontal plane large regions with increased turbulent kinetic energies can be found for the buoyant case.

3.4. Case D

With Case D the impact of different lengths of the two street canyon buildings is studied. Here the upstream street canyon building is longer than the downstream street canyon building (see Fig. 1). With this configuration, it is investigated, whether lateral flows can be increased by varying the building lengths of the street canyon buildings. The flow fields on the vertical PIV plane are given in Fig. 12. The flow fields are very similar to the flow fields measured for Case A. For the two forced convective flow regimes, the vortex centers are at a lower height in the street canyon compared to Case A. Only minor differences between Case A and Case D can be found for the buoyant cases. For Case D the flow fields on the horizontal PIV plane could not be measured with sufficient accuracy using PIV. The reason may be that the in-plane velocities on that PIV plane are too small compared to the out-of-plane velocities and therefore the PIV particles are not sufficiently moving within the PIV plane of the two images used to determine the flow fields.

The turbulent kinetic energies measured on the vertical PIV plane for Case D are presented in Fig. 13. As for the velocities also the turbulent kinetic energy fields are very similar for Case D and Case A, but the turbulent kinetic energies in the street canyon are smaller by a factor of 2 for Case D compared to Case A for isothermal conditions. For buoyant conditions the turbulent kinetic energies are only about 20–30% lower for Case D compared to Case A.

3.5. Case E

With Case E it is investigated whether a shorter upstream and a longer downstream street canyon building can divert air into the street canyon and lead to higher lateral velocities inside the canyon compared to Cases A and D. In Figs. 14–16 the same results are presented for Case E as previously for Cases A-C. The results on the vertical PIV plane are not significantly different from the results for Case A (and also Case D). On the horizontal PIV plane the velocities are for the isothermal conditions slightly higher (between 10% and 30%) for Case E compared to Case A. In Fig. 15, it can also be seen that only a part of the air is diverted into the street canyon due to the longer downstream building and a significant portion of air flows away without entering the street canyon. For buoyant conditions 30% to 50% higher turbulent kinematic energies can be found for Case E compared to Case A above the street canyon, but the regions with high turbulent kinetic energy are smaller on the horizontal PIV plane in the street canyon.

3.6. Discussion of the flow field results

The flow field results presented above showed the importance of studying the three-dimensional flow structures for street canyons with a finite length. Flows along the street canyon axis have an important

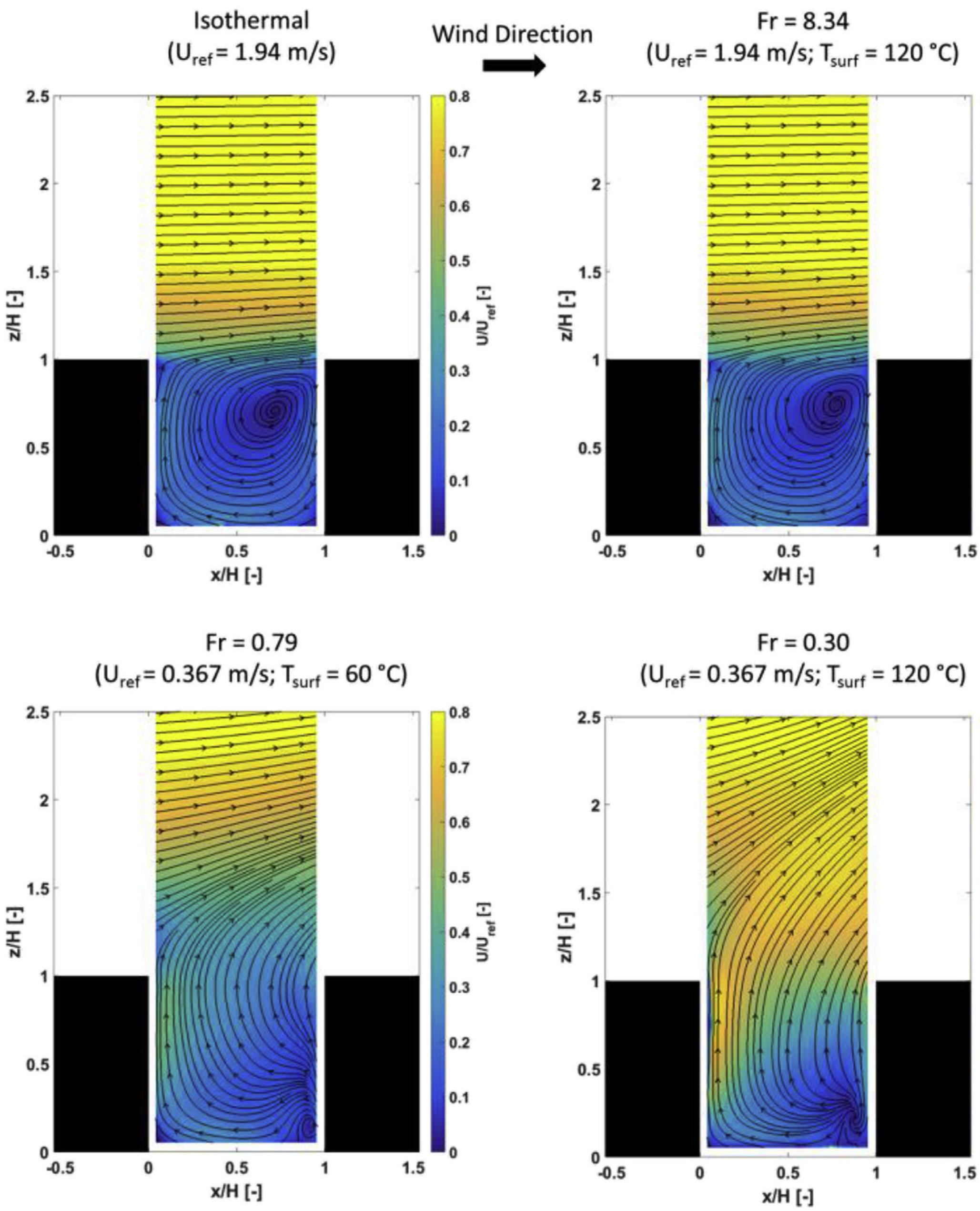

Fig. 14. Normalized (in-plane) wind speeds and streamlines for Case E on the vertical PIV plane. Results are given for isothermal conditions as well as for three different Froude numbers.

impact on the flow structures. These lateral flows are mainly important for buoyant flows or when the street canyon buildings have non-uniform heights. For a street canyon with uniform building heights a main vortex in the centre of the street canyon is formed, which is separated from the flow above the street canyon by a shear layer. The flow structure in the street canyon is significantly changed for buoyant flow. The main vortex disappears as air enters the street canyon from the lateral sides and leaves it in the centre of the street canyon again at the roof level. If the downstream building is higher compared to the surrounding buildings air is diverted from above the street canyon into the street canyon, which might improve the ventilation under a forced convective flow regime (see also below). In the opposite case the shear layer between the flow inside the street canyon and above the street canyon is found at the roof level of the higher upstream building and air can leave the street canyon at heights between the roof heights of the upstream and downstream street canyon buildings. The difference in lengths of the street canyon buildings has only a minor effect on the flow structures inside the studied street canyon. But nevertheless these minor effects still have an impact on the ventilation of the street canyon (see below).

3.7. Temperature measurements

In this section the results of the (indirect) air temperature

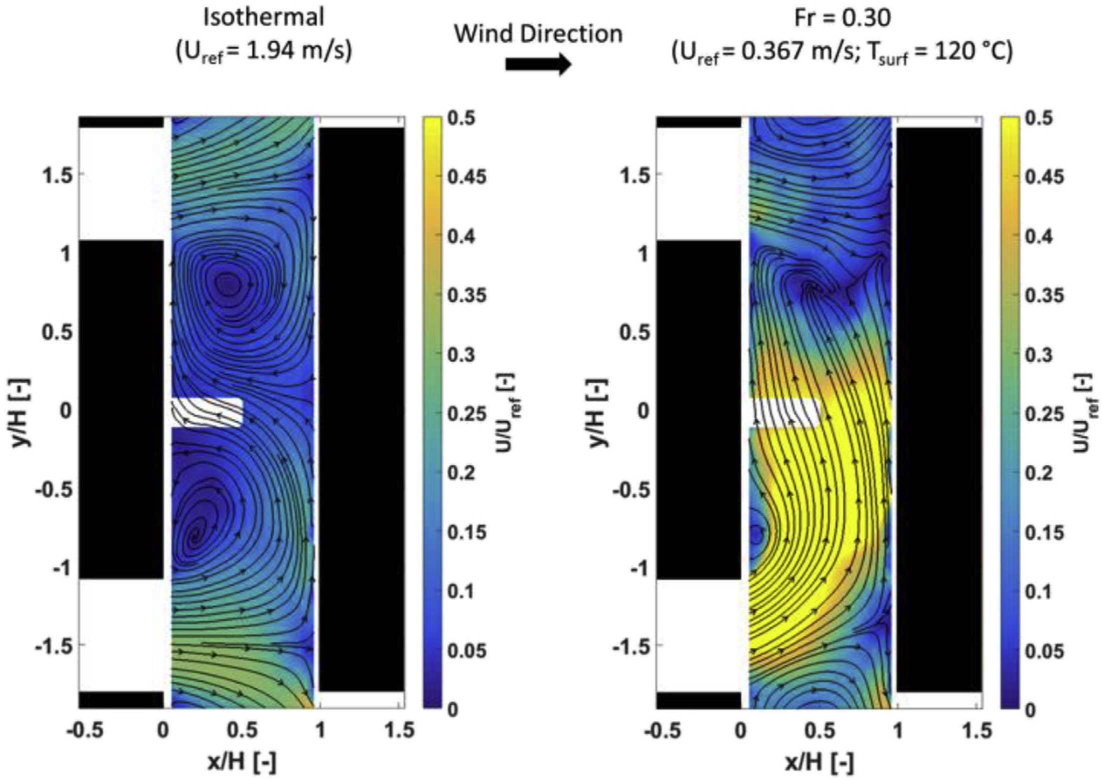

Fig. 15. Normalized (in-plane) wind speeds and streamlines for Case E on the horizontal PIV plane. Results are given for isothermal conditions as well as for the most buoyant conditions.

measurements are presented to study the impact on the different street canyon configurations on the local air temperatures in the street canyon. Only the results for the conditions with a Froude number of 8.34 are shown in Fig. 17, because for these conditions the lateral velocities in the vertical center-plane of the street canyon are low for all studied cases. Therefore the influence of lateral wind speeds on the temperature of the felt is lowest. Additionally, building geometries have a larger impact on the flow structures in forced convective flows compared to the more buoyant flows (see above).

For Case A the temperatures inside the street canyon are clearly higher compared to the temperatures of the atmospheric boundary layer flow above the street canyon. Inside the street canyon the temperatures are lowest at the top part of the windward wall of the street canyon. The highest temperatures can be found close to the heated ground. The temperatures are higher at the leeward wall compared to the windward wall, because the heat is transported from the ground in direction of the leeward wall due to the main vortex. In Case B, the temperatures are significantly lower compared to Case A and the lowest of all cases. This can be explained by the fact that cold air from the flow above the street canyon is diverted into the street canyon, which has a strong cooling effect. In Case C the temperatures are lower compared to Case A (but higher compared to Case B). For case C air can most easily leave the street canyon through the roof level, compared to all other cases. Colder air enters the street canyon through the lateral sides and cools the air inside the street canyon. The highest temperature of all cases is found for Case D, where a shear layer forms at the roof level (as for Case A) and therefore the ventilation at this level is low. The velocities in lateral directions might be the lowest leading to an overall low ventilation. This could not be proven here, because the velocities on the horizontal PIV plane could not be measured. Finally, the temperatures in the street canyon for Case E are also significantly lower compared to Case A although they have very similar flow structures. The temperatures for Case E are reduced due to the slightly higher velocities in the lateral direction leading to a better ventilation of the street canyon. Therefore the air temperature measurements show an impact of the lateral flows on the conditions in the center of the street canyon. This confirms the importance of the three-dimensional flow structures in street canyons on the heat removal from street canyons.

4. Discussion

In this paper the flow in urban street canyons under mixed and forced convective flow conditions was studied. The study shows interesting new results on the flow structures in street canyons and ventilation efficiencies, but to draw more general conclusions additional studies are still needed. The first limitation of this study is that only one wind direction was considered. Further, only a small number of geometries were studied. The total length of the street canyon was not varied. Different street canyon lengths might have an impact on the three-dimensionality of the flow in street canyons. Also the distance between the buildings in lateral and longitudinal wind directions can have a significant impact on the flow structures in urban areas. Here all distances were kept constant throughout the entire study. For the three cases: Case A, B, C, the building heights of all buildings were uniform and for two cases: Case D and E only one building is taller than the rest of the buildings. It still has to be studied if the wedged roofs used in this study have the same positive effect for urban neighbourhoods, where the surrounding buildings have non-uniform building heights.

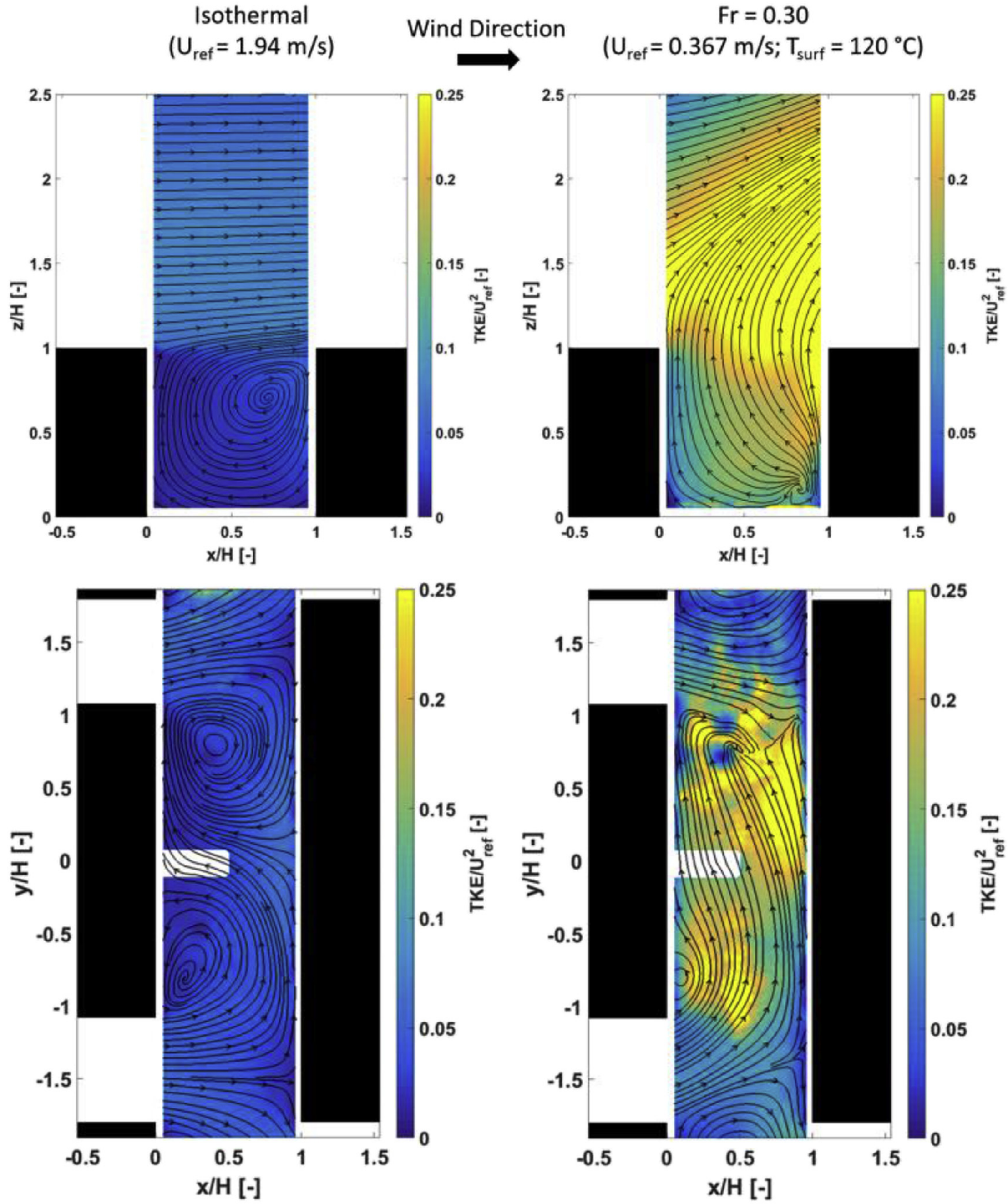

Fig. 16. Normalized turbulent kinetic energies and streamlines for Case E. Results are given for isothermal conditions as well as for the most buoyant conditions on the vertical and horizontal PIV planes.

A simplification was made by only heating the ground surfaces in a finite area. Heated building facades and roofs might also strongly influence the flow structures in the mixed convective flow regimes. Here the air entering the street canyon through the roof level and lateral sides was colder than the air inside the street canyon and therefore led to a cooling effect. No cooling effect or even a heating effect would be found, if the air entering the street canyon would already be heated due to other warm surfaces of the urban neighbourhood. This would also have an impact on the strengths of the buoyancy effects and on therefore possibly on the three-dimensional flow structures. Therefore the current studied configuration represents an urban area, where large surface and air temperature gradients exist within the urban area. These gradients could for example be caused by different surface albedos within the urban area, vegetation (e.g. grass) within the urban area or nearby water surfaces (e.g. rivers or lakes) or parks.

There are few limitations of the used measurement techniques. For the studied cases the flow fields could only be measured on a limited number of planes using PIV. To better understand the full three-

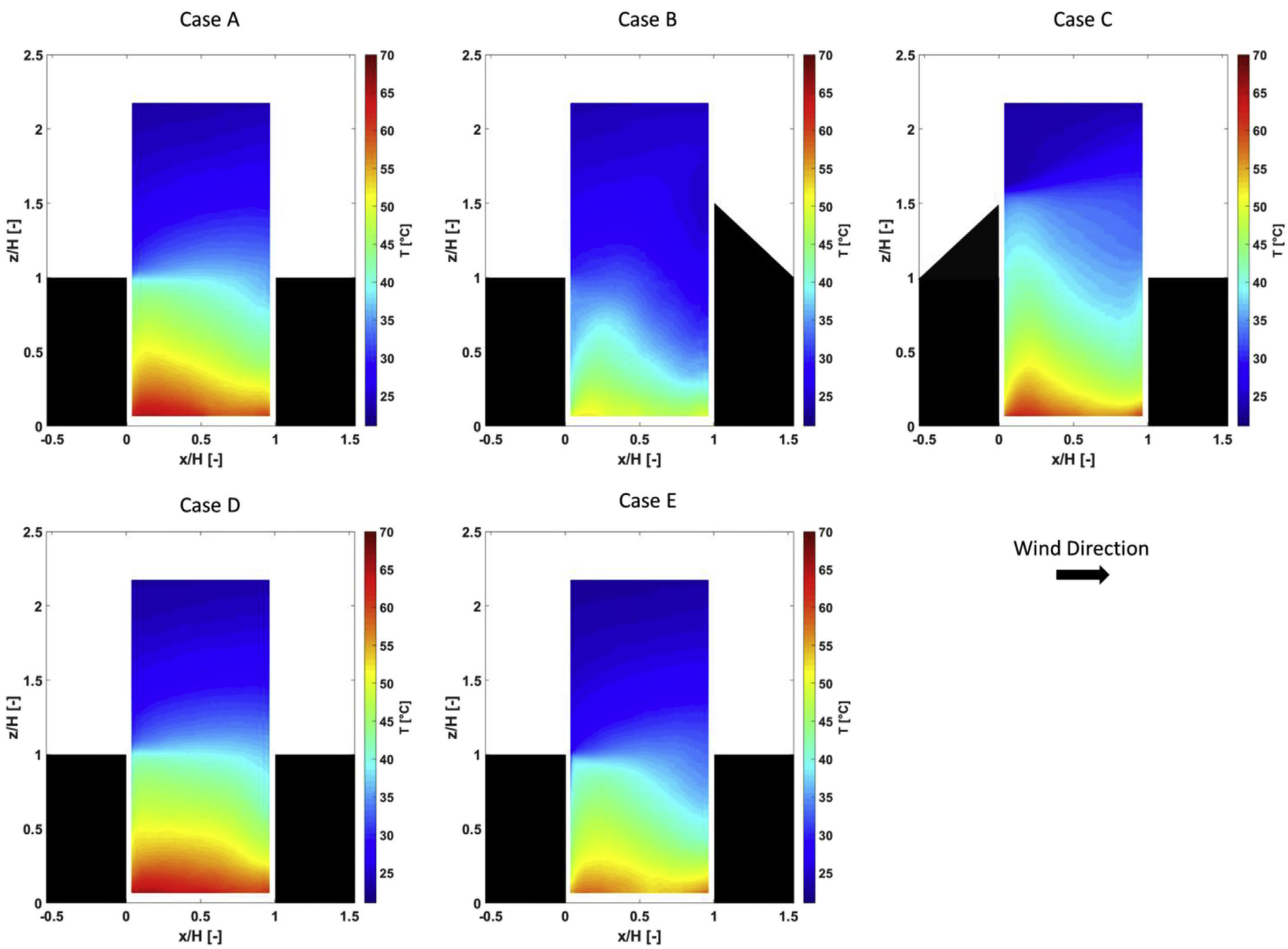

Fig. 17. Air temperatures measured on the vertical centre plane of the studied street canyon for all studied cases. Results are given conditions with Fr = 8.34 (U_{ref} = 1.94 m/s; T_{surf} = 120 °C).

dimensional flow structures the flow fields in the whole air volume would be needed. This could for example be achieved by conducting CFD simulations. Finally, the air temperature measurement technique should be improved to measure the air temperatures with high accuracy. Currently available temperature measurement techniques disturb the flow fields and are influenced by longwave radiation exchange with the wind tunnel and wind tunnel models.

5. Conclusions

In this study the effect of street canyon building geometries and buoyancy on the flow structures in street canyons was investigated by means of wind tunnel measurements. The focus was on the formation of three-dimensional flow structures, which improve the heat removal from street canyons. The three-dimensional flow structures in a street canyon with an aspect ratio of one and uniform building heights was compared with flows in street canyons with non-uniform building heights and non-equal lengths of the two buildings forming the street canyon. The wind tunnel floor was heated to different temperatures to study forced and mixed convective flows.

For forced convective flows the classical vortex structure with one main vortex can be found for a street canyon with uniform building heights. For mixed convective flows this vortex disappears. Air enters the street canyon from the lateral sides and leaves in the centre of the street canyon in the vertical direction at roof level. Similar flow structures are found for all studied geometries for low approach flow wind speeds and high ground temperatures. Buoyancy leads to a strong increase of the turbulent kinetic energies in and above the street canyons. For all studied cases with uniform building heights the wind speed in lateral directions are low for forced convective flows.

If the upstream street canyon building is taller than the downstream street canyon building, strong lateral flows can be found for conditions with low buoyancy forces. For this case upwards motions can be found in the centre of the street canyon instead of a standing vortex. This flow structure improves the heat removal from the street canyon and lower air temperatures are measured in the centre of the street canyon compared to the cases with uniform building heights. Also an increased building height of the downstream street canyon building leads to lower air temperatures inside the street canyon. For this case cold air from above the street canyon is diverted into the street canyon by the higher downstream building, which has a cooling effect.

Finally, a cooling effect could be found for geometries in which the upstream street canyon building is shorter compared to the downstream street canyon building. The temperatures in this case are reduced due to the slightly higher velocities in the lateral direction leading to a better ventilation of the street canyon. For the opposite configuration, where the upstream street canyon building is longer than the downstream street canyon building, the air temperature is found to be highest of all studied cases.

The results of this study show the importance of taking the full three-dimensional flow structures into account, when studying flows in urban street canyons. Assuming quasi-two-dimensional flows in street canyons might lead to misleading results. The results also show that three-dimensional flows can help ventilating urban areas and therefore urban planner should promote these flows by planning urban structures where flows are not blocked for long distances leading to more two-dimensional flows.

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