INFLUENCE OF HEAT FLUXES ON THE FLOW AND DISPERSION WITHIN A TWO-DIMENSIONAL STREET CANYON

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ABSTRACT: The aim of this study is to evaluate the influence of thermal fluxes on flow and dispersion within a two-dimensional street canyon. The study was carried out in a recirculating wind tunnel. The canyon axis was normal to the external velocity direction and the external flow simulated a neutral atmospheric boundary layer whose depth $\delta$ is approximately one order of magnitude larger than the canyon height $H$. A passive scalar (ethane) was injected continuously from a line source placed at ground level at the centre of the canyon. Particle Image Velocimetry (PIV) was used to measure flow within the cavity. Concentrations were detected with a Flame Ionisation System (FID). The boundary conditions inside the canyon were modified by heating the windward and the leeward walls of the canyon. The experimental results of PIV and FID measurements have been analyzed in order to define the dependence of the velocity and concentration fields on the intensity of the thermal fluxes imposed within the cavity.

1 INTRODUCTION

Over the last 3 decades, several studies have been performed in order to study flow and dispersion in urban street canyons. However, few of these investigated the role of heat fluxes generated by temperature difference $\Delta T$ between the canyon walls and the air within the canyon. The temperature difference is typically induced by the direct solar radiation and can reach 15 °C in summer in a town at mid latitudes [1]. The thermal fluxes generate buoyancy forces within the canyon which can have a relevant influence on the flow within it, especially in low wind conditions.

To date, these effects have been investigated numerically by Sini et. al. [2] and Kim and Baik [3] who focused on the dependence of the topology of the mean flow streamlines on increasing heat fluxes at the upwind and downwind wall [2] or from the ground [3].

Similar results have also been obtained experimentally, for low internal Froude number values, by Kovar-Pankus et al. [4] who investigated the flow in two-dimensional street canyon by means of wind tunnel experiments.

Full scale experiments were performed in central Nantes (France) by Vachon et al. [5] and in central Gothenburg (Sweden) by Offerle et al. [1]. In both cases the authors could not detect any evidence of secondary circulation of the air within the canyon and the influence of thermal fluxes seemed to be limited to a thin layer close to the heated wall.

The lack of experimental and numerical results on this topic motivates the need for further investigation. In particular, as far as we are aware, none of these studies focused on the influence of thermal fluxes on the structure and the intensity of the fluctuating flow within the
canyon and on the pollutant dispersion within it. To that purpose we have performed wind tunnel experiments on a simplified urban street canyon flow.

2 EXPERIMENTAL SET UP AND MEASUREMENT TECHNIQUES

The experiments were performed in a recirculating wind tunnel at the Laboratoire de Mécanique des Fluides et d’Acoustique at the Ecole Centrale de Lyon. The test section of the wind tunnel is 9m long, 1m high and 0.7m wide, with glass side walls. Similarly to Kovar-Pankus et al. [4] the measurements were carried within a two-dimensional street canyon overlain by a neutral atmospheric boundary layer, generated using a combination of Irwin spires [6] at the entrance to the test section and a series of square bars placed normal to the wind on the floor of the tunnel [7]. The depth $\delta$ of the external boundary layer is approximately one order of magnitude larger than the canyon height $H$, which is equal to 0.06m. The free stream velocity at the top of the boundary layer is $U_\infty = 4.5 m/s$.

The downwind wall of the canyon was heated uniformly by placing thermal resistances beside it (Figure 1). To verify the uniformity of the temperature distribution on the canyon wall, 8 t-type thermocouples were placed on it. The thermal fluxes were measured at canyon walls by means of 2 heat flux sensor of the size of 1 cm x 2 cm. Air temperature measurements were performed with t-type thermocouples placed on a moving support.

Velocities within the cavity were measured using Particle Image Velocimetry (PIV). Two coupled YAG laser sources provided pairs of laser pulses at a frequency of 4 Hz. The visualization light sheet was perpendicular to the canyon axis and measured 1 mm in width and the flow was seeded with micron-sized droplets produced by a smog generator. The observation field measured approximately 120 x 120 mm, and this was filmed at a resolution of 1280 x 1024 pixels. The interrogation window was fixed at 16 x 16 pixels, corresponding to an averaging area of 0.9 mm x 0.9 mm. The interrogation areas overlapped by 50% so that in total, each velocity field computation yielded a set of 240 x 240 vectors. In each configuration 1000 velocity fields were sampled at a frequency of 4 Hz and ensemble averaged statistics computed.

Ethane, chosen as a passive scalar, was injected from a two-dimensional ground level source placed at the centre of the canyon (Figure 1). The source was constructed from a 4 cm diameter porous polymeric tube, located in a slot cut into the floor of the tunnel [8]. Concentrations were measured using a Flame Ionisation Detector (FID) system with a sampling frequency of 300 Hz (Fackrell, 1980). The mass flow rate per unit length at the source was $M_q = 4 mg/s\cdot m$. The fluctuations in the mass flow rate were less than 1% [8].
3 RESULTS

3.1 Experimental conditions

If the external flow conditions are kept unaltered, the flow dynamics within a canyon depends on four adimensional parameters: a geometrical parameter, the aspect ratio between the height $H$ and the width $W$, and three dynamical parameters. These are the Prandtl $Pr$, the Reynolds $Re$ and the internal Froude number $Fr_{int}$ defined as

$$Pr = \frac{\nu}{k}, \quad Re = \frac{UH}{\nu}, \quad Fr_{int} = \frac{U}{\sqrt{gH \frac{\Delta T}{T_0}}}$$

where $\nu$ is the kinematic viscosity, $k$ the thermal conductivity, $g$ the gravitational acceleration, $T_0$ a reference temperature and $U$ a velocity scale.

The definition of the characteristic velocity scale is not trivial. Kovar-Pankus et al. [4] assume $U$ as the velocity at the top of the external boundary layer flow $U_\infty$. However it could be argued that this is not necessarily a characteristic scale for the flow in the canyon, since same $U_\infty$ could produce different boundary layer flow, and therefore different canyon flows, depending on the upwind wall roughness. A more suitable value could be the velocity difference of the mean horizontal velocity $\Delta U$ across the shear layer at the top of the cavity [9] or the maximal mean velocity value within the cavity. The latter value, which is approximately equal to 0.4 m/s, is be assumed here, giving a Reynolds number of about $3 \cdot 10^3$.

Experiments are performed for a fixed square canyon geometry, with unaltered conditions in the external flow and by imposing three different values of the thermal fluxes at the downwind wall of the canyon. These generate three temperature difference $\Delta T$ between the heated wall and ambient air ($T_a = 22^\circ C$) for the three cases studied.

<table>
<thead>
<tr>
<th>Fr_{int}</th>
<th>$\Delta T , [^\circ C]$</th>
<th>$F , [W/m^2]$</th>
<th>$\Delta T , [^\circ C]$</th>
<th>$F , [W/m^2]$</th>
<th>$\Delta T , [^\circ C]$</th>
<th>$F , [W/m^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>44</td>
<td>0.7</td>
<td>97</td>
</tr>
</tbody>
</table>

Table 1: Heat fluxes, internal Froude number $Fr_{int}$, temperature difference $\Delta T = T_w - T_b$ between the heated wall and ambient air ($T_a = 22^\circ C$) for the three cases studied.

In the next paragraph we analyse the influence of varying $Fr_{int}$ on the mean temperature field, the mean and fluctuating flow field and on the mean concentration of a passive scalar.

It is worth noting that, since the velocity scale is different, the values of the internal Froude number considered here cannot be directly compared to those of Kovar-Pankus et al. [4]. However, taking $U_\infty$ as velocity scale in order to compare the conditions of the two experiments, it is evident that the $Fr_{int}$ values in the present case are about one order magnitude higher than those obtained by Kovar-Pankus et al. [4], since the dimension of the canyon in our experiments is considerably smaller.
3.2 Temperature field

Figure 2: Mean temperature (°C) field within the canyon for the three cases studied. The temperature distribution changes in the whole canyon, not only close to the downwind wall, and results in an overall variation on the topology of the iso-lines.

3.3 Velocity Fields

Figure 3 shows the vertical profile of mean horizontal velocity and horizontal profile of mean vertical velocity within the canyon for the three cases studied. No relevant influence of thermal fluxes could be detected on the mean flow within the cavity. This result differs from that obtained by Kowar-Panskus et al. [4] who observed considerable differences in the flow topology.

In fact even if the values of ΔT are similar in the two experiments, the Fr_{int} values differ of almost an order of magnitude. This feature explains the different dynamical conditions repro-
duced in the two experiments which are due to the radically different effects of the buoyancy force on the flow dynamics.

Differently from the mean velocity field, the distribution of the turbulent kinetic energy (t.k.e.) within the canyon shows a clear influence of the thermal fluxes imposed at the downwind wall. As Figure 4 shows, the t.k.e. levels increase with increased thermal flux intensity. These differences are distributed in the whole cavity and extend up to shear layer at the top of it. Even if the buoyancy forces do not influence the mean flow, they have a great impact on the thermal production of t.k.e., which is proportional to the correlation between the fluctuating velocities and temperatures.

3.4 Concentration Fields

Recent studies [9] have shown the key role of the fluctuating component of the velocity field in the transfer of pollutant out of the canyon. We would therefore expect the different t.k.e. value would have a great impact on the mean concentration of a passive scalar within the canyon. In fact, as it is shown in Figure 5, the concentration field is altered by the presence of the thermal flux. The distribution of the concentration is almost the same, but their values show a general tendency to decrease for increasing intensity of $F$. This means that increasing values of $F$ enhances the mass transfer from the canyon to the external flow.

<table>
<thead>
<tr>
<th>$\Delta T$ [K]</th>
<th>First case</th>
<th>Second case</th>
<th>Third case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;C&gt;$ [mg/m$^3$]</td>
<td>1166</td>
<td>932</td>
<td>900</td>
</tr>
<tr>
<td>$u_d$ [m/s]</td>
<td>0.057</td>
<td>0.071</td>
<td>0.074</td>
</tr>
</tbody>
</table>

Table 2: Spatially averaged concentration within the canyon $C^*$ and estimation of the mass transfer velocity $u_d$ between the canyon and the external flow.

To quantify this effect we can adopt a simple box model and split the domain in two regions with uniform concentration, the cavity and the external flow, separated by a discontinuity surface. Assuming this simple model, we can express the turbulent mass flux (per unit length) at the top of the canyon in stationary conditions as

$$M_q = W u_d (C^* - C_0)$$
where $M_{q_{st}}$ is the mass inflow rate (per unit length) within the canyon, $u_d$ is the transfer velocity, $C_0$ is the concentration in the external flow and $C^*$ represents the spatially averaged value of the mean concentration within the canyon. Since $C_0 = 0$ we write

$$u_d = \frac{M_q}{C^*W}$$

The computed values of $u_d$ together with the values of $C^*$, are given in Table 2, showing how the transfer velocity is enhanced for decreasing $Fr_{int}$.

![Figure 5: Mean concentration field (mg/m$^3$) of a passive scalar (injected by a line source at ground level) for the three cases studied.](image)

### 4 CONCLUSION AND FURTHER WORK

We have presented some preliminary results of wind tunnel experiments that we have performed in order to study the effect of thermal fluxes on flow and pollutant dispersion within a square canyon.

The experimental results show that, even if the thermal fluxes are not strong enough to modify the topology of the mean flow streamlines, they do influence the intensity of the t.k.e. field within the cavity, which is generally increased for enhanced thermal fluxes. This feature induces higher mass transfer velocity from the canyon to the over lain atmospheric flow and therefore to slower passive scalar concentration within the canyon. We can therefore conclude that, for the case studied, these heat fluxes assist the canyon ventilation.

It is worth noting that these results have been achieved for a square canyon heated uniformly on the downwind wall and we would expect different results for different positions of the heat source and for different canyon aspect ratio. For this reason a new series of experiments has been performed in order to study the dependence of the mass exchange velocity on thermal fluxes when a counter rotating recirculation cell forms at the top of the canyon. Experimental results are currently been analysed and will be presented in a further publication.
5 REFERENCES


9 Salizzoni, P., Soulhac, L. and Mejean, P. “Street canyon ventilation and atmospheric turbulence” submitted to Atmospheric Environment (2009)