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Impact of buoyancy on urban heat removal at a local scale:
A time-resolved PIV-LIF study in a water tunnel

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ABSTRACT: *In the past decades, the portion of the population living in urban areas has continuously increased. Due to the high building density, the microclimate in urban areas is significantly different compared to rural areas. The air temperatures are higher due to the urban heat island (UHI) effect, urban surfaces have high temperatures due to absorption of solar radiation and the wind speeds are lower due to wind sheltering by buildings. The deterioration of the urban climate has an important impact on thermal comfort and health of the people living in urban areas as well as on the energy demand of buildings. In urban areas, buoyant flow structures can often be found at meso-scale as well as at local scale. We study the heat removal from urban areas for mixed and forced convective flows using time-resolved planar velocity & temperature measurements (PIV-LIF) in the new ETH/Empa large-scale water tunnel facility. In case of mixed convective flows, we demonstrate using a row of heated buildings that buoyant forces are able to overcome the turbulent shear layer and have a significant impact on heat removal by inducing a convective vertical heat flux between the buildings.*

1. Introduction

The 'urban heat island' (UHI) effect refers to increased air temperatures inside a city compared to its surrounding countryside. Increased heat gains and reduced heat losses in urban areas are the main causes of the UHI effect [1]. This change in the energy balance between incoming radiation, and losses in sensible and latent energy results in an increased energy storage in cities [1, 2]. For example, wind speeds are lower inside a city, which leads to a decrease in sensible heat release from buildings. With the increase in population and global warming, the air temperatures in cities are known to increase further, thereby having a detrimental effect on human comfort, health and increased energy demands for cooling in cities. Complex three-dimensional and unsteady flow structures are found in urban areas. The interaction of a turbulent atmospheric boundary layer (ABL) with buildings results in flow separation at building edges and formation of turbulent shear layers. The interaction of these turbulent shear layers with buoyancy-induced airflows caused by the heated surfaces adds further complexity.

Most urban microclimate studies [3-6] in the past have focused on urban airflows driven by wind on generic building geometries like a street canyon (isothermal, forced convection). This research aims to include the important effect of buoyancy in the analysis of urban airflows. Buoyancy in urban areas (upward motion of warm air) is induced close to building facades heated by solar and longwave radiation. This temperature difference can also cause large raising thermal plumes at the city/city quarter scale that interact with wind and significantly modify the urban flow structures (non-isothermal, free and mixed convection regime). A thorough understanding of the interaction of buoyancy with the turbulent shear layers is critical to understand the heat removal process. A few experimental studies that consider buoyancy have been reported in literature [7-8]. To the author's knowledge, experimental studies quantifying simultaneously velocity and temperature fields in buoyancy driven urban air flows have so far not been reported. Quantifying turbulent heat and bulk convective fluxes by simultaneous measurement of flow (PIV) and temperature (LIF) is critical in understanding the impact of buoyancy on urban heat removal.

2. Experimental Set-up

Non-isothermal urban airflows are studied at different flow regimes (mixed and forced convection) using a generic setup consisting of three heated aluminum cubes (Figure 1). The heated cubes are spaced such that the aspect ratio (H/D: H: building height; D: distance between buildings) is 1 and hence represents the skimming flow regime [1]. The measurements are carried out in the new Empa/ETH atmospheric boundary layer water tunnel (test section: 0.6 × 1 m^2, length: 6m, water volume: 25 m^3). The water tunnel is equipped with a simultaneous particle image velocimetry (PIV) and laser-induced fluorescence (LIF) system. The PIV-LIF measurement system allows non-intrusive, simultaneous measurement of velocity and temperature fields with a high spatial and temporal resolution (100 Hz).

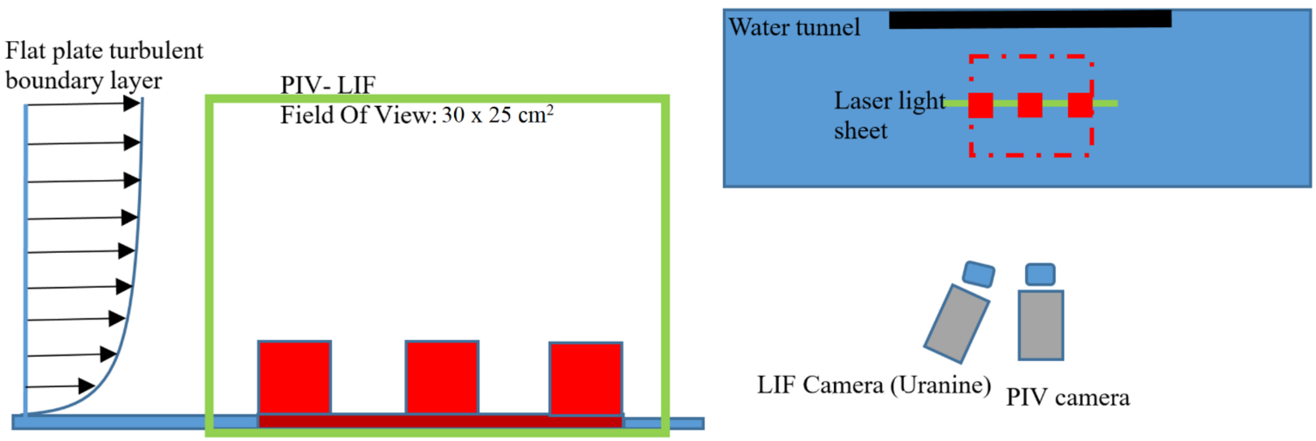

Fig 1: Schematic diagram of the PIV-LIF set up in the water tunnel

The row of aluminum cubes is placed on a heated plate. The plate is heated with water at approx. 80°C, which is circulating in channels inside the heated plate. The water is heated with a 5kW electric heating machine. The cubes are placed on the plate using a double-sided aluminum foil tape with high thermal conductivity. The plate temperature is 52°C and cube surface temperature is 32°C measured using thermocouples at the center of the surfaces. Measurements are performed at the cubes placed 5.5 m downstream of the contraction inside the water tunnel test section. At this location the flat plate turbulent boundary layer has been fully developed.

In order to compare the experimental measurements carried out on scaled models to a full-scale scenario, the Reynolds number (ratio of inertia to viscous forces) and the Richardson number (ratio of buoyant to inertia forces) must be matched as far as possible. The Reynolds number (Re) here is defined with respect to the cube height, H = 0.05m and the freestream velocity, and the Richardson number (Ri) is defined as,

$$\mathrm{Ri} = \frac{g\beta\,\Delta T\,H}{U_\infty^2}$$

where $\Delta T = T_p - T_\infty$, T_p is defined as the heated plate temperature, T_∞ is the ambient temperature in the water tunnel (~ 22°C), U_∞ is the free-stream velocity, β is the thermal expansion coefficient, g is acceleration due to gravity. The Richardson number is O(-1) in case of forced convection where buoyancy effects can be neglected, above O(1) for natural convection where effects of wind can be neglected and between O(-1) - O(1) in which both buoyancy and inertial forces play a critical role, termed as the mixed convection regime. In case of forced convection, a critical Reynolds number (>5000 for bluff bodies [9]) exists above which flow can be considered Reynolds number independent. This concept however breaks when considering mixed convective flows as no such critical Reynolds number exists. Instead, Richardson numbers that are more important in the study of non-isothermal flows are closely matched. For example for a 25m high building with surface temperatures of 50°C, a wind speed of 1 m/s and air temperature is 22°C, the Ri number would be 4.39. Non-isothermal measurements are studied at various Reynolds (Re) and Richardson (Ri) numbers as shown in Table 1. Corresponding isothermal measurements are also obtained for comparison.

U_∞ m/s	Re	ΔT °C	Ri	Regime
0.018	930	30	8.03	Mixed
0.025	1250	30	4.39	Mixed
0.025	1250	19.4	2.83	Mixed
0.115	5750	28	0.21	Forced
0.285	14250	22	0.03	Forced

Table 1: PIV-LIF measurements carried out at different Re, Ri number

Simultaneous PIV-LIF (planar PIV, single dye LIF- 1 dye/ 1 spectral band) measurements are acquired at a frequency of 10 Hz using Dynamic studio. The number of images acquired are 5000. The PIV-LIF setup consists of a Litron Nd-YAG laser (532 nm) 100mJ @100 Hz used as an excitation source along with one planar PIV camera and one planar LIF camera: HiSense Zyla 2MP cameras (single frame @50Hz, f: 50 mm lens, FOV: 30 × 25 cm^2). The PIV camera is perpendicular to the flow and the LIF camera is placed at an angle of 15° with a Scheimpflug (Figure 1). The aperture for PIV camera is set at 4.8 and the LIF camera is set at 1.4. Uranine (also called Fluorescein, Disodium fluorescein: $C_{20}H_{10}O_5Na_2$) is selected as the fluorescent dye to measure temperature (conc. 2 mg/L). Uranine has a temperature dependent absorption coefficient [10], high quantum efficiency and is non-toxic. Uranine can be disposed more easily as compared to commonly used rhodamine dyes and hence its use in a large-scale water tunnel does not lead to environmental problems. The LIF camera is mounted with an optical filter for Uranine dye (535-630 nm). The disadvantage of a single dye LIF is that it does not compensate for the spatial variation of laser sheet/pulse-to-pulse laser fluctuations and dye absorption. This ratiometric technique [11] corrects for laser power fluctuations, laser sheet non-uniformities and dye absorption errors, thus has significant advantages in accurately measuring temperature fields as compared to single dye LIF (1d/1c) presented here. For this, an additional non-toxic dye is needed so a two-dye ratiometric LIF method (two dye, two color) can be performed. Chlorophyll dye [12] is being tested as the second non-toxic dye and initial results obtained are promising [13].

3. Results and Discussions

3.1 Flow Statistics

Mean flow statistics for different cases are obtained by averaging 5000 samples. The contours of time averaged velocity magnitude and vertical component v (normalized by U_∞) is compared for isothermal and non-isothermal cases (Fig. 2). In all cases, flow separation and the corresponding formation of turbulent shear layers can be found at the building edges. In the isothermal case, the flow structure at low Reynolds number (Re=1250) is significantly different compared to higher Reynolds numbers (Re=14250). For the lower Reynolds number the flow reattachment on the second cube does not occur due to a larger shear layer formation. Such a flow structure does not represent urban flows as Reynolds number independency has not been achieved. This case is presented to show the differences compared to the non-isothermal cases.

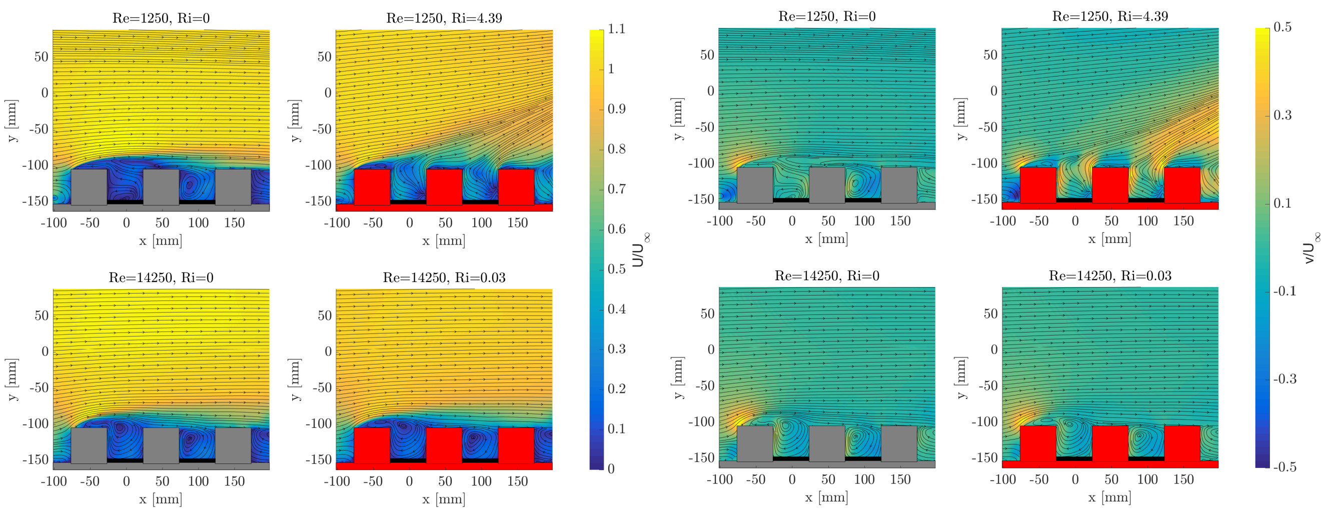

Fig 2: Time averaged velocity magnitude U (left) and vertical component v (right) for isothermal (cubes in grey color) and non-isothermal (cubes in red color) cases in mixed (top) and forced (bottom) convection regime

In the mixed convection regime (non-isothermal case: Re=1250, Ri=4.39) the influence of buoyancy on the mean flow structure can be clearly seen. Buoyancy forces are strong enough to prevent the formation of turbulent shear layers at the roof level. As a result, the turbulent shear layer is no longer horizontal as in case of isothermal flows, but at an angle with the horizontal. Large vertical velocities caused by buoyancy can be seen at the windward and leeward walls in between the buildings. At high Re number and low Ri (non-isothermal case: Re=14250, Ri=0.03), buoyancy does not play a significant role and the mean flow structure is similar to the corresponding isothermal case.

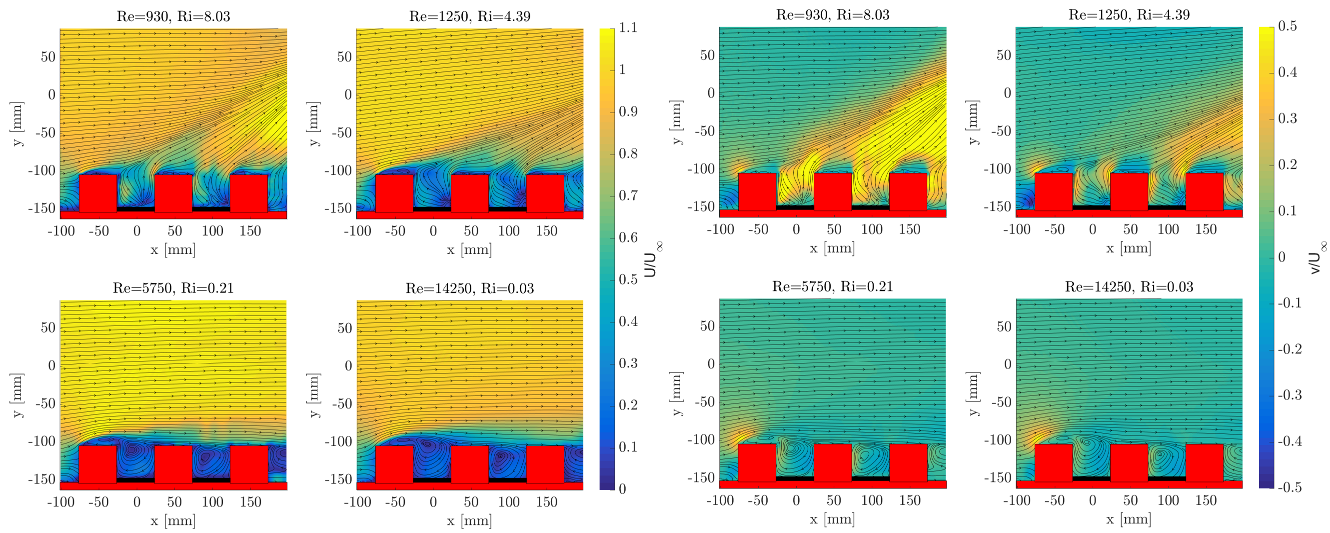

Fig. 3: Time averaged velocity magnitude U (left) and vertical component v (right) in mixed (top) and forced (bottom) convection regime for various Re, Ri numbers

As evident from Equation 1, the Ri number can be increased either by decreasing the freestream velocity U_∞ or by increasing the plate temperature (T_p). Fig. 3 shows contours of time averaged velocity magnitudes and vertical component for the case when Ri number is increased by decreasing freestream velocities. For low Richardson numbers (Ri = 0.03, 0.21) the flow regime changes to that of forced convection and the mean flow structure is the same as for the isothermal cases. Increasing Richardson number to 4.39 we see high vertical velocities in between the buildings caused by buoyancy. For the case of Richardson number of 8.03 the impact of buoyancy is significantly stronger and higher vertical velocities are observed compared to the case with a Richardson number of 4.39. Also, increasing Richardson number (from 4.39 to 8.03) increases the angle of the turbulent shear layer with respect to the horizontal.

The turbulence intensity (TI) based on the free stream velocity (normalised TKE with the assumption of isotropic turbulence for the determination of the out-of-plane velocity components) and the important Reynolds stress component $u'v'$ for these cases are shown in Fig. 4. The TKE is much higher in mixed convection flows as compared to forced convection. It can be seen that turbulence is produced due to buoyancy forces. The mean Reynolds stress component $u'v'$ is also found to be higher when buoyancy is dominant.

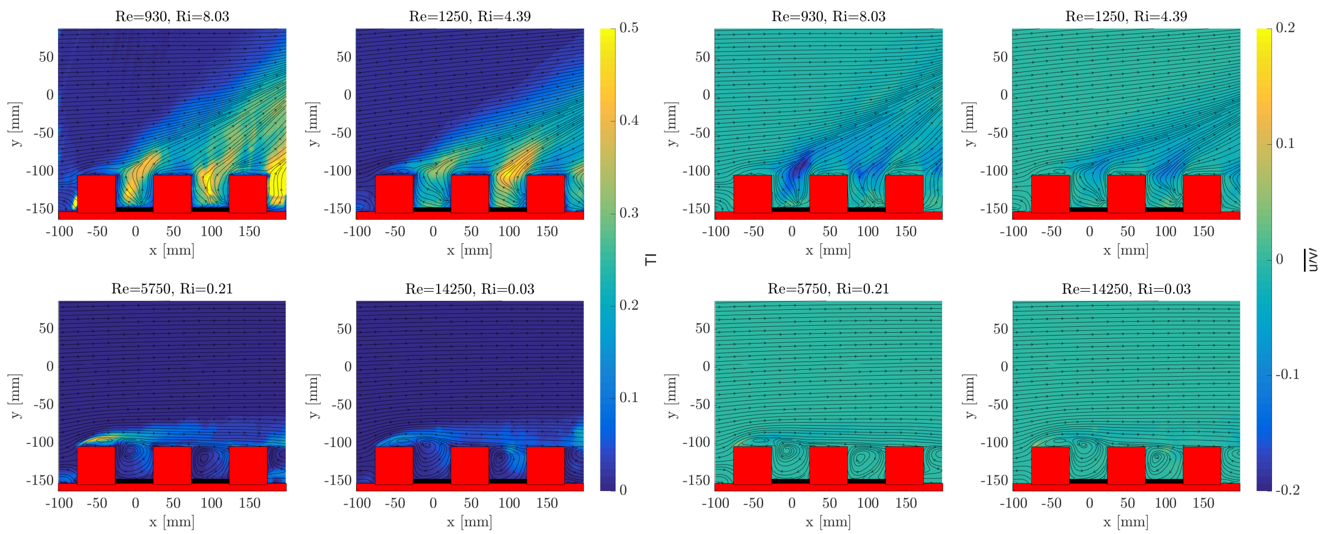

Fig 4: Time averaged turbulence intensity TI and Reynolds shear stress component u'v' in mixed and forced convection regime for various Re, Ri numbers

Fig. 5 shows mean flow properties when the Ri number is decreased by reducing the plate surface temperature, keeping the freestream velocity the same. With lower plate temperatures the mean vertical velocity component, TI and u′v′ are reduced as the effect of buoyancy is decreasing. Also, the angle formed by the turbulent shear layer with respect to the horizontal is decreased.

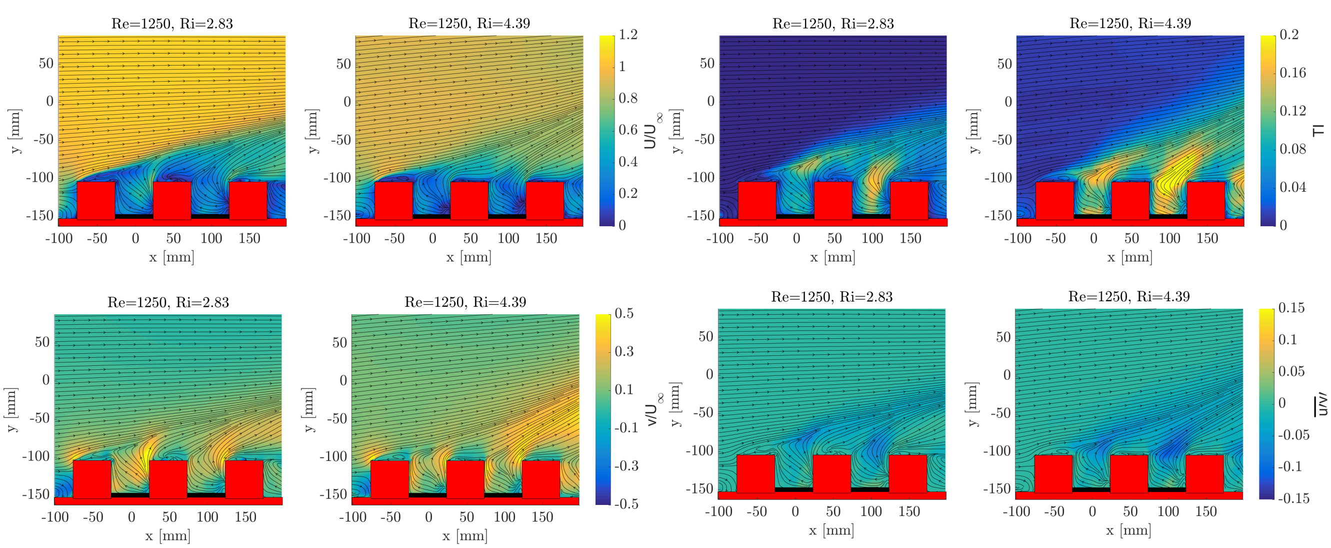

Fig. 5: Time averaged velocity magnitude U (top left), vertical component v (bottom left), TI (top right) and u'v' (bottom right) component in mixed convection regime for two different plate surface temperature

3.2 Flow Dynamics

So far, flow statistics provided an overall picture of the flow pattern in non-isothermal flows. However, mean flow statistics seldom provide information on c oherent structures present in the flow. Since coherent structures are responsible for most of mass and heat transfer, it is important to capture these turbulent flows with sufficient temporal and spatial resolution to understand heat removal in urban flows.

A snapshot of the temperature field and corresponding velocity field for the mixed convection case with Ri = 4.39 is shown in Fig. 6. Higher temperatures are found near the ground between the buildings. The temperatures above the buildings become lower as heat is convected by the buoyant flow structures. We observe that the snapshot of the temperature field is noisy because of the single dye LIF (one dye, one color) measurement presented here. As discussed in the experimental setup section, a ratiometric LIF using two non-toxic dyes (the other promising non-toxic dye being chlorophyll) is needed for future measurements.

The instantaneous horizontal and vertical velocity components show turbulent flow structures that originate between the buildings that are ejected to the flow above the buildings (Fig. 7). The time series of these instantaneous velocity components shows in a dynamic manner how buoyancy with the help these ejected flow structures is able to break through the shear layer generated by the incoming turbulent boundary layer.

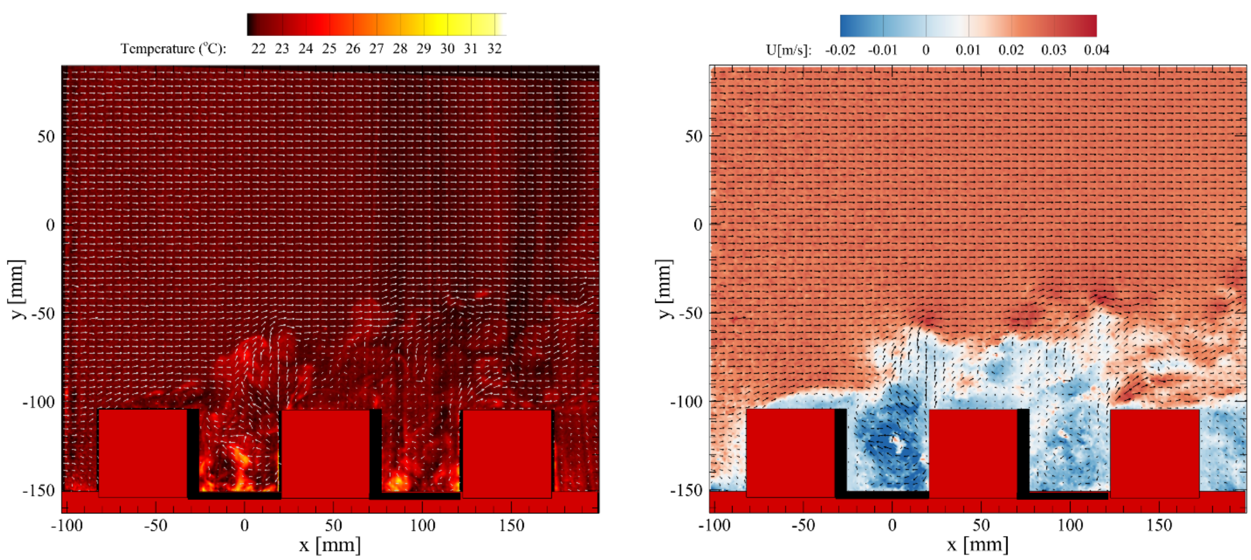

Fig. 6: Snapshot of temperature field (left) and corresponding u component of velocity field (right) for the mixed convection case: Re=1250, Ri=4.39.

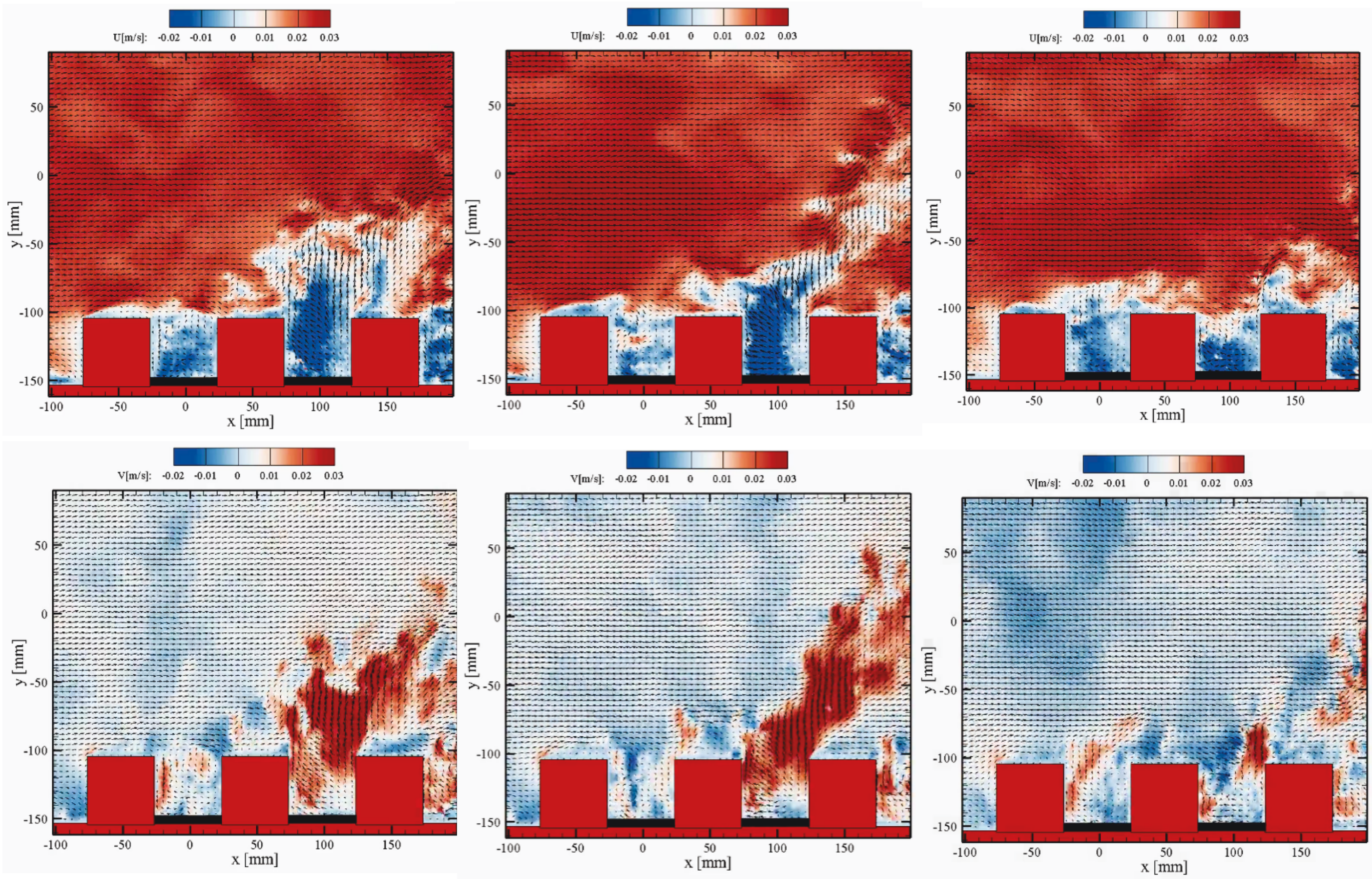

Fig. 7: Time series of streamwise u (up) and vertical velocity component, v (down) for Re=1250, Ri=4.39

In order to better understand the role of these turbulent flow structures in urban heat removal, a quadrant analysis is carried out. Reynolds shear stress components ($u'v'$) can be conditionally averaged based on the sign of u', v' fluctuations (Fig. 8). Coherent events and corresponding flow structures can thus be selected using this technique. As shown earlier in flow statistics (Fig. 4), the negative contribution of $u'v'$ (i.e. that of sweep and ejections) is much larger than contribution of outward and inward interactions ($u'v' > 0$). Fig. 9 shows ejection events due to buoyancy and sweep events due to wind flow entering the canyon (all events shown i.e. unfiltered quadrant analysis). In order to distinguish ejections events from sweep events, they are shown as positive. In future, similar quadrant analysis for the turbulent heat flux component $v'T'$ will be carried out.

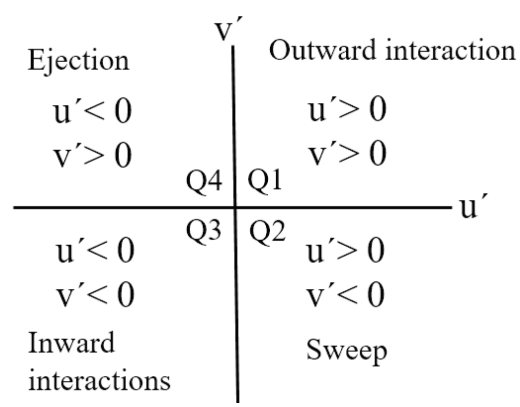

Fig. 8: Quadrant analysis of Reynold stress component $u'v'$

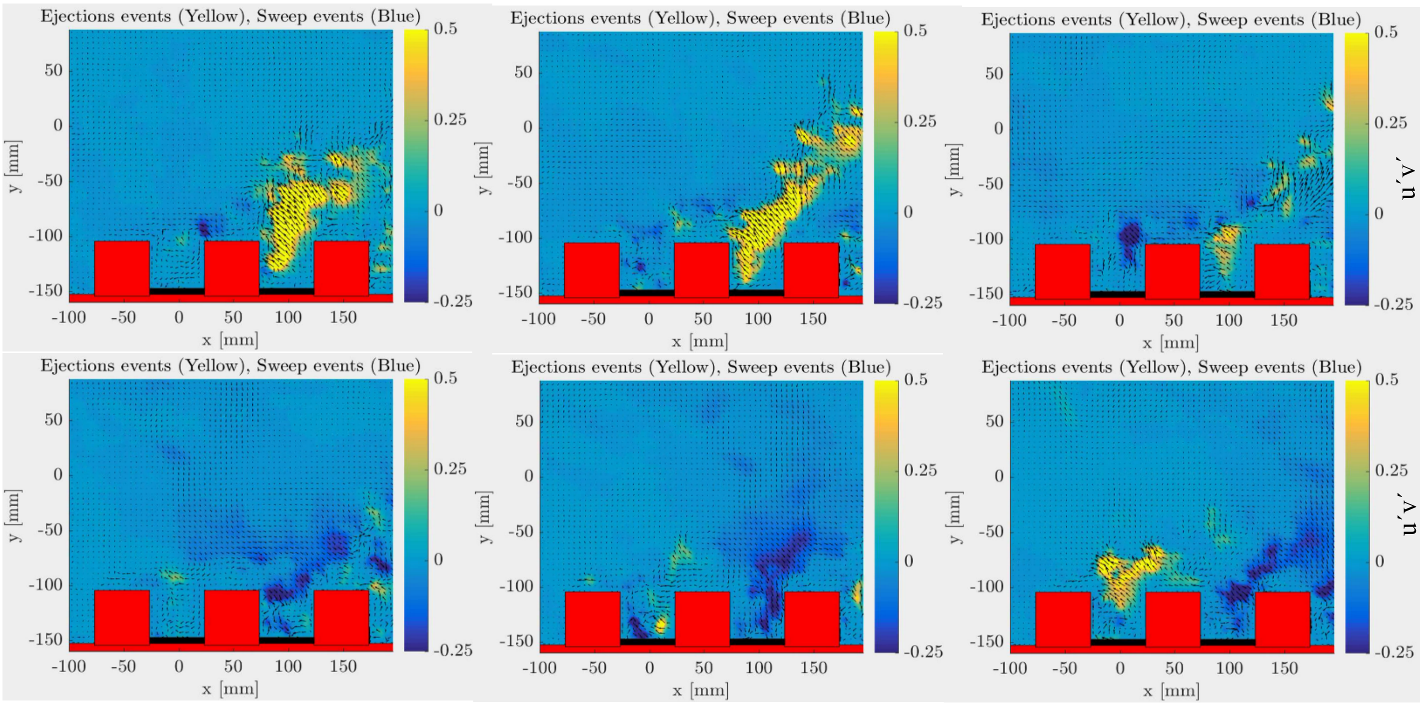

Fig. 9: Time series of the ejections(+) and sweep events(-), u´v´ component for Re=1250, Ri=4.39

3.3 Mean convective and turbulent heat fluxes

As PIV-LIF provides velocity and more importantly instantaneous temperature measurements, the urban heat removal mechanisms can be quantified using convective (uT,vT) and turbulent heat fluxes (u´T´, v´T´). The mean convective and turbulent heat fluxes are shown in Fig. 10 for the case with a Richardson number of 4.39. We see that between the buildings heat cannot be removed in the stream-wise direction as seen by the horizontal convective heat flux component, uT. Buoyancy on the other hand has significant contribution in the removal of heat as it provides an additional vertical momentum and hence induces a vertical convective heat flux, vT from the volume between the buildings to the flow above the buildings. Buoyancy also causes thermal turbulence and has a contribution to the mean turbulent heat fluxes. The mean turbulent heat fluxes are present mainly in the shear layers. They have a lower magnitude compared to the convective heat fluxes, nevertheless, also contribute to the removal of heat between the buildings.

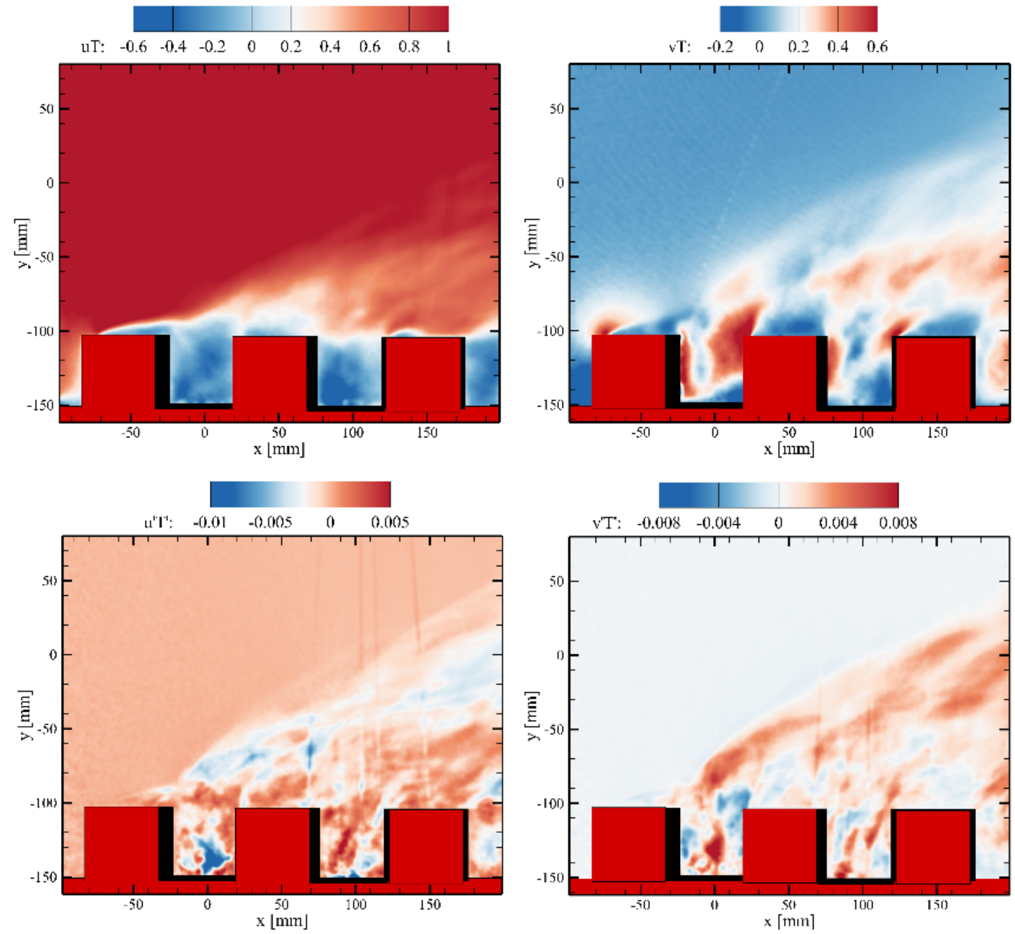

Fig 10: Mean convective heat flux components uT, vT (top), turbulent heat flux components u´T´, v´T´ (bottom), all normalized by U_∞ T_∞ for Re=1250, Ri=4.39

4. Conclusions

We demonstrate the role of buoyancy on urban heat removal by performing simultaneous PIV-LIF measurements of turbulent flow around an array of heated cubes. Analysis of the PIV-LIF measurements provides mean and, more importantly, instantaneous velocity components and temperature fields. We show that in mixed convection regime buoyant flow structures are strong enough to overcome the turbulent shear layer formed by the incoming boundary layer and the turbulent shear layer is no longer horizontal as in case of isothermal flows. We also see that buoyancy has significant contribution to the production of the TKE in the flow. Buoyancy helps in the removal of heat due to the addition of vertical momentum in between the buildings as seen by the convective heat flux component vT.

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