Thermal Effects on the Airflow in a Street Canyon – Nantes '99 Experimental Results and Model Simulation

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1 Introduction

The airflow within a street canyon is dominated by aerodynamic, thermal or other effects such as traffic influences. Understanding these effects is crucial for improving the knowledge of mechanisms that govern the air pollutant dispersion in urban streets. The aerodynamic effects, including building geometry and architecture as well as street canyon dimensions, have been extensively studied mainly with wind-tunnel experiments (e.g. Oke, 1987) and numerical models (e.g. Hunter et al., 1992) and only with a few full-scale experiments (e.g. Louka et al., 2000).

Thermal effects result mainly from the variation of solar heating of the street walls and ground during the day. It is expected that the thermal effects are greatest under low wind conditions and wind perpendicular to the street. The input of such effects on the airflow within a street canyon is insufficiently investigated. Sini et al. (1996) have studied these effects numerically within a model cavity and demonstrated that wall temperatures can largely influence the in-street flow and its vertical transport capabilities. However, further validation of these results is required. The temperature stratification during the day was the subject of a full-scale experiment within a street in Kyoto (Nakamura & Oke, 1988). Nevertheless, only one velocity point-measurement was available and no further information on the structure of the dynamic field is available. Therefore, further work is necessary in order to understand the thermal effects on the flow structure and pollutant dispersion within a street canyon.

The Nantes '99 experimental campaign aimed at providing an insight on the thermal effects on wind and CO concentration fields within a street canyon. The detailed database that was developed is a useful tool for the evaluation of numerical models that deal with this topic.

2 Study approach

2.1 The Nantes '99 experimental campaign

The field experimental campaign was conducted in June 1999. This summer month is usually characterised by high solar intensities and generally low wind-speeds. Apart from studying the thermal effects on wind flow and dispersion, the Nantes '99 campaign aimed at investigating the effects of traffic on the wind field developing within the street and the dispersion of vehicular exhausts as shown in another joined paper of this conference (Vachon et al., 2001).

Rue de Strasbourg is a three-lane one-way street situated in the centre of Nantes and is one of the most traffic congested streets of the city. The orientation of the street long axis is approximately north to south. It is an asymmetric street canyon with its west side slightly lower (h_w=19.4m) than its east side (h_e=22.8m). The aspect ratio of the width of the street, W, over the mean height of the buildings, H, is W/H=0.7 implying that a main vortex develops within the street when the ambient wind is perpendicular to its axis. Detailed description of the experimental site and the available measurements can be found in (Vachon et al, 2000). Surface temperature of the building walls was measured at four levels. Air temperature was measured at the similar levels and at seven horizontal positions at each of these levels as shown in Figure 2.1. Measurements from several days with low easterly winds perpendicular to the street and intense solar radiation were analysed.

2.2 Numerical modelling

A standard k-ε model (CHENSI) developed within the laboratory was used for the numerical simulations. A detailed description of the model regarding the numerical scheme and the boundary conditions for wind and turbulence is available on the web site of the CFD working group of the TRAPOS network (http://www.dmu.dk/atmosphericenvironment/trapos/cfd-wg.htm). For temperature, a wall function with the widely used Jayatilleke parameter was used (Sini et al., 1996).

Initially, two-dimensional calculations were performed with size of the cells within the street equal to 24.75cm. Due to the non-availability of measurements at the inlet of the calculated domain, in the particular case upstream the eastern side, the velocity and turbulent kinetic energy profiles were such that would lead to wind speed, U_{ref}, and turbulence values, k_{ref}, similar with the measured ones at the reference position (roof of west building), i.e. U_{ref}~1m/s and k_{ref}~0.1m^2/s^2.

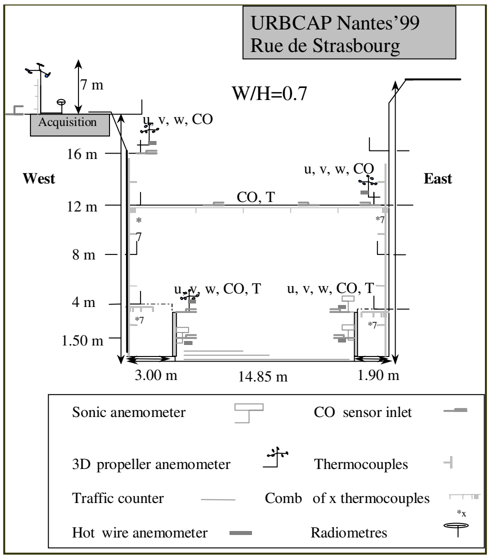

Figure 2.1. Two dimensional schematic representation of the measuring site and instruments involved.

3 Results

3.1 Nantes '99 experimental results

Here, results from the 22nd of June are presented. Figure 3.1 shows the distribution of wall temperature at four different heights during the day. It is clear that the North-to-South orientation of the street long axis results to the solar heating of its west side in the morning and progressively to its east side in the afternoon.

At periods of intense solar heating the surface temperature may exceed by as much as 18°C the air temperature as shown in Figure 3.2 at 11am local time with the temperature gradient being quite steep in the first 1m from the wall. At this time the windward wall is heated. This leads to a strong convection close to the wall receiving direct solar radiation affecting the transport of pollutants from the canyon to the layer aloft.

The investigation of such effect on the airflow was complicated due to the absence of wind speed measurements at the positions of temperature measurements as well as due to the combination with the traffic effect. The examination of the flow field using the available measurements was made with a two-dimensional projection of the velocity vectors as shown in Figure 3.3. A main re-circulation was suggested by the measurements, which was present during the whole day for wind perpendicular to the street. It is anticipated that the thermal effects are local, close to the building walls. However, the wind-speed measurements were taken farther from the walls than the temperature measurements, therefore the thermal effects close to the walls are not clear with the available flow measurements. For this reason, an additional experiment was conducted during September 2000 investigating air temperature and wind at the same locations within 1.5m from the walls. The analysis of these data is expected to give some further intake in the thermal effects on the airflow close to the walls.

3.2 Numerical simulations

Initially, the dynamic field was calculated without any temperature effects (isothermal case). The features of the simulated flow field (Figure 3.4) are a main re-circulation and a secondary vortex at the windward corner at the floor of the street canyon.

Fitted profiles on the surface temperature of the leeward and the windward walls at 11am provided the initial temperature conditions for the simulations with CHENSI as shown in Figure 3.5. The profiles were extended for the whole height of the walls. The simulations (Figure 3.6) show that the heated windward wall has created a distinctive effect on the main flow, which is now characterised by two main counter-rotating vortices and a secondary smaller eddy at the leeward side at the bottom of the street. The re-circulation of the isothermal case has been suppressed at the top of the canyon, while a strong updraft close to the heated wall leads to transfer of air from the canyon floor to the roof-level.

It is apparent that CHENSI overestimates the thermal effects on the flow within Rue de Strasbourg leading to the prediction of a largely modified street flow. This is probably due to the wall function for temperature used in the model. A more appropriate temperature boundary condition for modelling such flows would be a heat flux condition. This quantity may be calculated with the new experiment performed in Rue de Strasbourg in September 2000. In addition, it is expected that under such low velocities within the street canyon the airflow is probably three-dimensional rather than two-dimensional as it was also observed in the ENFLO wind tunnel during an experiment of heated cavity that is presented in a separate paper of this conference (Kovar-Panskus et al., 2001). Therefore, a three-dimensional simulation is now considered that will calculate the airflow within Rue de Strasbourg and in its neighbourhood.

4 Discussion-Conclusions

The Nantes ’99 experimental campaign suggested that the overall effect of the heated walls on the street canyon flow dynamics is small. Thermal effects are important in a narrow region close to the windward heated wall. As the flow in the wall boundaries carries air from the street level upwards, where normally cleaner air is transported from above, thermal effects may still be important from the air quality point of view even if they are proven to be weak in the overall flow. The heat flux close to the heated wall is an important quantity for modelling such flows. For this reason, a new experiment was carried out in Rue de Strasbourg during September 2000 simultaneously looking at the temperature and the wind speed at several positions within 1.5m from the wall. In this way instead of using temperature wall function the use of heat flux boundary conditions will be considered. In addition, heated walls affect the flow close to the wall in all three dimensions and therefore the numerical simulations that are now performed treat the thermal effects in three dimensions.

Acknowledgements

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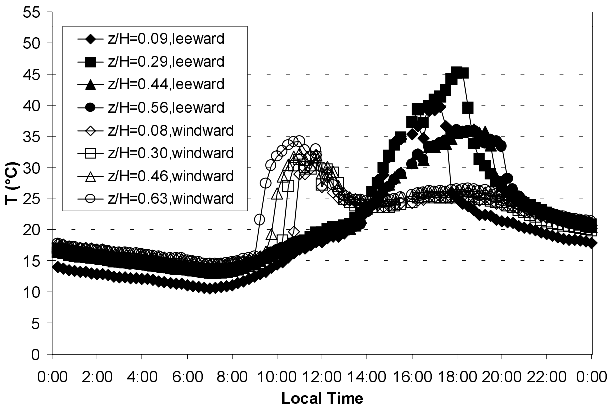

Figure 3.1. Wall temperature distribution during the 22nd of June.

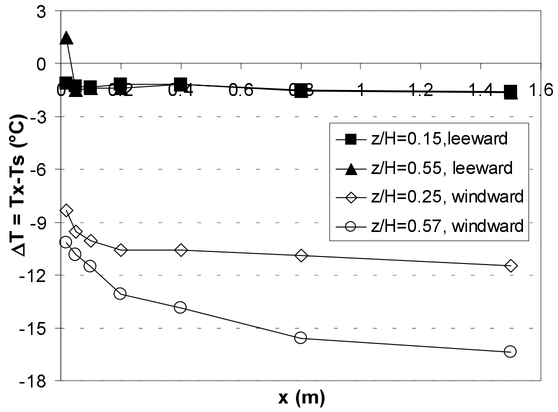

Figure 3.2. Measured ΔT between air and walls versus distance from the walls at different locations.

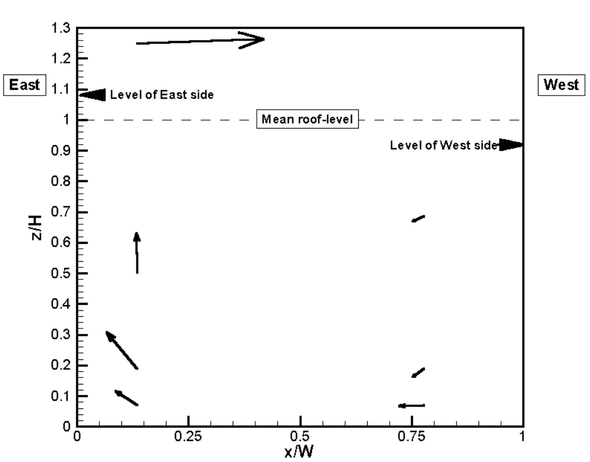

Figure 3.3. Two-dimensional wind speed measured on 22/6/99 at 11am local time.

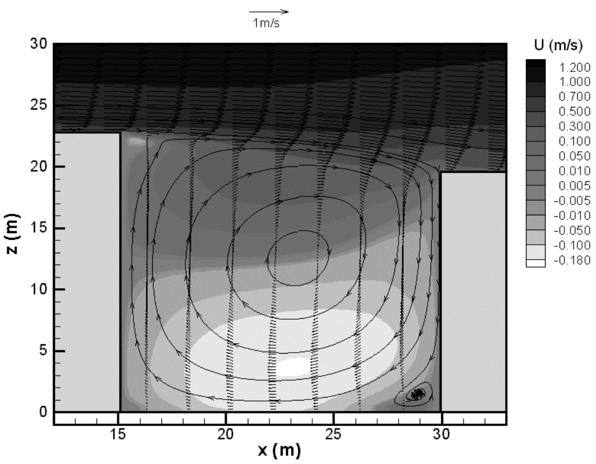

Figure 3.4. Simulated wind field without thermal effects.

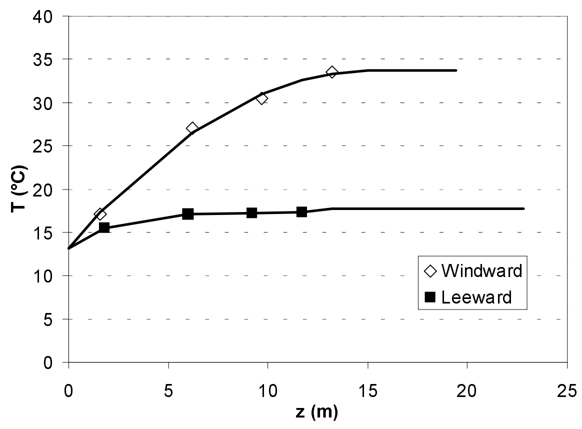

Figure 3.5. Measured leeward and windward wall temperature profiles.

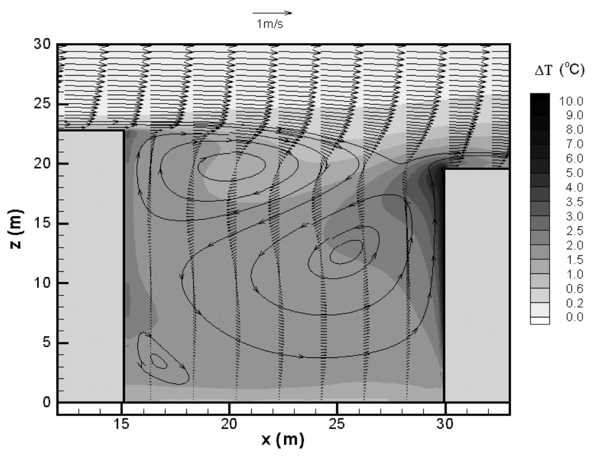

Figure 3.6. Simulated wind field with thermal effects and temperature isocontours.