Urban Wind Flows: Wind Tunnel and Numerical Simulations - Preliminary Comparison

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Abstract: Previous studies have indicated that wind flow models based on the k-ε formulation are able to simulate the broad features of flows as observed in field programs and wind tunnel studies. k-ε models are increasingly being used to investigate the dispersion of pollutants and the transfer of heat within and out of urban canyons. In these situations realistic modelling requires greater fidelity on the part of the wind flow specification in that some confidence needs to be placed on the actual magnitude of the wind speeds and turbulent viscosities used in the dispersive components of the models. To this end a preliminary comparison of wind tunnel and numerical modelling was undertaken. It has demonstrated general agreement between the two types of modelling but has also indicated two distinct differences. These are in the magnitude of the flow near canyon boundaries and in the relative importance of turbulence in the diffusion process. The k-ε model appears to have produced much stronger flow along the boundaries and much less turbulent dispersion throughout the centre of the canyon.

1. INTRODUCTION

The urban environment continues to be studied as we seek better understanding of the atmospheric processes which determine air quality and general human comfort. Given the difficulties of performing extensive field programs within cities other approaches are being followed. They consist of field programs using small scale buildings to approximate an urban canyon (Johnson et al., 1996), wind tunnel studies and numerical modelling. The difficulty in applying wind tunnel results is that all of the significant processes involved have to be scaled in a consistent way so that their interaction within the tunnel reflects what is observed under similar conditions in the atmosphere. The problem with numerical models is that they include within their mathematical formulation only a few (but hopefully the most significant) of the processes at work. Neither of these modelling activities can be assumed unequivocally to match the real world.

The aim of this study is to investigate examples of wind tunnel and numerical simulations of the same urban environment and to emphasise differences noted. The wind tunnel experiments reported here were performed at the Meteorologisches Institut der Hamburg Universita, while the numerical studies were performed by the authors.

2. WIND TUNNEL

The atmospheric wind tunnel at Hamburg University is an open circuit wind tunnel that draws air from the room and exhausts inside the same room. The test section is approximately 11.5 m long and has a cross-sectional area of 1 m × 1.5 m. The ceiling is adjustable to minimise the longitudinal pressure gradient over the model and was used to simulate neutrally stable flows. The simulated boundary layer is about 450 mm thick.

The uniform urban model used in the experiment consisted of a set of 28 bars placed parallel to each other. The building models were made of aluminium and were of uniform size 1.4 m × 0.06 m × 0.06 m. The blocks were laid on the floor equally spaced 0.06 m from each other and almost completely spanning the width of the tunnel so as to form a rectangular set of parallel street canyons perpendicular to the mean flow direction and with an aspect ratio equal to one. The test street canyon was located 8.75 m downstream of the vortex generators. A long urban fetch consisting of 19 bars and a shorter fetch of 7 bars were provided upwind and downwind, respectively. Upstream and downstream of the urban model, the floor was covered with 20 mm high Lego™ elements placed in a regular array following a staggered pattern. This arrangement corresponds to a two-dimensional simulation of an idealised large city with tall buildings 30 m high at a scale of approximately 1:500. During these experiments a free stream velocity of about 3 m s^{-1} was maintained.

Two distinct experiments were performed in the wind tunnel; the first in August, 1995 and the second in November, 1995. In this paper they are referred to as Experiment 1 and Experiment 2.

3. NUMERICAL MODEL

The numerical model used (SCAM) consists of a wind model CITY (Paterson and Apelt, 1989) and a dispersion model SCALAR (Johnson and Hunter, 1995). It uses CITY to predict a steady-state flow regime within an urban canyon based on an upwind profile and the canyon geometry, then simulates (using SCALAR) the dispersion of a scalar emitted into that flow. Time-varying concentrations throughout the canyon and beyond are provided. Under typical wind-speeds, these concentrations become constant within about 10 minutes or so.

In comparing the predicted concentrations against those observed in the wind tunnel it is the combination of CITY and SCALAR that is being tested. CITY provides four inputs at each grid point to SCALAR; three mean wind components and turbulent viscosity. These form the basis of the dispersive calculations which yield the predicted concentrations. The simulation was performed for the full-scale urban canyon being represented by the wind tunnel i.e. for buildings 30 m high. To reduce computation time the length of the buildings was reduced from 700 m to 300 m. This was not deemed significant given that the flow is essentially two dimensional and concentrations were computed at mid-canyon only.

3.1. Model Modifications

On investigation of the setup of the wind tunnel experiment it was found that the existing form of CITY was inadequate. The problem was that CITY only recognised two distinct roughness lengths; those of the ground surface and of the building surface. Within the wind tunnel the fetch roughness length is much larger than that within the canyon. Accordingly CITY was modified to accept different roughness lengths for fetch, wall, roof and canyon floor. The decision to add the capability of different wall and roof roughness lengths was in anticipation of further urban climate studies where buildings with smooth roofs but rough walls are likely to be encounted.

These model changes were tested by comparing model output, using the four options set to previously modelled values, with that obtained by the simpler version of the code.

Measurements taken in the wind tunnel with no model buildings present indicated that the roughness length was about 1.7 mm. Scaling this up suggests a value of 0.85 m. It is not possible in CITY to have a roughness length greater than the height of the lowest grid cell which is uniform over the whole region. Setting this to 0.5 m (for accurate computations within the canyon) necessitated choosing 0.45 m for the roughness length of the ground surface. Given that the building walls and roofs and canyon floor are smooth their roughness lengths were set at 0.01 m.

3.2. Numerical Problems

The first step was to simulate the tunnel wind regime. Some numerical problems arose in that CITY was unable to converge to a steady flow. This had occasionally been a problem previously but had not caused major difficulties in that minor adjustments to some of the input parameters, such as roughness length, had resolved the issue. Close study of graphical displays of flow cross-sections (Figure 1) indicated (surprisingly) that convergence was being achieved within the canyon. This region was expected to present the most difficulty given that the flow there is more complex than in any other section of the domain. On the other hand, convergence was not evident in the region immediately upwind of the leading building edge. It appeared that some form of oscillation was taking place between several possible flow configurations. After further investigation it was decided that the problem was due to the influence of the upwind boundary. Our previously accepted wisdom based on Paterson (1986) was that an upwind fetch of twice the building height is sufficient to eliminate the effects of that boundary whereas five building heights are required for the downwind fetch. We chose five building heights for the upwind fetch and achieved convergence.

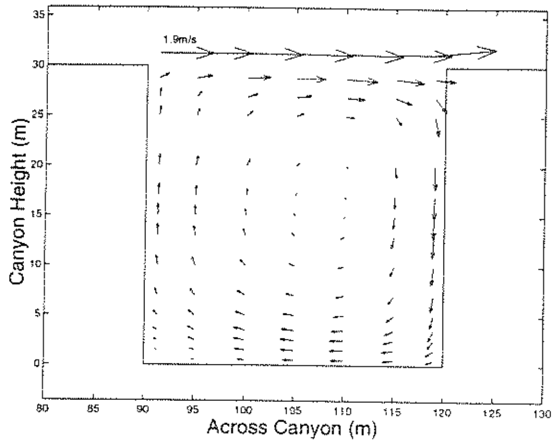

Figure 1: Predicted wind flow across mid-canyon

4. SOURCE CONFIGURATION

The source, of length 0.9 m in the wind tunnel, was located at street level and centred in the street. It consisted of 302 hypodermic tubes of 0.25 mm internal diameter which achieved a high discharge pressure drop, rendering the gas flow insensitive to local pressure fluctuations in the canyon above the source. The discharge velocities from the holes, of the order of 1 m s^{-1}, could potentially disturb the flow in the street canyon. Hence the discharge tube holes were covered with a metal strip canopy so that any initial vertical gas momentum was deflected laterally. The system was supplied with a mixture of ethane at 4 litres per hour and synthetic air at 150 litres per hour. Given the molecular weight of ethane as 30 this corresponds to an emission rate of 1.52 mg s^{-1} m^{-1} at 20°C and standard pressure. In Experiment 2 the rates were 4 l h^{-1} and 50 l h^{-1}, respectively.

5. NUMERICAL SIMULATION

The simulation was performed on an urban canyon which matched that which was being simulated in the wind tunnel. That is the canyon was set up with building walls 30 m high and an aspect ratio of one. In this initial test, rather than attempt to simulate the 28 buildings which formed the cityscape, a single canyon was used. Although additional buildings could be added (at significant computational cost), it was thought that a single canyon would be adequate to study in broad terms the relationship between the numerical simulation and the wind tunnel data.

The grid chosen was finer close to buildings and ground and then expanded further away (Figure 2). The roughness lengths used were 0.01 m for building surfaces and canyon floor, and 0.45 m outside the canyon. The

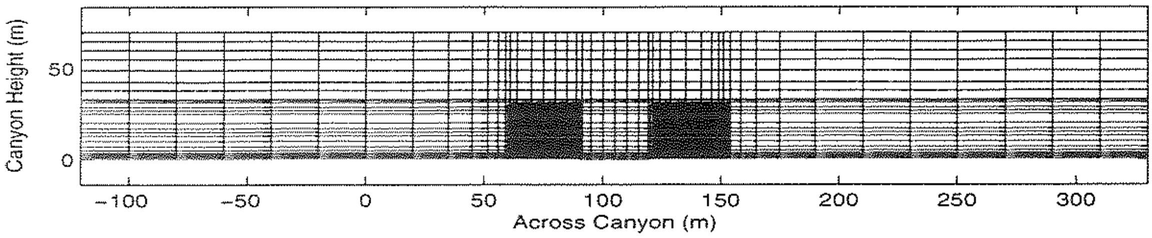

Figure 2: Grid used for numerical simulations

input wind profile was logarithmic based on a roughness length of 0.45 m and a wind speed of 3 m s^{-1} at a height of 250 m. The emissions were introduced at the same rate as in the wind tunnel and were released uniformly in the bottom grid cells at the centre of the canyon and along 0.9/1.4×300 (192.8) m of the canyon. The release rate was 1.52 mg $s^{-1}m^{-1}$. Steady state concentrations were achieved after 10 minutes.

6. CANYON CONCENTRATIONS

In Experiment 1 samples were collected at 10 locations along the test canyon perimeter at locations shown in Figure 3. In Experiment 2 concentration time series were recorded at 49 locations in the street cavity up to z = 60 mm and at 21 additional points above the street for z up to 70 mm. Concentration contours were produced of the non-dimensional concentration given by $K = CULH/Q_e$ (Figure 4) where C is concentration, U is reference wind speed, L is length of line source, H is height of buildings and Q_e is emission rate. Pavageau (1996) identified three regions of relatively small concentration gradients in all directions. They are (i) at the windward lower corner, (ii) along the upper half of the leeward wall approximately between z/H = 0.6 and z/H = 0.9, and (iii) around the vortex centre. The first area is a recirculation zone in which pollution is trapped by a secondary vortex. In the second region, the flow moves upward and parallel to the wall and then detaches from it at z/H between 0.7 and 0.8. In these regions of weak concentration gradients, the main mechanism of dispersion may be turbulent diffusion.

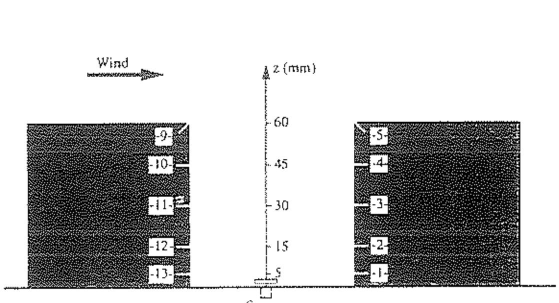

Figure 3: Sampling locations for wind tunnel Experiment 1 (Pavageau,1996)

The concentration contours produced by SCAM (Figure 5) show a similar pattern. (Note that the contours continue to the bottom of the canyon for the numerical results whereas in the wind tunnel no measurements were available there.) The major difference is the region of lower concentrations centred on the vortex. This suggests much less turbulent diffusion in that region for the numerical model simulation.

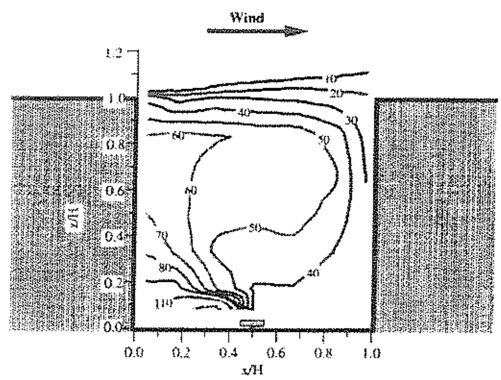

Figure 4: Non-dimensional concentration contours (Pavageau, 1996)

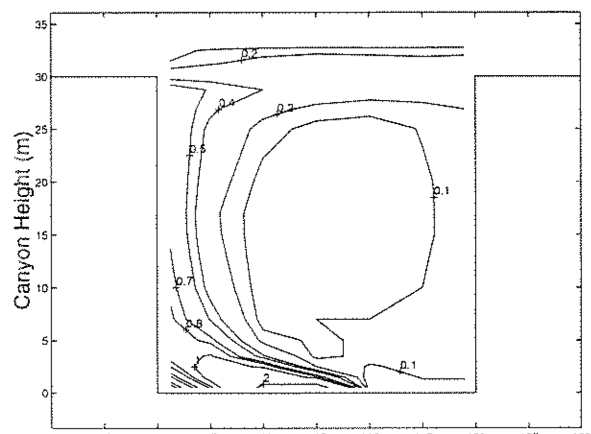

Figure 5: Concentration contours produced by SCAM (mg m^{-3})

6.1. Boundary Concentrations

As well as considering the range of concentrations throughout the canyon it is also instructive to consider those predicted at specific points. The points chosen are those ports where instruments were placed in the wind tunnel. SCAM does not predict concentrations at the surface of the canyon (where these measurements were taken). The grid points closest to the walls are of the order of 1 m away and are the ones used in the following discussion.

Port	Wall	Height mm	Tunnel ppm	Numerical ppm	Ratio
9	Leeward	60	95	45	2.1
10		45	477	271	1.8
11		30	517	279	1.9
12		15	517	340	1.8
13		5	724	287	2.5
1	Windward	5	245	53	4.6
2		15	249	57	4.3
3		30	229	61	3.8
4		45	191	66	3.5
5		60	159	90	1.8

Table 1: Comparison of wall concentrations

A general relationship, which can be observed by considering the ratio of tunnel values to numerical values, is that up the leeward wall and across the top of the canyon the numerical concentrations are about one half of those measured in the wind tunnel (Table 1). Given the relationship between concentrations and wind speed this suggests that the wind speed predicted by CITY is larger along the canyon boundaries than that produced in the wind tunnel. In this context, note the relatively strong boundary flows in Figure 1. Down the windward wall the ratio is even greater. This suggests that less ethane is being recirculated within the canyon by SCALAR than was the case in the wind tunnel. The reason for this is not clear.

6.2. Within-canyon Concentrations

Figures 4 and 5 indicate the isolines of ethane based on concentrations measured in the wind tunnel and predicted by SCALAR respectively. In the case of the wind tunnel the concentrations are non-dimensionalised whereas those from SCALAR are in mg m^{-3}. It was not possible to non-dimensionalise the SCALAR values in the same way because of a slight inconsistency in the reported factor used. In any event, we are concerned more at this point with the relative dispersion of ethane throughout the canyon, rather than absolute concentrations.

What is clear from the these figures is that each represents a concentration pattern consistent with a flow regime consisting of a vortex established in the upper half of the canyon similar to that displayed in Figure 1. It thus appears that CITY has determined a within-canyon flow which matches that produced in the wind tunnel.

The significant difference between the two figures is the much greater concentration gradients observed in the numerical simulation than in the wind tunnel. Our current view is that the greater concentration gradients predicted by the numerical model result from CITY producing much less turbulent dispersion than that observed in the wind tunnel; otherwise the large gradients observed could not be maintained.

7. CONCLUSION

The numerical simulation and the wind tunnel study have produced similar flow regimes within the canyon with two distinct differences. These differences are (1) the numerical simulation generated stronger circulating flow around the boundary of the canyon, and (2) the numerical simulation generated less turbulent diffusion within the canyon. The two effects may be linked in that, in order to maintain momentum balance in the wind flow, a reduction in the magnitude of the advective term may lead to a corresponding increase in the turbulent diffusive term. They indicate that some modification of the specification of the k-ε model may be warranted or else some normalisation of the output from the model applied. Recently Castro and Apsley (1997) have employed modifications of a k-ε model to simulate flow and dispersion over hills of various slopes. A similar approach may be warranted in urban canyon modelling. This issue will now be explored.

8. REFERENCES

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