MODELLING TRANSPORT AND DISPERSION OF POLLUTANTS IN STREET CANYONS

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ABSTRACT

The transport and dispersion of pollutants in a street canyon, and the intersection between two streets, have been studied using experiments and numerical simulations. The study of the street canyon demonstrates the importance of the geometry of the canyon (aspect ratio, dissymmetry) in determining both the topology of the flow and the concentration distribution; the flow is also very sensitive to wind direction. The study of the street intersection shows how the intersection influence flow and dispersion in the adjoining streets. This work has been used to develop new, practical models for flow and dispersion in city streets; these models are compared here with the results from the wind tunnel experiments and the numerical simulations.

KEYWORDS
Atmospheric dispersion, urban street-canyon, wind-tunnel experiment, numerical simulation.

INTRODUCTION

Many practical problems involving air pollution in urban areas depend on the flow and mixing that takes place within individual streets. Pollutants are emitted within the streets by urban traffic, and are inhaled there by the inhabitants; pollution monitors are located within streets, and the concentrations they measure can depend quite sensitively on local conditions. In order to estimate the exposure of inhabitants, or evaluate the representativity of concentrations measured by pollution monitors, we need to understand how pollutants are dispersed within the urban canopy, and how this dispersion depends on factors such as street geometry and external meteorological conditions. Finally, in order to apply this to practical problems, we need simple, rapid models which can be used to evaluate many different situations.

Several simple practical models for flow and dispersion within a street have been proposed, based on the concept of a `street canyon'; these models are usually based on empirical relations derived from wind tunnel or full scale measurements (eg. Johnson *et al.*,1973 ; Eerens *et al.*, 1993 ; Berkowicz, 1997). Recently, this type of flow has also been studied numerically, using standard 3D CFD codes (eg. Sini *et al.*, 1996 ; Albergel & Jasmin, 1997 ; Delaunay, 1998). In order to apply such simple models to real street geometries, which are inevitably more complicated than the very simplified configurations assumed in the models, we need to improve our understanding and modelling of some of the important physical processes involved. In particular, in this paper, we focus on the influence of the street geometry and street intersections, and the direction of the wind. Such parameters are not usually included in the simplest of street canyon models, but the results presented here show that their influence is at least as great as those processes which are modelled, and so it is difficult to justify their neglect. We compare our results with two simple models which we have developed – CARMEN (Soulhac & Perkins, 1998-a) for flow in a single street canyon, and SIRANE (Soulhac & Perkins, 1998b) for flow in a network of streets – which include these effects.

This paper summarises some of the recent results that we have obtained in wind tunnel and numerical studies of the influence of street geometry, wind direction and street intersections.

EXPERIMENTAL CONDITIONS

The experiments were conducted in the atmospheric wind tunnel at the Ecole Centrale de Lyon which has a test section 4.7 m wide, 2.5 m high and 14 m long. The boundary layer profile was created using a combination of Irwin vortex generators at the entry to the test section, and roughness elements placed over the first 7.2 m of the test section. In all the experiments the fluid velocity outside the boundary layer was 5 ms^{-1}. Fluid velocities were measured using a 3-component Laser Doppler Anemometer and gas concentrations were measured using an FID, with Ethane as the tracer gas (figure 1). The gas was released from a line source similar to that described by Meroney *et al.* (1996).

The flow within the cavity was not significantly modified by the presence of the measurement instruments in the test section. The transmission optics of the LDA were located above the cavity, at a distance of 7 times the cavity depth, and concentration samples were obtained via a hypodermic tube (external diameter 0.25mm) connected to the combustion head of the FID, which was also located above the cavity, at a distance of 3 times the cavity depth.

The experiments on the street canyon were performed using a two-dimensional cavity let into the floor of the test section, so that the incident flow was parallel to the top of the cavity; there were no obstacles upwind of the cavity. Four different configurations were studied – a square cavity, a `deep' cavity, an asymmetric `ascending' cavity and an asymmetric `descending' cavity. The characteristic dimension of all the models was 100 mm, giving an approximate scale of 1/200 for buildings that are 20 m high.

The experiments on the street intersection were performed using a series of blocks to represent a regular array of intersecting streets, all having the same square cross section. The measurements were made in a street in the middle of this array; the length of the street was five times its width.

NUMERICAL MODELS

The numerical simulations were carried out using the atmospheric dispersion code MERCURE (Carissimo *et al.* 1995), and some results have been compared with similar calculations performed using CHENSI (Sini *et al.* 1996). Both codes solve the Reynolds-averaged Navier-Stokes equation, using a standard k-ε model, with a three-dimensional structured grid.

The temperature of the fluid was assumed to be uniform, and identical to the temperature on the boundaries. The transport and dispersion of a passive scalar was computed using a finite volume method. For the case of an 'infinite' road, the flow above and within the road was assumed to be two-dimensional, so the computations were carried out on a domain (the x-z plane) measuring 80m high and 200m wide. The calculations for the street intersections were, of necessity, fully three-dimensional, and were performed on a domain measuring 80m high, 200m wide and 200m long. In all the calculations the characteristic dimension of the street was 20m, and the grid resolution close to the solid boundaries was 50cm. The aerodynamic roughness of the building surfaces was 1.5 cm.

RESULTS

Street Canyon – the influence of street geometry

We consider here a two-dimensional street, perpendicular to the incident wind. The two principal parameters that determine the flow within the street are the aspect ratio (H/W) and any asymmetry in the street cross section. The reference condition is therefore a square cavity. Measurements of velocity and concentration (figure 2) show that the gas released within the cavity is transported towards the upwind face by a recirculating eddy. Since the situation studied here is stationary – the average concentration at any position does not change over time – it follows that the average concentration within the cavity depends entirely on the exchange between the cavity and the external flow. The concentrations within the cavity are determined by the fact that the concentration gradient at the interface must be such as to maintain the same flow rate of material across the interface as the inlet flow rate of tracer gas at the line source.

The flow within the cavity is significantly different for an aspect ratio of 3 (figure 3). Firstly, a second, counter-rotating eddy appears within the cavity, so that the flow in the bottom half of the cavity is now in the opposite direction to that for a square cavity, and the peak concentration now appears on the downwind face of the cavity. (Lee and Park, 1994, suggested that the second eddy appears if the aspect ratio exceeds 2.1; our experiments suggest that it is not possible to define a single value for the transition between one and two eddies – it appears to depend on the surface roughness in the cavity, amongst other parameters.) The second important feature concerns the average concentrations within the cavity, compared with those obtained for a square cavity having the same width (and therefore a depth equal to one third of that for the deep cavity). In steady state conditions the flux of pollutant into the cavity must equal the flux out of the cavity across the interface with the external flow, and this flux depends on the turbulence at the interface, and the concentration gradient at the interface. Now in both configurations the flow conditions at the interface and the pollutant flux into the cavity are identical, so it follows that the concentration gradients at the interface, in steady state conditions, must also be identical. And since the concentrations in the external flow are also identical in the two configurations, it follows that the concentrations inside the deeper cavity must be higher than those inside the square cavity. Also, the velocities themselves are lower than in the square cavity, leading to a more uniform concentration distribution within the cavity.

In order to investigate the influence of the asymmetry of the street cross section, we have studied two cases in which one side of the cavity is of height H and the other is of height 2H – an `ascending' cavity and a `descending' cavity. The velocity and concentration fields for these two configurations are shown in figures 4 and 5 respectively. The results for the `ascending' cavity are not very different from those for the square cavity; there is a single eddy, and the concentration is highest on the upwind face of the cavity. However the flow changes significantly for the `descending' cavity; there are now two counter-rotating eddies, and the peak concentration now occurs on the downwind face of the cavity.

Street canyon – influence of wind direction

There have been very few studies of the influence of wind direction on the pollution levels within a street canyon, although this can have a significant effect. We have therefore measured concentrations for wind directions of 0° (wind parallel to the street), 15°, 30°, 45°, 60°, 75° and 90° (wind perpendicular to the street). Because the change in wind direction makes it impossible to ignore the influence of the conditions at each end of the street, these experiments have been carried out in a street of finite length, forming part of an array of identical streets.

To begin with, we present results for the two extreme cases, 0° and 90°. The concentration field created by a wind perpendicular to the street is shown in figure 6a, in a section measured at the mid-point of the street segment; the presence of a large scale recirculating structure can be easily inferred from the variations in the concentration within the cavity, with much higher concentrations on the upwind face than on the downwind face. In general, there are significant variations in concentration within the cavity, and the concentrations remain high compared with those outside the cavity. The concentration field is very similar to that measured in the `infinite' street (figure 2); however, measurements made at other points along the street (not presented here) show that the concentrations are highest at the mid-point and fall off towards the intersections. The vertical concentration profile on the street centreline is shown in figure 7-a, together with the results from MERCURE, CHENSI and CARMEN (a simple street canyon model, described in Soulhac & Perkins, 1998-a); all three models agree reasonably well with the data.

When the wind is parallel with the street, the recirculating structure within the cavity disappears completely, and the concentration field becomes very different. The concentrations in a section halfway along the street are shown in figure 6-b; the concentration field is symmetrical about the street centreline, and in the region $z<H/5$ the maximum concentration occurs along the street centreline. Above $z=H/5$, the maximum concentration at any height occurs at the walls of the cavity, rather than at the centre. Figure 7-b shows a vertical profile of concentrations on the street centreline; the results agree well with the street canyon model CARMEN.

For the intermediate wind directions we have measured concentrations within the street at a few key points, in order to be able to estimate the average concentration in the street. In general, the average concentration in the street increases as the wind becomes more nearly perpendicular (figure 8), and, in particular, it increases rapidly with angle as the angle tends to 90°. This is explained by the fact that the structure of the flow in the cavity changes very rapidly at small angles; the recirculating flow which is present at 90°, and which effectively `traps' the pollutant in the street disappears rapidly as the angle increases, and the wind then tends to `ventilate' the street. It should be noted, however, that when the wind becomes parallel to the street the length of the line source within the street becomes an important parameter; in these experiments the source was quite short, but in real life it could easily be of the order of a kilometre or more in length. In such situations the cumulative emissions from such a long line source could outweigh the ventilation induced by the wind parallel to the street. Figure 8-b also shows that the average concentrations predicted by the model SIRANE (Soulhac & Perkins, 1998-b) agree reasonably well with the measured data, over the whole range of wind direction.

Street intersections

We have studied the influence of wind direction on the dispersion of a pollutant in the vicinity of an intersection, using numerical models and wind tunnel experiments. The velocity fields and streamlines computed by MERCURE are shown in figure 9 a-f, for three different values of wind direction. The flow in the street upwind of the intersection tends to be helical; at the intersection itself, part of the flow separates and is diverted into one of the side streets whilst an equal flow enters the intersection on the opposite side, from the other side street. This gives rise to two zones of recirculating flow in the two streets which exit from the intersection; downwind of these zones, the flow re-establishes a helical pattern across the whole street.

This rather complicated flow pattern has an important influence on dispersion and mixing within the intersection; we have used the velocity fields computed by MERCURE to simulate the dispersion of a passive tracer gas, released from a line source located along the centreline of the principal street. The resulting ground level concentration fields (z=0) within the streets are shown in figures 10-a, c, e, for three different wind directions. Concentration measurements from the wind tunnel experiments are shown in figures 10-b, d, f for comparison. The most important point to note is that in all cases the concentrations vary significantly around the intersection, because of the way in which the flow divides between the different streets; this seems to contradict the idea proposed by Yamartino & Wiegand (1986) that the principal effect of a street intersection was to promote intense mixing of pollutants.

CONCLUSIONS

The work presented here forms part of a larger project which aims to develop simple practical models for the transport and dispersion of pollutants in a network of city streets. Such simple models must be based on a firm understanding of the dominant physical processes which occur, and this paper provides a brief summary of some of our investigations of those processes.

The wind tunnel experiments and the numerical simulations confirm that street geometry and wind direction both play important roles in determining the concentration distribution within a street, and the comparisons with the simple models that we have developed suggest that it is possible to capture the most important features of these processes using relatively simple, practical models.

ACKNOWLEDGEMENTS

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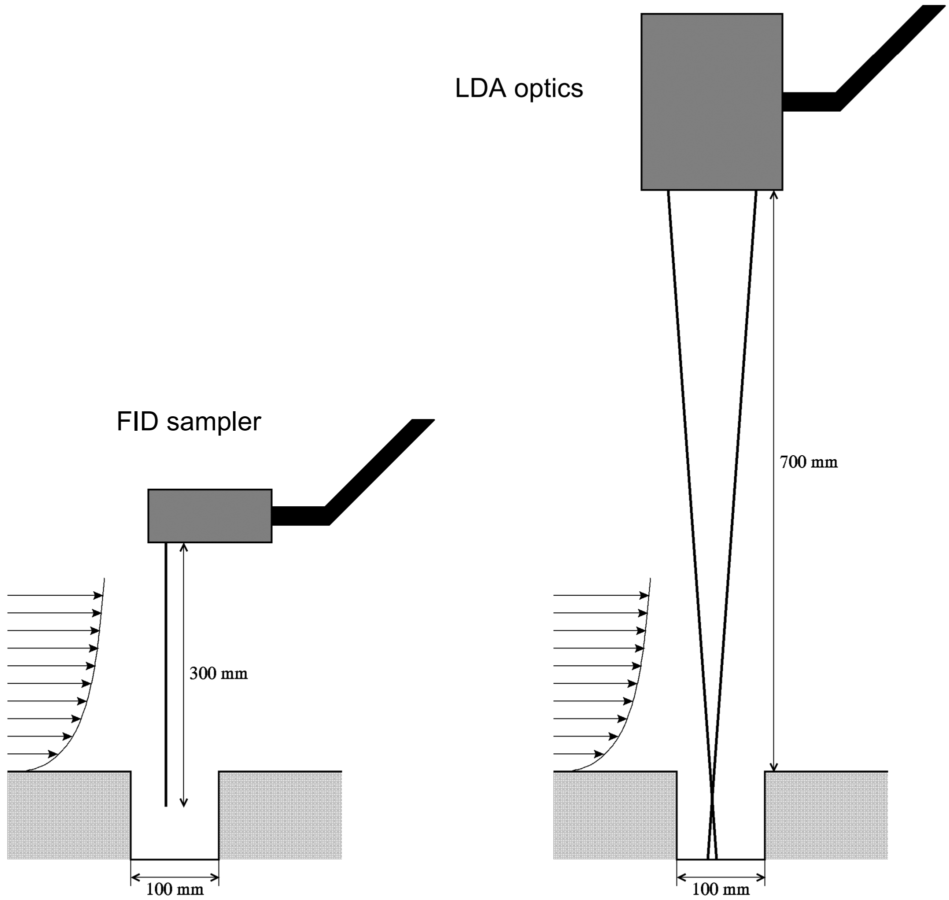


Fig. 1. Experimental set-up for concentration and velocity measurements.

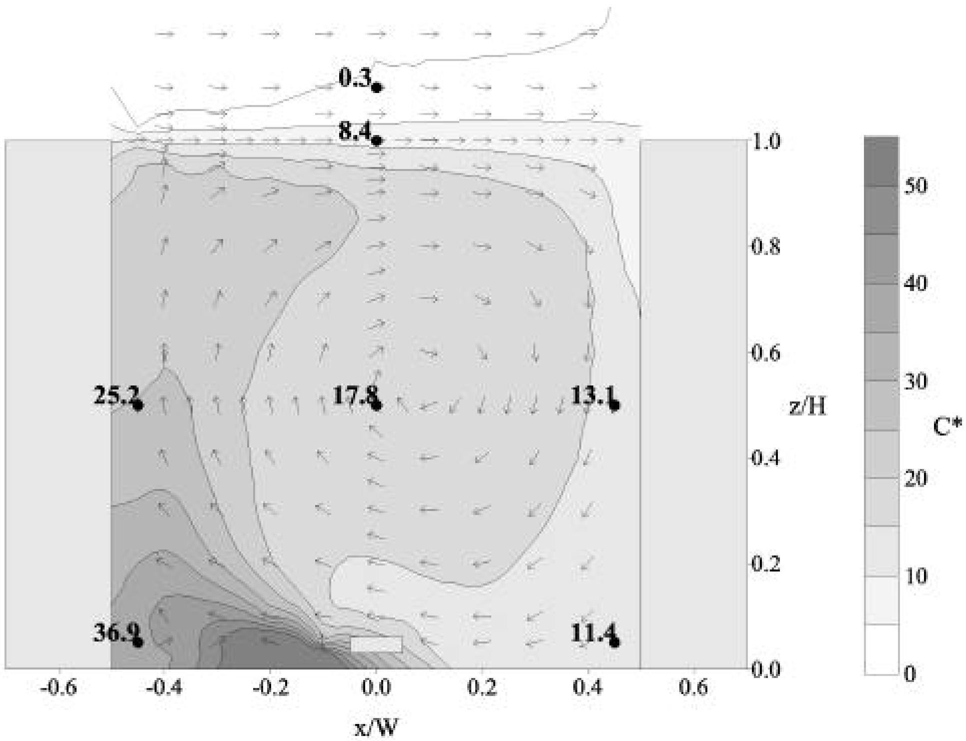


Fig. 2. Velocity and concentration fields in a square street where H/W=1 (wind-tunnel experiments). Concentration values are dimensionless.

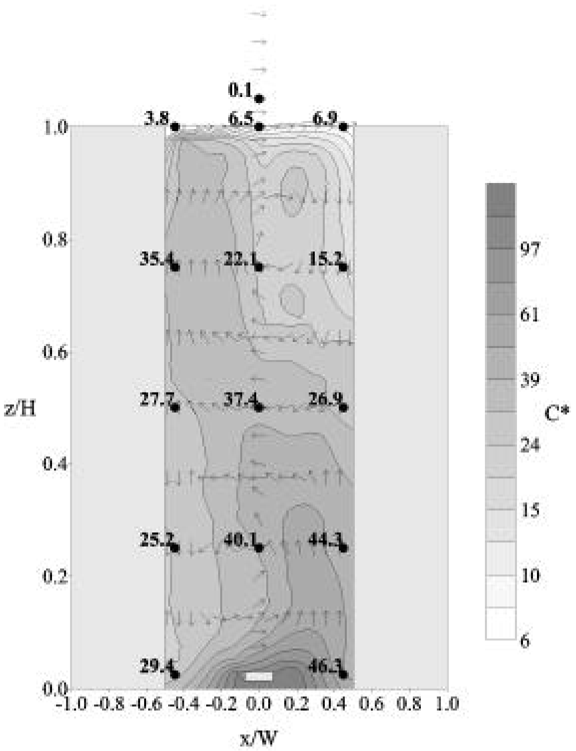


Fig. 3. Velocity and concentration fields in a narrow street where H/W=3 (wind-tunnel experiments).

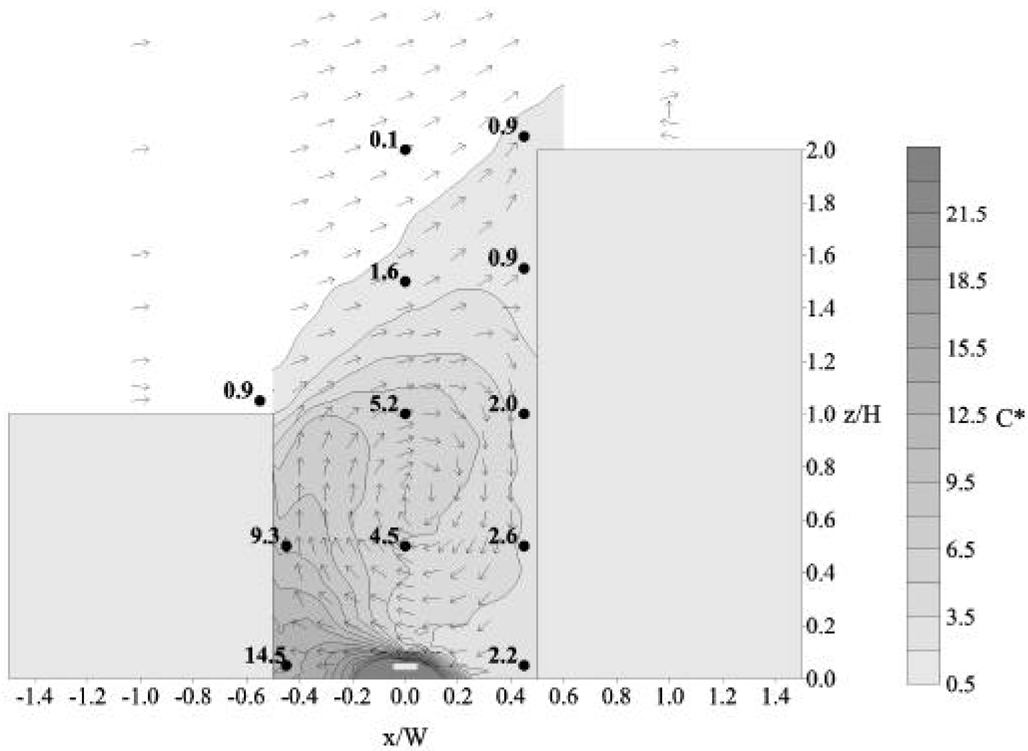


Fig. 4. Velocity and concentration fields in an asymmetric street (wind-tunnel experiments).

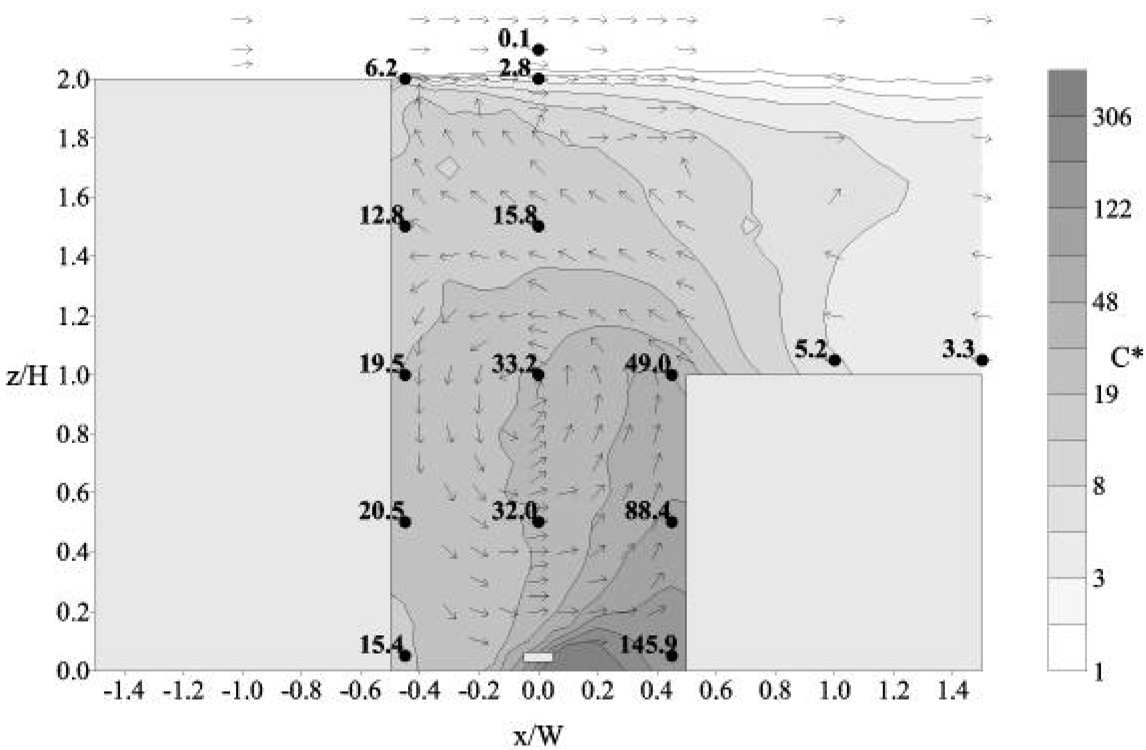


Fig. 5. Velocity and concentration fields in an asymmetric street (wind-tunnel experiments).

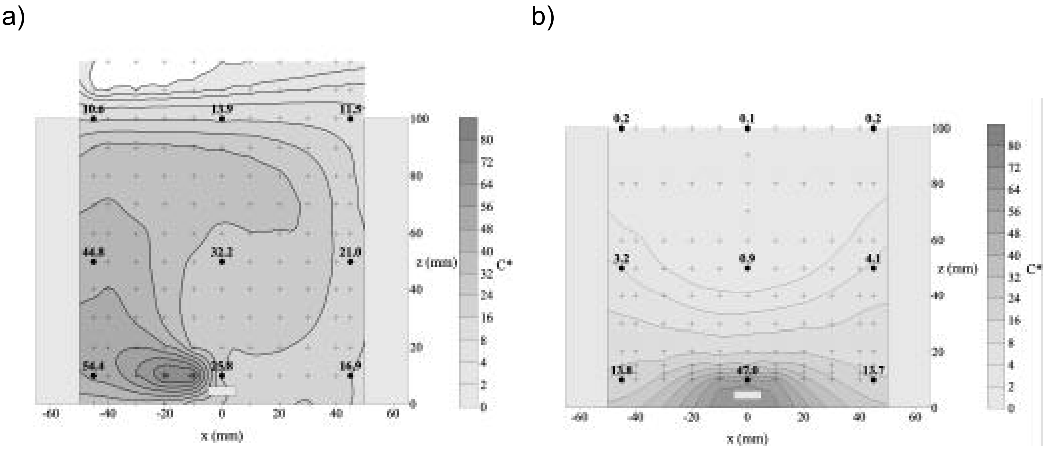


Fig. 6. Concentration fields in a square street (wind-tunnel experiments).

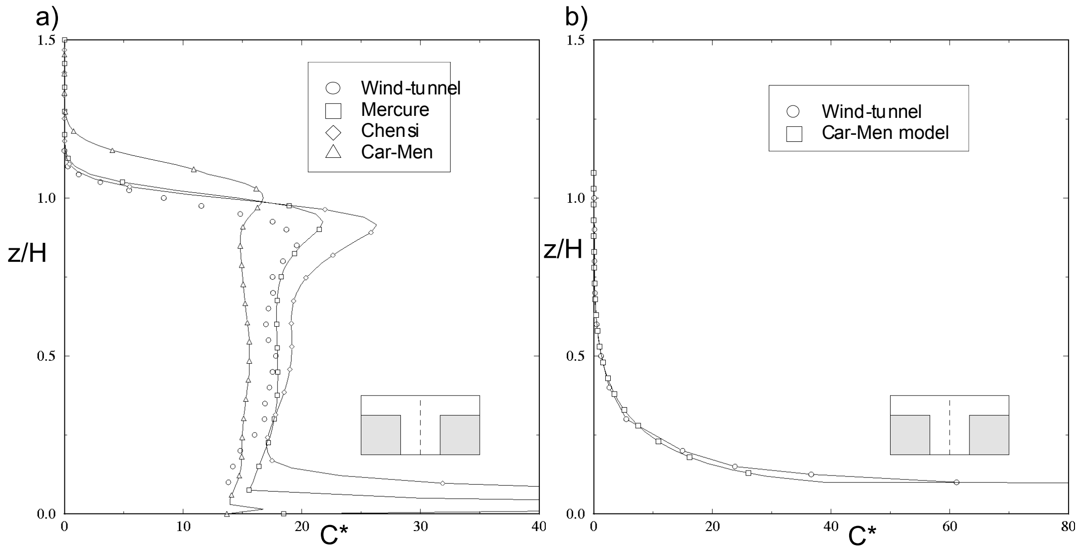


Fig. 7. Vertical concentration profiles on the street centerline.
Comparisons between models and experiments.

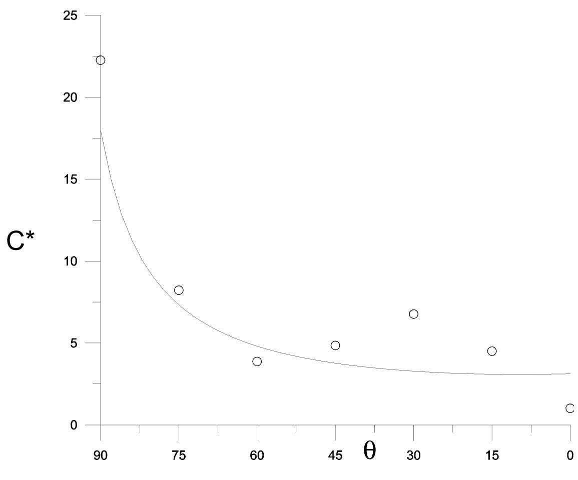
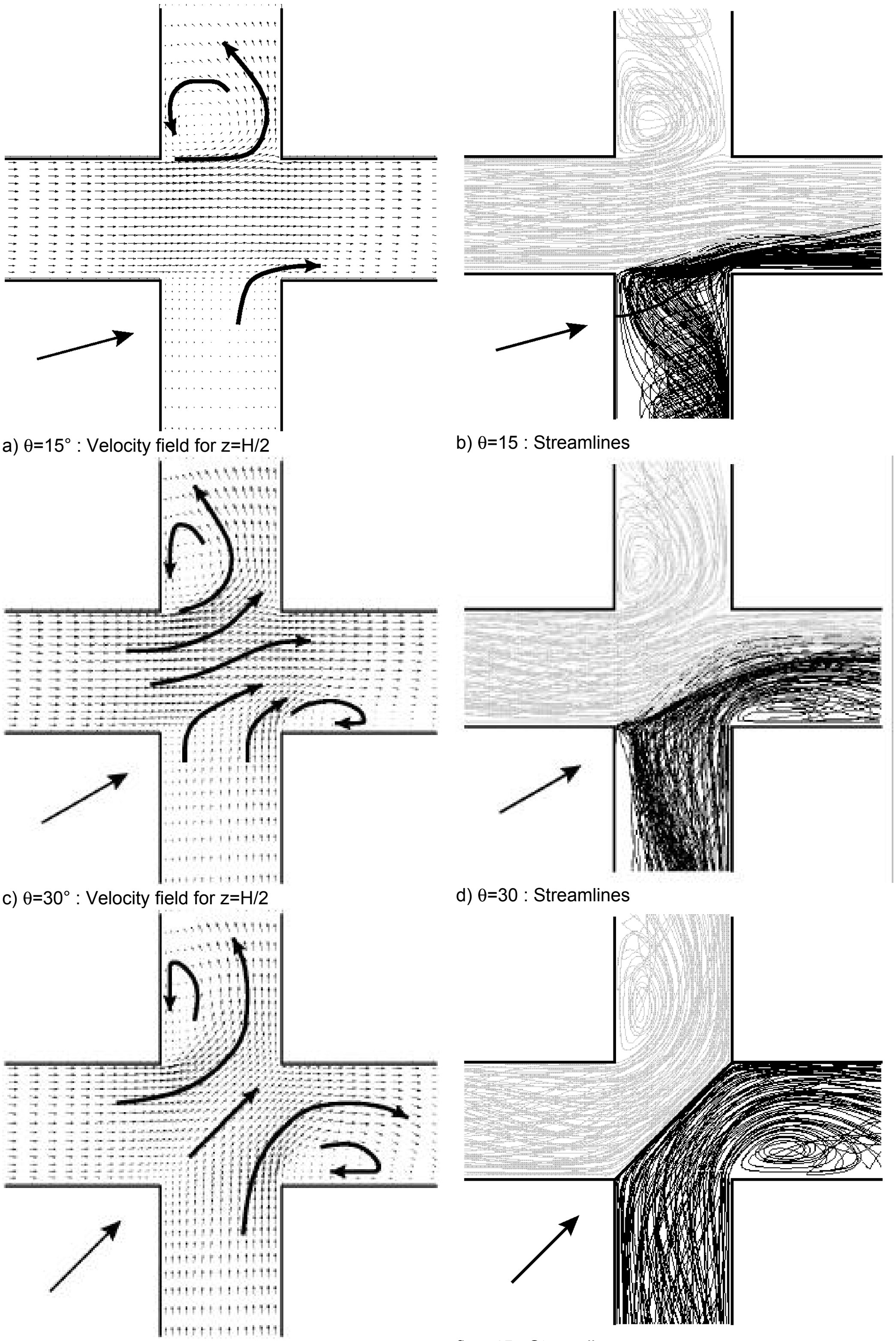


Fig. 8. Mean concentration in the street for different wind directions.
Comparisons between model and experiments



a) θ=15° : Velocity field for z=H/2

b) θ=15 : Streamlines

c) θ=30° : Velocity field for z=H/2

d) θ=30 : Streamlines

e) θ=45° : Velocity field for z=H/2

f) θ=45 : Streamlines

Fig. 9. Velocity field and streamlines in an intersection between two streets (Mercure calculations).

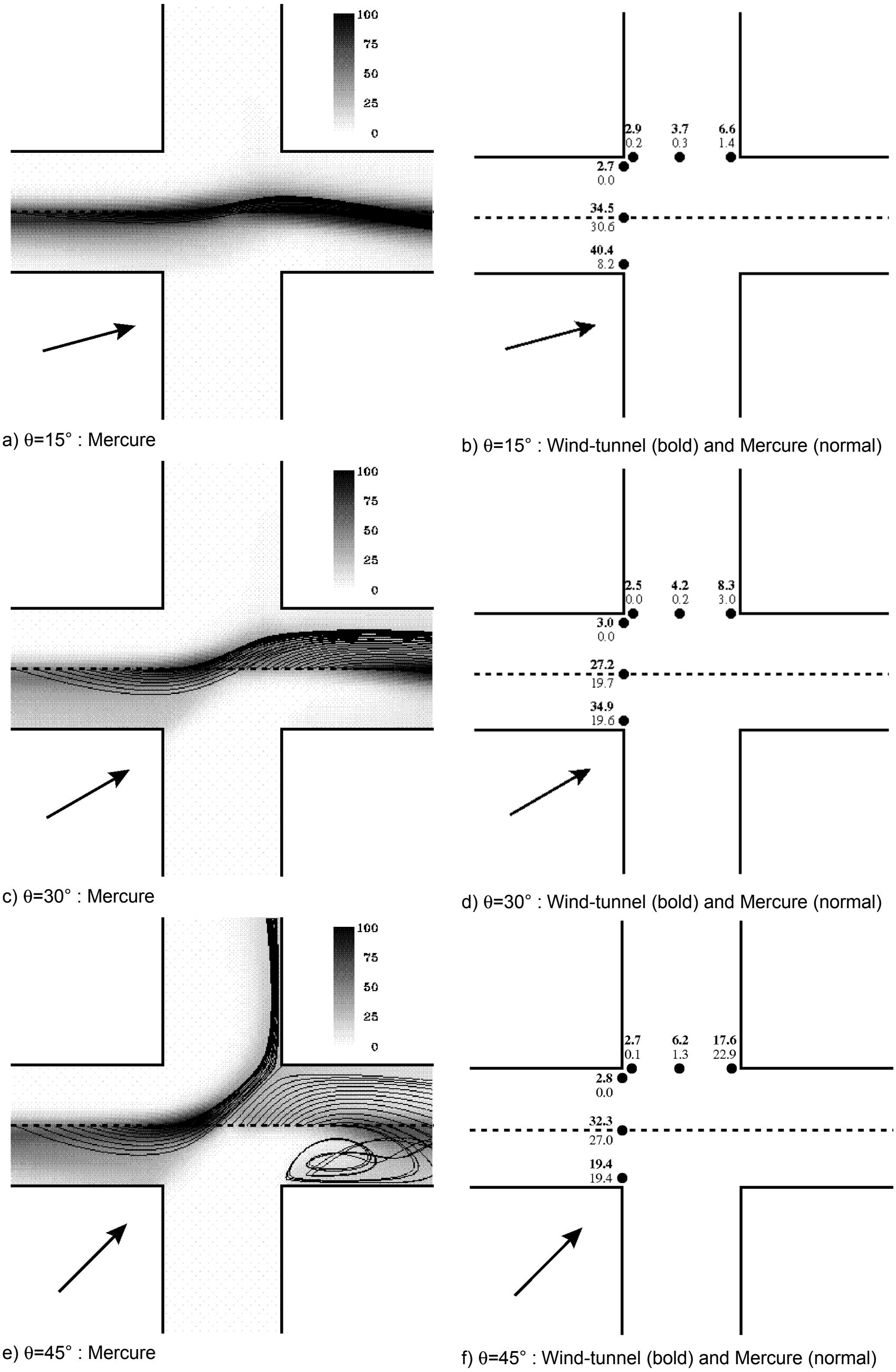


Fig. 10. Dispersion in an intersection between two streets. On the left, Mercure calculations : concentration field for z=0 and streamlines from the source. On the right, concentration measurements at z=0 from wind tunnel experiments and comparisons with Mercure values.

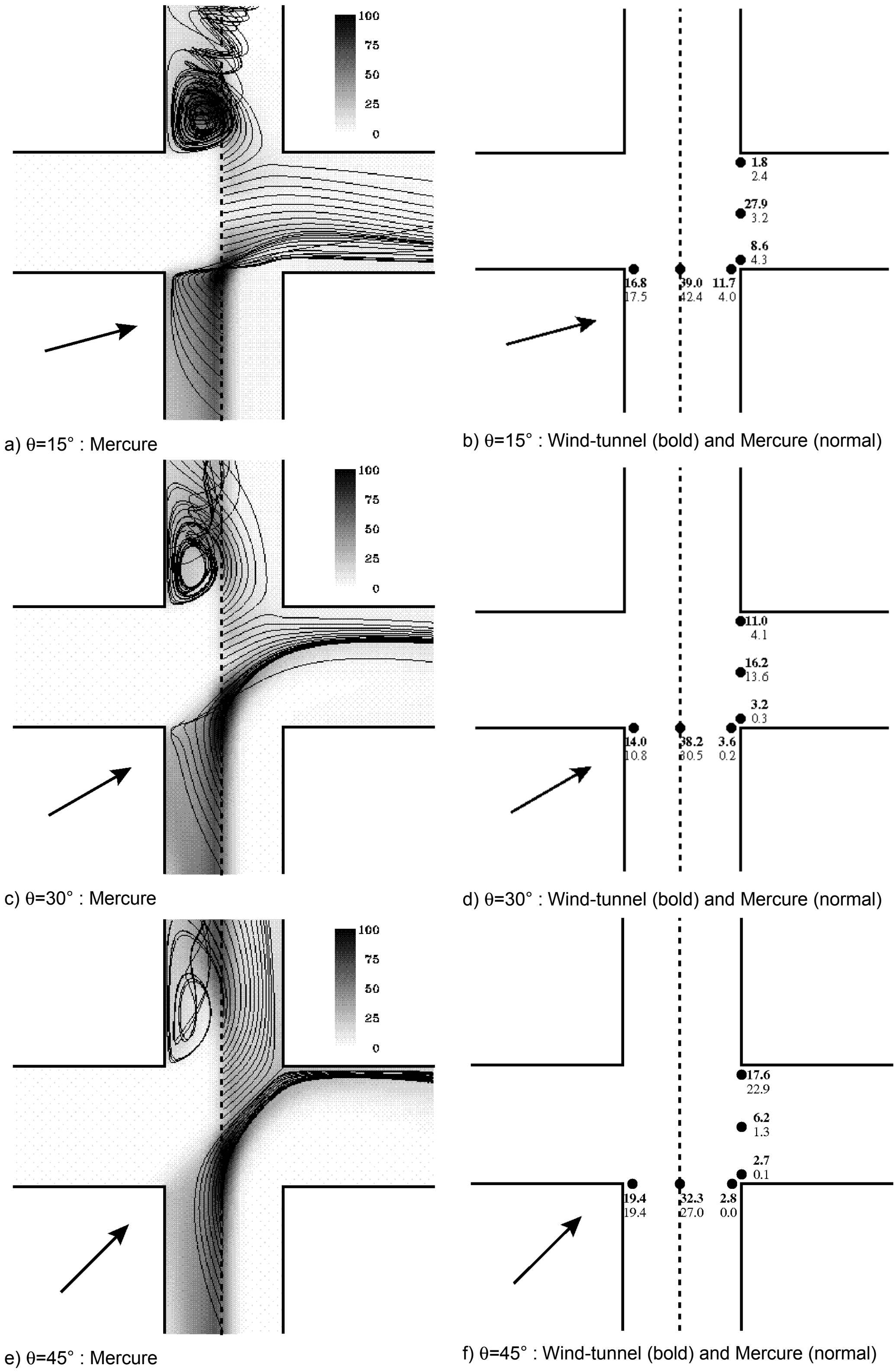


Fig. 11. Dispersion in an intersection between two streets. On the left, Mercure calculations : concentration field for z=0 and streamlines from the source. On the right, concentration measurements at z=0 from wind tunnel experiments and comparisons with Mercure values.