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 0.68m/s and 2.32m/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.

Keywords

Buoyancy, Wind tunnel, PIV, Street canyon, Froude number

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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 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 set up 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 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:

$$Re = \frac{U_{FS} H}{\nu} \quad (1)$$

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:

$$Fr = \frac{U_{FS}^2}{gH \frac{T_w - T_{ref}}{T_{ref}}} \quad (2)$$

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 possible for Froude number similarity to relate the temperature difference in the wind tunnel to a temperature difference at full-scale. Different combinations of wind speeds and surface to air temperature differences could lead to the specific Froude numbers used in this study.

3. Experimental Setup

This study was conducted in the closed loop ETHZ/Empa atmospheric boundary layer wind tunnel in Dübendorf (Switzerland). To model the flow in an urban street canyon a $W \times H \times L$ (W : width; H : height; L : length) of 20 x 20 x 180 cm cavity was constructed in the wind tunnel (figure 1). The flow direction was normal to the axis of the cavity. The aspect ratio H/W was 1 and the spanwise aspect ratio L/W was 9. According to Kovar-Panskus et al. [4] the highest degree of flow two-dimensionality in a section of the street canyon was achieved in their wind tunnel with a spanwise aspect ratio

of 8.8. Moonen et al. [19] showed that boundary effects are negligible for street canyon geometries with spanwise aspect ratios > 10 .

The wind tunnel floor and the street canyon surfaces were made out of aluminium plates, thus forming a low roughness surface. With such low roughness a more accurate near wall modelling (Low-Reynolds number modelling) can be applied in CFD, when the experimental data of this study are used for the validation of CFD simulations.

Heating mats with an output power of 1680 W each were attached at the back of each aluminium plate forming the street canyon to increase the surface temperatures. Due to the high thermal conductivity of aluminium, the temperature was almost uniform over the whole heated surface. The surface temperatures were kept constant with PID controllers monitoring the surface temperatures with thermocouples. Because no cooling system for non-heated surfaces was installed in the wind tunnel tests, some heating up of other surfaces due to conduction, convection and radiation could not be avoided, but remained limited to some degrees.

The flow field in a cross-section of the street canyon was measured with particle image velocimetry (PIV). The images were acquired with a CMOS 12 bit dual frame camera with a spatial resolution of 2016 x 2016 pixels (with a pixel size of $0.1 \times 0.1 \text{ mm}^2$). For the illumination of the DEHS (Di-Ethyl-Hexyl-Sebacat) particles a dual cavity Nd:YLF laser was used. The size of the field of view was $19.8 \times 19.8 \text{ cm}^2$, what is slightly smaller than the dimensions of the street canyon. The flow very close to the surfaces could not be measured, due to laser light reflections on the surfaces, with intensities that could damage the camera sensor. These reflections are brighter than the illuminated particles and therefore no flow field can be computed in these areas.

Best practice guidelines for PIV [20-22] were taken into account to minimise the errors of the measurements. The sampling rate was estimated from the integral time-scale and was chosen to be 4 Hz to acquire statistically independent samples. To measure at least 10 rotations of the slowest vortices, 300 double frame images at 4 Hz were recorded what corresponds to a sampling time of 75 s. The separation time between the two frames was 780 μs , what is the maximum separation time that could be acquired for the used camera. The vector fields were computed by means of a standard cross-correlation function via FFT employing multigrid analysis with two refinement steps with a refinement ratio of 2 and a final interrogation window size of 32×32 pixels with 50% overlapping. From the instantaneous vector fields the averaged velocities (V_{AVG}) and the root mean square velocities (V_{RMS}) are determined as follows:

$$V_{AVG} = \frac{1}{n} \sum_{i=1}^n V_i \quad (3)$$

$$V_{RMS} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (V_i - V_{AVG})^2} \quad (4)$$

where n is the number of samples.

For the turbulent kinetic energies (k) all three velocity components need to be accounted for. To account for the out of plane component, it is assumed that this third component behaves like the other two:

$$k = \frac{1}{2} V_{RMS}^2 + \frac{1}{4} V_{RMS}^2 = \frac{3}{4} V_{RMS}^2 \quad (5)$$

To study the repeatability of the measurements, the measurements of the isothermal street canyon were conducted three times (on different days). The results of the velocities and turbulent kinetic energies (TKE) on the horizontal and vertical centrelines of the street canyon were used for the repeatability analysis. As a criterion for the repeatability the standard deviation divided by the freestream values was used. For the velocities this value was everywhere below 1%. For the TKE it was almost everywhere below 3% with some extreme values of 5-10%. Therefore it can be concluded that the measurements are repeatable.

To measure the air temperatures inside the street canyon T-type thermocouples were used. The temperatures were measured for 2 min to determine the time averaged temperatures. The measurements were conducted on an equidistant grid of 10 x 10 measurement points, where the first measurement points were located at a distance of 1 cm from the street canyon walls. The uncertainty of the temperature measurements was $\pm 3^\circ\text{C}$ originating from the radiation exchange between the thermocouple and the heated walls. The uncertainty was estimated by measuring air temperatures with different types of radiation shielding. The temperatures were not measured in parallel of the flow fields. Therefore the temperature measurements were not influenced by the PIV system.

Table 1 gives the different surface temperatures and freestream velocities at which the measurements were conducted together with the corresponding Reynolds and Froude numbers.

The flow direction was normal to the street canyon axis, and the inflow temperature was 23°C . The inflow temperature was monitored. The heating-up of the air inside the wind tunnel was less than 1°C during the measurements. The heating-up was slow due to the large air volume and the heavy metal construction of the wind tunnel. In addition, the wind tunnel is located in a room with air conditioning and could be flushed to maintain a constant air temperature. Due to the low roughness of the aluminium plates the boundary layer was rather thin and did therefore not correspond to a specific scaled atmospheric boundary layer. The boundary layer velocity and TKE profiles were measured at the centre position of the street canyon, before the street canyon was installed and are given in figure 2 (normalized by the freestream velocity and the square of the freestream velocity). Thus not the inlet profiles were measured, but the profiles that develop in the empty wind tunnel. A Reynolds independency can be observed for the velocities, but the TKEs are not totally Reynolds number independent, what means that there could still be some decay of the TKE.

4. Results

In this section the results of the wind tunnel measurements are given. For all results presented in this section the surface temperatures of the heated surfaces are 130°C , if not otherwise indicated.

4.1 Streamlines

The streamlines for all studied cases with surface temperatures of 130°C are given in figure 3 for three different Reynolds numbers. For most cases one main vortex in the centre and two small vortices in the lower corners of the street canyon are formed. Only for the cases with windward wall heating and low Reynolds numbers two counter rotating vortices of similar size can be found. Globally, buoyancy introduces three different changes in the flow field. The first change is an increase of the velocity magnitude, which can be observed at low Reynolds numbers for all cases except for windward wall heating. The second change is a relocation of the centre of the main vortex. This is mainly observed for ground heating and for the case, where all surfaces are heated. The third change is a complete re-arrangement of the vortex structures, observed for the case with windward wall heating. For all considered cases the changes are more pronounced at low Reynolds numbers (mixed convective flow regime) than at high Reynolds numbers (forced convective flow regime).

4.2. Isothermal case

First the flow field in an isothermal street canyon is studied. Normalised velocity and TKE profiles on the horizontal and vertical centrelines of the street canyon are given in figure 4. The velocities are significantly lower inside the street canyon than in the freestream. The velocities are almost a linear function of x and y position. This is typical for a rotational vortex (see also figure 3). The highest TKEs can be observed in the shear layer ($y/H = 1$). The second highest TKEs can be found close to the windward wall, where the air of the freestream enters the street canyon from above and hits the windward wall. The profiles are very similar for most Reynolds numbers. Only the results for the lowest Reynolds number deviate slightly from the other results. Therefore it can be concluded that for the setup used in this study the flow is Reynolds independent for Reynolds numbers above about 13000 ($U_{FS} = 1\text{ m/s}$).

Figures 5 and 6 show the contour plots of the normalised velocities and TKEs inside the street canyon for the isothermal and heated cases at three Reynolds numbers. For the isothermal case the contour plots are very similar for the three presented Reynolds numbers. This confirms the conclusion that the flow is in a Reynolds independent regime. The velocities are increasing with increasing distance from the centre of the street canyon and then decreasing again close to the walls. The highest velocities and TKEs can be found at the windward wall and in the shear layer at the top of the street canyon. TKE is produced at the top of the windward wall and is then transported by the vortex in clockwise direction.

4.3. Windward wall heating

For the cases with windward wall heating buoyancy significantly changes the vortex structure. Streamlines for the five different Reynolds numbers are presented in figure 7. Besides the main vortex a second counter rotating vortex is formed. This secondary vortex is located in the lower part of the street canyon and has a similar size as the main vortex at lower Reynolds numbers. For high Reynolds numbers (30700) the size of the secondary vortex is decreased and at the highest Reynolds numbers the flow structure becomes similar to the vortex structure of the isothermal case. In figure 8 the trajectories of the centre of the main and secondary vortex are given as a function of the Reynolds number for three different windward wall temperatures (trajectories for the other measured cases are similar). With increasing freestream velocities the centre of the main vortex is moving first horizontally from the top middle to the top right and then diagonally towards the centre of the street canyon, where also the centre of the vortex for the isothermal case is located. This behaviour is similar for all four windward wall temperatures. Simultaneously the centre of the secondary vortex is moving with increasing wind speed from the right side to the left and then downwards to the right bottom corner of the street canyon, where also a small corner vortex is situated in the isothermal case.

Due to the counter-rotating secondary vortex the velocities inside the street canyons are lower compared to the velocities for the isothermal case (figure 5). With increasing Reynolds number, the normalised velocities do not change significantly. The TKEs however are for the two lower Reynolds numbers higher than for the isothermal case (figure 6). The highest TKEs can be found at the top right corner of the street canyon. That is the position, where the cold air enters the street canyon and hits the air, which is rising due to buoyancy at the windward wall. The hitting of two opposite flows produces TKE. With increasing Reynolds numbers the flow evolves to a forced convective flow and therefore less TKE will be produced by buoyancy.

4.4. Ground heating

In the case of ground heating, the street canyon velocities increase strongly compared to the isothermal case (figure 5). The increase of velocity is strongest for the lower Reynolds numbers. The velocity increase is much less for the two higher Reynolds number, but the velocities are still higher than for the isothermal case. The increase is caused by buoyancy which accelerates the flow especially at the leeward wall when the heated air starts to rise. The velocities are higher for this case than compared to leeward heating (see section 4.5), because in the former case the air at the bottom of the leeward wall has already a high temperature, while for the latter case the air starts only to heat up when hitting the leeward wall. Comparing to all cases, ground heating results in the highest velocities inside the street canyon. There is also a strong increase of the TKE for the lowest Reynolds number (figure 6). The highest TKEs can be found at the bottom corner of the windward wall, because in that corner buoyancy is acting against the main flow direction and therefore most TKE is produced.

Figure 9 shows the trajectory of the centre of the main vortex as a function of the ground temperature for four different Reynolds number. For low Reynolds number the main vortex is moving with increasing ground temperatures in clockwise direction around the centre of the street canyon. For high Reynolds number the main vortex remains at a fixed position for different ground temperatures (forced convection case).

4.5. Leeward wall heating

For leeward wall heating, the main vortex becomes also strengthened by the buoyancy effect (figure 5), mainly for low Reynolds numbers. The velocities are however lower than for ground heating, because the residence time of the heated air inside the street canyon is shorter. Also the TKEs are increased but much less compared to the other cases with buoyancy, because buoyancy acts in the same direction as the main flow in the street canyon (figure 6). Therefore the highest TKEs can be found at the top of the windward wall, where the air enters the street canyon.

In figure 10 normalised velocity profiles are given on the vertical centreline of the street canyon for different Reynolds numbers and different leeward wall temperatures. At low Reynolds numbers a strong increase of the velocities with increasing leeward wall temperature can be observed. For a leeward wall temperature of 130°C the velocities inside the street canyon are more than doubled compared to the isothermal case. For high Reynolds numbers no strong dependency of the velocity profiles on temperature can be noticed, because the flow is in a forced convective flow regime.

4.6. All surfaces heated

In this case the main vortex is again strengthened by buoyancy for all Reynolds numbers (figure 5). The velocities are lower than for the case of only ground heating, because from one side the flow is accelerated due to leeward wall and ground heating, but at the same time the velocities are decreased by windward wall heating inducing an opposite flow. The highest velocities can be found close to the leeward wall, which is also explained by the observation above. For this heating case the highest TKEs of all studied cases can be observed, because of the opposite flows induced by the surface heating. Also more heat is added, what causes stronger buoyancy effects (figure 6). The highest TKE can be found again close to the windward wall, where buoyancy is acting against the main flow direction and therefore causes a high production of TKE.

In figure 11 the trajectories of the centre of the main vortex are presented as a function of the surface temperature for five different freestream velocities. No clear trends can be observed. For high Reynolds numbers the centre of the vortices is located at similar positions as for the isothermal case, because the flow is in a forced convective regime. For low freestream velocities the flow gets strongly buoyant and the movement of the centre of the main vortex is less structured than for the other cases.

For the case with all surfaces heated the air exchange rate was also studied by analysing the vertical velocities at the top plane of the street canyon. The normalised vertical velocity profiles for different surface temperatures are given in figure 12. The air exchange rate is defined as the absolute value of air entering (or leaving the street canyon). We observe that the air exchange rate is strongly increased by buoyancy at low Reynolds numbers. At high Reynolds numbers the air exchange rate is not changed with increasing surface temperatures. We remark that the (volume) flow rate out of the street canyon seems higher than the flow rate into the street canyon, which from a point of view of mass conservation is rather remarkable. This may be attributed to the density difference between the heated air leaving, and the colder air entering the street canyon. A second reason could be 3D flow effects, or flows out of plane of the cross section measured by PIV.

4.7. Temperature measurements

In figure 13 contour plots of the air temperature normalized by the surface temperatures for the case, where all surfaces are heated, are given for two different surface temperatures and three different Reynolds numbers. For all cases it can be seen that the cold freestream air is entering the street canyon at the top of the windward wall. Further the vortex structure can be recognised in the temperature field. The highest temperatures are measured at the top of the leeward wall. With increasing Reynolds numbers the temperatures inside the street canyon are increasing, because the street canyon velocities and therefore also the heat fluxes become higher. Generally the temperatures close to the heated walls are higher than in centre of the street canyon. We also find higher temperatures in the bottom corners, where small secondary vortices prevent the removal of heat. We remark that for the case with surface temperatures of 130°C and a Reynolds number of 30700 a region of high temperatures is found at $x/H=0.25$. This high temperature region is maybe

caused by the above mentioned 3D structure of the flow field. Another cause could be the insertion of thermocouples influencing the street canyon flow.

5. Discussion

Wind tunnel measurements were conducted for a cavity type street canyon. Instead of using a row of buildings, a cavity was chosen to represent an urban street canyon, because flow around this geometry can be better validated with CFD simulations. For the same reason no scaled atmospheric boundary layer was used for the approach flow. To mimic solar radiation, the surfaces of the street canyon were heated to spatially constant surface temperatures. This is not a realistic representation of the temperature distribution for real cases, where the sun irradiates (partly) surfaces of the street canyons. Using spatially constant temperatures has however the advantage that the surface temperatures can be controlled better and therefore the measurements are repeatable. We have to mention that with the used PIV measurement technique the 3D effects could not be captured and therefore only 2D flow fields could be measured. The geometry of the street canyon was chosen in such a way that the flow has the highest possible two-dimensionality.

6. Conclusion

In this study the influence of buoyancy on the flow in urban street canyons was investigated by means of wind tunnel measurements. The measurements were conducted at different Reynolds numbers (9000 – 30700) and different leeward wall, windward wall and ground temperatures (70-130°C) to obtain flow fields within a wide range of Froude numbers (0.65-17.3). Significant changes of the flow fields for cases with high surface temperatures and low Reynolds numbers are found. For an isothermal street canyon a main vortex in the centre of the street canyon and two small vortices in the corner of the street canyon can be observed. If the windward wall is heated, a secondary counter-rotating vortex is formed for low Reynolds numbers. For all used surface temperatures a similar relocation of the main and the secondary vortex with increasing Reynolds numbers is observed. For ground heating the main vortex is strongly strengthened. At low Reynolds numbers the centre of the main vortex changes its locating in clockwise direction around the centre of the street canyon for increasing surface temperatures. With leeward wall heating the velocities inside the street canyon are also increased but less compared to the case with ground heating. For all cases the turbulent kinetic energy (TKE) is increased due to buoyancy, but the strongest increase can be found for the case, where all three surfaces are heated. The production of TKE is strongest for this case, because most heat is added to the flow and because buoyancy at the windward wall is acting against the main flow direction and therefore the highest production of TKE can be found close to the windward wall. If all surfaces are heated, the main vortex is strengthened, but not as strongly as for the case with ground heating. The flow is accelerated close to the leeward wall and the ground but slowed down close to the windward wall. Temperature measurements for those cases show, how the cold air is entering the street canyon close to the windward wall and is heated up inside the street canyon. At low Reynolds numbers the air exchange rate of the street canyon strongly increases with increasing surface temperatures. This effect decreases strongly at higher Reynolds numbers, where the buoyancy effects are less present.

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Figures

Figure 1: Dimensions of the wind tunnel model.

Figure 2: Time averaged boundary layer velocities normalised by the freestream velocity and the TKE (k) normalised by the square of the freestream velocity.

Figure 3: Streamlines for various configurations of heated surfaces and for three different Reynolds numbers.

Figure 4: Normalised velocity (left) and TKE (right) profiles on the horizontal and vertical centrelines of the street canyon (isothermal case).

Figure 5: Contour plots of the normalised velocities inside the street canyon for various configurations of heated surfaces and for three different Reynolds numbers.

Figure 6: Contour plots of the normalised TKEs inside the street canyon for various configurations of heated surfaces and for three different Reynolds numbers.

Figure 7: Streamlines for cases with windward wall heating and five different Reynolds numbers.

Figure 8: Trajectories of the centre of the main and secondary vortex as a function of the Reynolds number for three different windward wall temperatures.

Figure 9: Trajectories of the centre of the main vortex as a function of the ground temperature for four different Reynolds numbers.

Figure 10: Normalised velocity profiles on the vertical centreline of the street canyon for different Reynolds numbers and different leeward wall temperatures.

Figure 11: Trajectories of the centre of the main vortex as a function of the Reynolds number for five different surface temperatures.

Figure 12: Normalised vertical velocity profiles at the top plane of the street canyon with different surface temperatures, for two different Reynolds numbers.

Figure 13: Contour plots of the air temperatures normalized by the surface temperatures inside the street canyon for surface temperatures of $70^{\circ}C$ and $130^{\circ}C$ (all surfaces heated) and three different Reynolds numbers.

Tables

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

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