

ANALYSIS OF NUMERICALLY MODELLED LOCAL CONCENTRATION GRADIENTS IN STREET CANYONS: IMPLICATIONS FOR AIR QUALITY MONITORING

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ABSTRACT

The main objective of this study is to analyse numerically-modelled, local concentration gradients in street canyons. In a preliminary analysis of the physical processes within an urban built environment, a single idealised street canyon has been used. It has been shown that very steep concentration gradients exist at the leeward lower corner of the street canyon. Consequently, small differences in monitoring station positioning may yield significant variations of measured mean concentration due to large local concentration gradients.

The study has been extended to assess the behaviour of local concentration gradients using a more complex urban geometry such as: a staggered cross-road, an idealised complex configuration of street canyons, and finally a real configuration of street canyons.

The numerical modelling results obtained in this study are compared with both the field measurements obtained during a continuous air monitoring campaign of Glasgow City Council, Scotland, and physical modelling in the wind tunnel at the University of Hamburg, Germany.

These results have significant implications for the positioning of monitoring equipment, not just in street canyons, but in wind tunnel experiments as well. Nevertheless, the obtained results are tentative and require a detailed, specifically designed, physical modelling investigation.

1. INTRODUCTION

The flow patterns that develop around buildings govern the distribution of pressure and, consequently, the concentration distribution of pollutants in a built environment. The vast majority of studies are focused on physical processes within a single street canyon, i.e. the concentration distribution is represented as a function of idealised geometrical characteristics of street canyons, and wind direction and speed (Assimakopoulos, 2001; Baik, *et al.*, 2002; Chan *et al.*, 2002):

Concentration distribution = f (width, height, length, canyon orientation, wind speed)

However, the superposition and interaction of flow patterns associated with adjacent buildings predominantly govern the dispersion of air pollutants within a built environment. Accordingly, the concentration distribution function becomes much more complex, taking into account the additional parameters:

Concentration distribution = f (width, height, length, canyon orientation, wind speed, building geometry, upwind building configuration, intersection location and geometry)

Applying and extending Professor Spalding's well-known, 'NOKFOS' principle (NObody Knows FOr Sure), concerning the applicability of certain turbulence models to the specific situation, this paper is aimed at optimising the use of the numerical methods available in PHOENICS (Cham, 2001) and to analyse numerically-modelled, local concentration gradients in street canyons.

2. NUMERICAL MODELLING

Pollutant dispersion in urban street canyons is usually investigated numerically using a two- or three-dimensional flow and dispersion model. The majority of those models are based on the isotropic, two-equation, standard k-ε turbulence models, ignoring the effect of turbulence anisotropy on the dispersion characteristics in urban street canyons. The effect is considered in the present study by introduction of different turbulence models.

A three-dimensional flow model has been set-up using the incompressible, steady-state Navier-Stokes equations coupled with the continuity equation and pollutant conservation equation:

$$\partial_i(\rho U_i) = 0 \quad (1)$$

$$U_i \partial_i(\rho U_j) = \partial_i \{ \mu (\partial_i U_j + \partial_j U_i - \overline{\rho u_i u_j}) \} - \partial_j P \quad (2)$$

$$U_i \partial_i(\rho C) = \partial_i \{ D \partial_i(\rho C) - \overline{\rho c u_i} \} \quad (3)$$

where

$$-\overline{u_i u_j} = \nu_t (\partial_i U_j + \partial_j U_i) - \frac{2}{3} k \delta_{ij} \quad (4)$$

$$-\overline{c u_i} = (\nu_t / \sigma_c) \partial_i C \quad (5)$$

$-\overline{u_i u_j}$ and $-\overline{c u_i}$ are the Reynolds stresses and pollutant fluxes, respectively; ν is the laminar viscosity; D is the laminar diffusivity; ν_t is the turbulent viscosity; k is the turbulent kinetic energy; σ_c is the turbulent Schmidt number. Equations (1) – (3) have general form of transport/conservation equations, with similar equations for the turbulence models:

$$\partial_i(\rho U_i \Phi) - \partial_i(\rho \Gamma_\Phi \partial_i \Phi) = S_\Phi \quad (6)$$

The standard k-ε turbulence model is summarised in *Table 1*.

Table 1: Summarised standard k- ε turbulence model

Equation	Φ	Γ_Φ	S_Φ
Turb. Kin.	k	$\nu + \nu_t / \sigma_k$	$\rho(G - \varepsilon)$
Energy			
Dissipation Rate	ε	$\nu + \nu_t / \sigma_\varepsilon$	$\rho(k / \varepsilon)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon)$

$$G = \nu_t (\partial_k U_i + \partial_i U_k) \partial_k U_i; \nu_t = C_\mu k^2 / \varepsilon$$

$$(\sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu) = (1.0, 1.314, 1.44, 1.92, 0.09)$$

Despite this physical drawback the standard k - ε turbulence model is by far the most widely used two-equation eddy viscosity turbulence model in numerical modelling of dispersion of air pollutants in a street canyon. Knowing that in a complex configuration of street canyons the area of significant importance for human health is located near a boundary, i.e. pavement, the assumption that ε requires no extra terms near walls causes a significant problem.

This turbulence model was compared with the Renormalization Group k - ε turbulence model (RNGKE) in a real street canyon, Hope Street in Glasgow (Mumovic and Crowther, 2002). It was shown in that work that the RNGKE model performs better than the standard k - ε model; therefore it is to be expected that, in the case of more complex configurations, this difference will be equally significant.

However, concern has to be expressed for accuracy of this model when the Reynolds number is relatively low. The model is summarised in Table 2.

Table 2: Summarised RNG k- ε turbulence model

Equation	Φ	Γ_Φ	S_Φ
Turb. Kin. Energy	k	$\nu + \nu_t / \sigma_k$	$\rho(G - \varepsilon)$
Dissipation Rate	ε	$\nu + \nu_t / \sigma_\varepsilon$	$\rho(k / \varepsilon)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon - \alpha\varepsilon)$

$$G = \nu_t (\partial_k U_i + \partial_i U_k) \partial_k U_i; \nu_t = C_\mu k^2 / \varepsilon$$

$$\alpha = C_\mu \eta^3 (1 - \eta / \eta_0) / (1 + \beta \eta^3); \eta = Sk / \varepsilon$$

$$S = \sqrt{2S_{ij}S_{ij}}; S_{ij} = 0.5(\partial_j U_i + \partial_i U_j)$$

$$(\sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu, \eta_0, \beta) = (0.7194, 0.7194, 1.42, 1.68, 0.0845, 4.38, 0.012)$$

This Chen-Kim modification of k - ε model has been selected for testing because of its success for a number of separated-flow calculations (Stevanovic, 2001). The ε production term is divided into two parts, the first of which is the same as for the standard model but with a smaller multiplying coefficient, and the second, which allows the 'turbulence distortion ratio' (G/ε) to exert an influence on the production rate of ε . The model is summarised in Table 3.

Table 3: Summarised Chen-Kim modification of k-ε turbulence model

Equation	Φ	Γ_Φ	S_Φ
Turb. Kin.	k	$\nu + \nu_t / \sigma_k$	$\rho(G - \varepsilon)$
Energy			
Dissipation Rate	ε	$\nu + \nu_t / \sigma_\varepsilon$	$\rho(k/\varepsilon)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon) + \rho C_{\varepsilon 3}f_1G^2/k$

$$G = \nu_t (\partial_k U_i + \partial_i U_k) \partial_k U_i; \nu_t = C_\mu k^2 / \varepsilon; f_1 = 1 + (0.05 / f_\mu)^3$$

$$f_\mu = [1 - \exp(0.0165 \text{Re}_k)]^2 (1 + 20.5 / \text{Re}_t); \text{Re}_k = \sqrt{k} y_N / \nu; \text{Re}_t = k^2 / \varepsilon \nu$$

y_N - distance to the nearest wall

$$(\sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}, C_{\varepsilon 2}, C_{\varepsilon 3}, C_\mu) = (0.75, 1.15, 1.15, 1.9, 0.25, 0.09)$$

The two-scale k - ε model (TSKE) has been chosen because of its capability to model the cascade process of turbulent kinetic energy, and to resolve the more complex details such as separating and reattaching flow, which is one of the major problems in the case of a complex configuration of street canyons. The model is summarised in Table 4.

Table 4: Summarised Two-Scale k-ε turbulence model

Equation	Φ	Γ_Φ	S_Φ
Turb. Kin.	k_p	$\nu + \nu_t / \sigma_{kp}$	$\rho(G - \varepsilon_p)$
Energy			
in production range			
Turb. Kin.	k_T	$\nu + \nu_t / \sigma_{kT}$	$\rho(\varepsilon_p - \varepsilon)$
Energy			
in dissipation range			
Transfer Rate	ε_p	$\nu + \nu_t / \sigma_{\varepsilon p}$	$\rho(C_{p1}G \frac{G}{k_p} + C_{p2}G \frac{\varepsilon_p}{k_p} - C_{p3}\varepsilon_p \frac{\varepsilon_p}{k_p})$
in production range			
Dissipation Rate	ε	$\nu + \nu_t / \sigma_\varepsilon$	$\rho(C_{T1}\varepsilon_p \frac{\varepsilon_p}{k_T} + C_{T2}\varepsilon_p \frac{\varepsilon}{k_T} - C_{T3}\varepsilon \frac{\varepsilon}{k_T})$
in dissipation range			

$$G = \nu_t (\partial_k U_i + \partial_i U_k) \partial_k U_i; k = k_p + k_T$$

$$\nu_t = C_\mu k^2 / \varepsilon_p = C_\mu k^2 / \varepsilon$$

$$(\sigma_{kp}, \sigma_{\varepsilon p}, C_{p1}, C_{p2}, C_{p3}, C_\mu) = (0.75, 1.15, 0.21, 1.24, 1.84, 0.009)$$

$$(\sigma_{kT}, \sigma_\varepsilon, C_{T1}, C_{T2}, C_{T3}) = (0.75, 1.15, 0.29, 1.28, 1.66)$$

Considering that spatial resolutions are different in street canyon measurements, wind tunnel measurements, and computational domains of CFD models, some discrepancies between experimental and numerical results may be expected. That is the main reason for evaluating the developed CFD models with both wind tunnel data, and field measurements. This study comprises the three test-cases: (1) a single street

canyon, (2) a staggered cross-road, and finally (3) an idealised case of a complex configuration of street canyons.

3. TEST CASE ONE: A SINGLE STREET CANYON

The preliminary study, presented in this section, was conducted on a computational model of Hope Street in Glasgow (Mumovic and Crowther, 2002).

As can be seen in *Figure 1. (a,b,c,d)* very steep concentration gradients exist at the leeward lower corner of the street canyon. Moreover, similar results are obtained using the four different turbulent models mentioned in the previous section. Consequently, small differences in monitoring station positioning may yield significant variations of measured mean concentration, due to large values of horizontal, $\partial C / \partial x$, and vertical, $\partial C / \partial y$, local concentration gradients.

These results have more significant implication for positioning of monitoring equipment, not just in street canyons, but in wind tunnel experiments as well. Generally speaking, it suggests that monitoring stations should not be positioned at the lower leeward side of a street canyon. However, these numerical results are obtained within an idealised single street canyon, neglecting the complexity of a real built environment.

By contrast, one can observe relatively smooth concentration gradients at the windward side, at the upper leeward side of street canyon, and possibly in the central part of a vertical cross section of the street canyon.

Nevertheless, the obtained results are tentative and require validation by field measurements or physical simulation studies.

The numerical modelling results are in qualitative agreement with field measurements (DePaul and Sheih, 1984) and show increased concentrations of the air pollutants at the leeward side of the street canyon, and concentrations decreasing with height above the ground on both sides of the street. The increased concentration at the leeward side is due to the accumulation of pollutants locally advected by the large wind vortex that covers most of the canyon, as is clearly demonstrated in *Figure 2*.

Although three-dimensional, this present study assumes that the wind direction is perpendicular to the street canyon and may, therefore, be compared with other, two-dimensional studies with the same aspect ratio. For example, excellent qualitative agreement has been achieved with the two-dimensional street canyon modelling of Huang *et al.* (2000). Both studies show that the pollutant emitted from the bottom of the street canyon tends to follow the course of the trapped vortex.

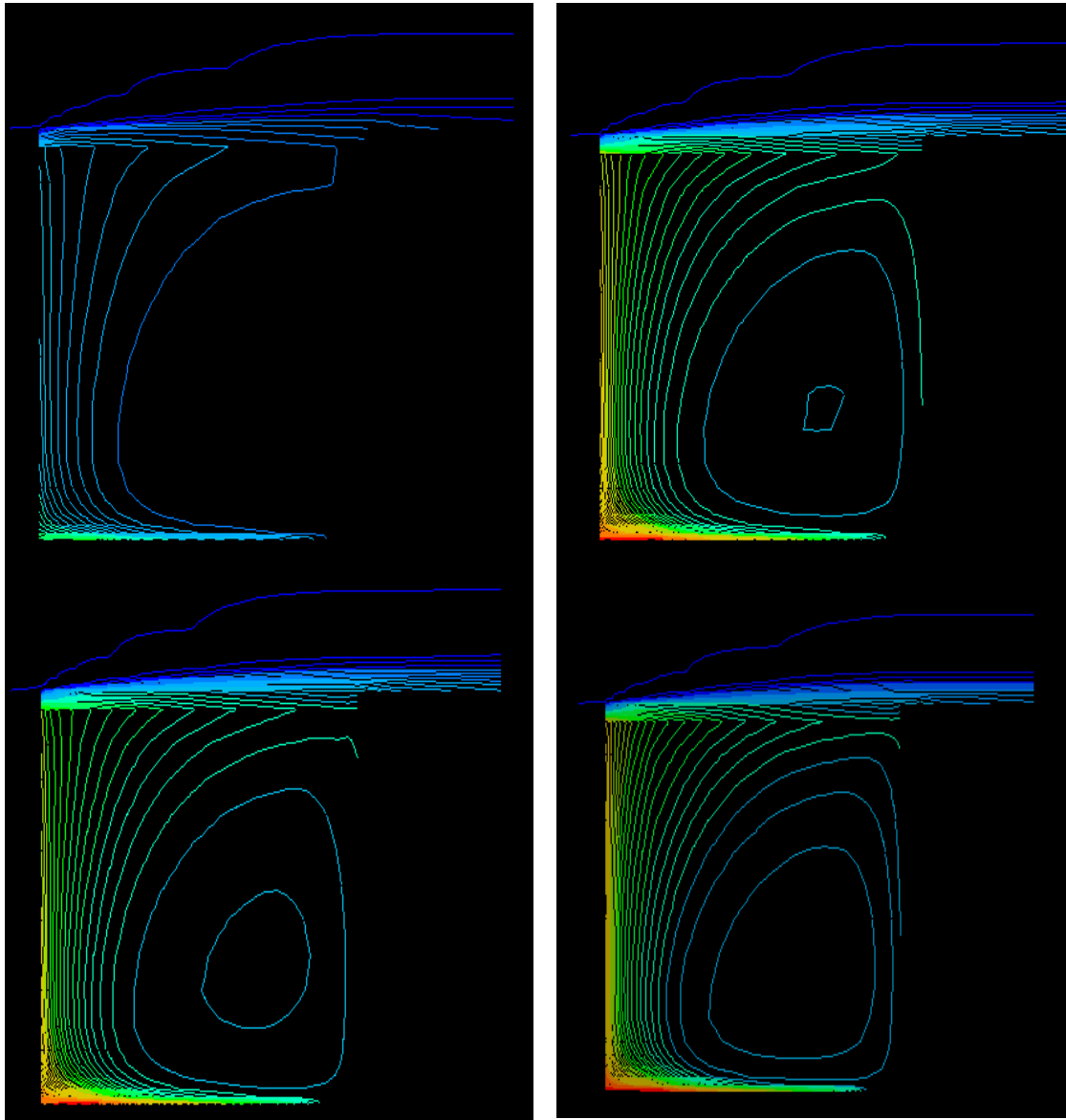


Figure 1. Dispersion of the pollutants for different turbulent models: upper row : (a) standard k- ϵ model, (b) RNG k- ϵ model, lower row: (c) Chen-Kim k- ϵ model, (d) Two-scale turbulence model

Spatial distribution of mean concentration in the test cross section obtained during physical modelling of Pavageau and Schatzmann (1999) shows very favourable qualitative agreement with this study (*Figure 2*).

Recently, Sagrado *et al.* (2002) carried out wind tunnel experiments on the pollutant dispersion in a two-dimensional street canyon. Again, qualitatively agreement is excellent in the case of the aspect ratio equal to one, for an isolated single street canyon.

As the field measurements data used for the assessment of the model presented in this section were not sufficient for complete and reliable quantitative validation, the

rigorous testing was undertaken using the computational model of a staggered cross-road.

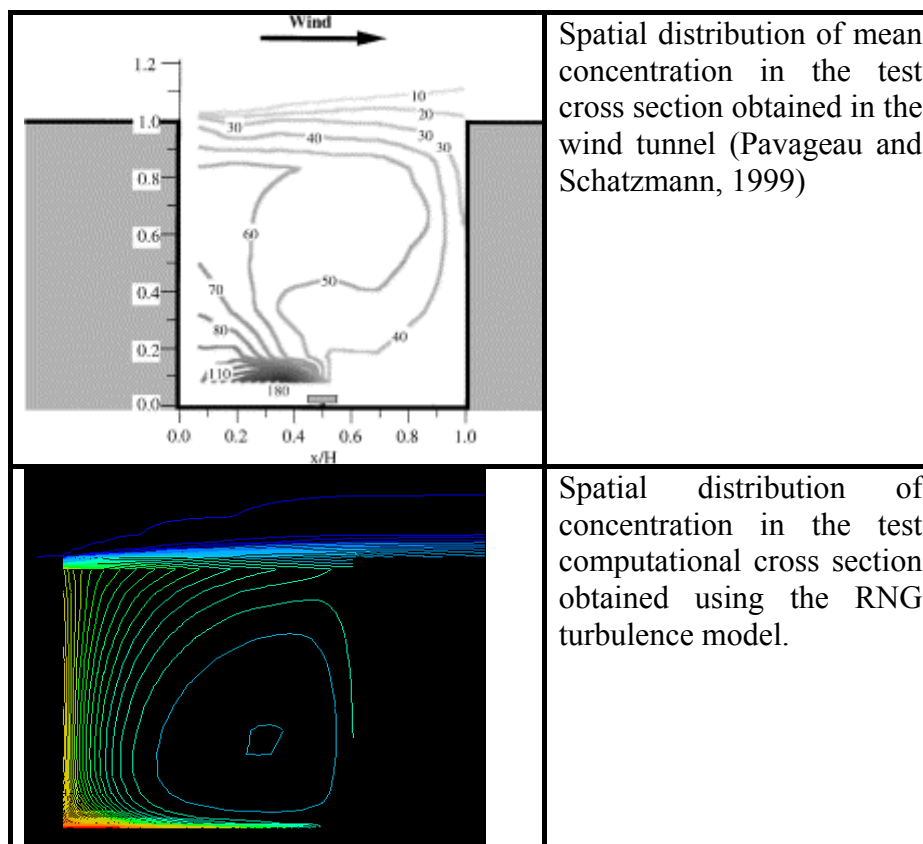


Figure 2 . Qualitative comparison of physical and numerical modelling of a street canyon with the same aspect ratio

4. TEST CASE TWO: A STAGGERED CROSS-ROAD

The previous section depicted the interpolated concentration contours, in the main street canyon vortex and dispersion of the air pollutants, circling around an imaginary axis parallel to the street direction and located approximately at half of the building height for the aspect ratio equal to one.

In this section, the spatial distribution of concentration in the test cross-sections of a staggered grid will be closely examined. This simulation matches the one that was being simulated in the wind tunnel of the University of Hamburg (Mumovic, *et al.*, 2003a, Mumovic, *et al.*, 2003c). *Figure 3* shows the numerical results obtained in two test cross-sections.

In the first cross-section, the approaching flow is passing over the centre-line of a flat roofed square building (*A-A*). The downstream square building is characterised by a symmetrical slanted roof. Similar results have been obtained (*Figure 3a*). It can be seen that the large horizontal, $\partial C / \partial z$, and vertical, $\partial C / \partial y$ concentration gradients exist in the lower part of the leeward side of the street canyon.

Although the approaching flow is passing over a slanted roof, in the second cross-section ($B-B$), similar results are obtained. The lower leeward part of the street canyon is also characterised by large concentration gradients. As has been shown (Mumovic, *et al.*, 2003b) the centre of the vortex is located near the slanted roof, which means that occurrences of large concentration gradients are inevitable in the area of the slanted roof level.

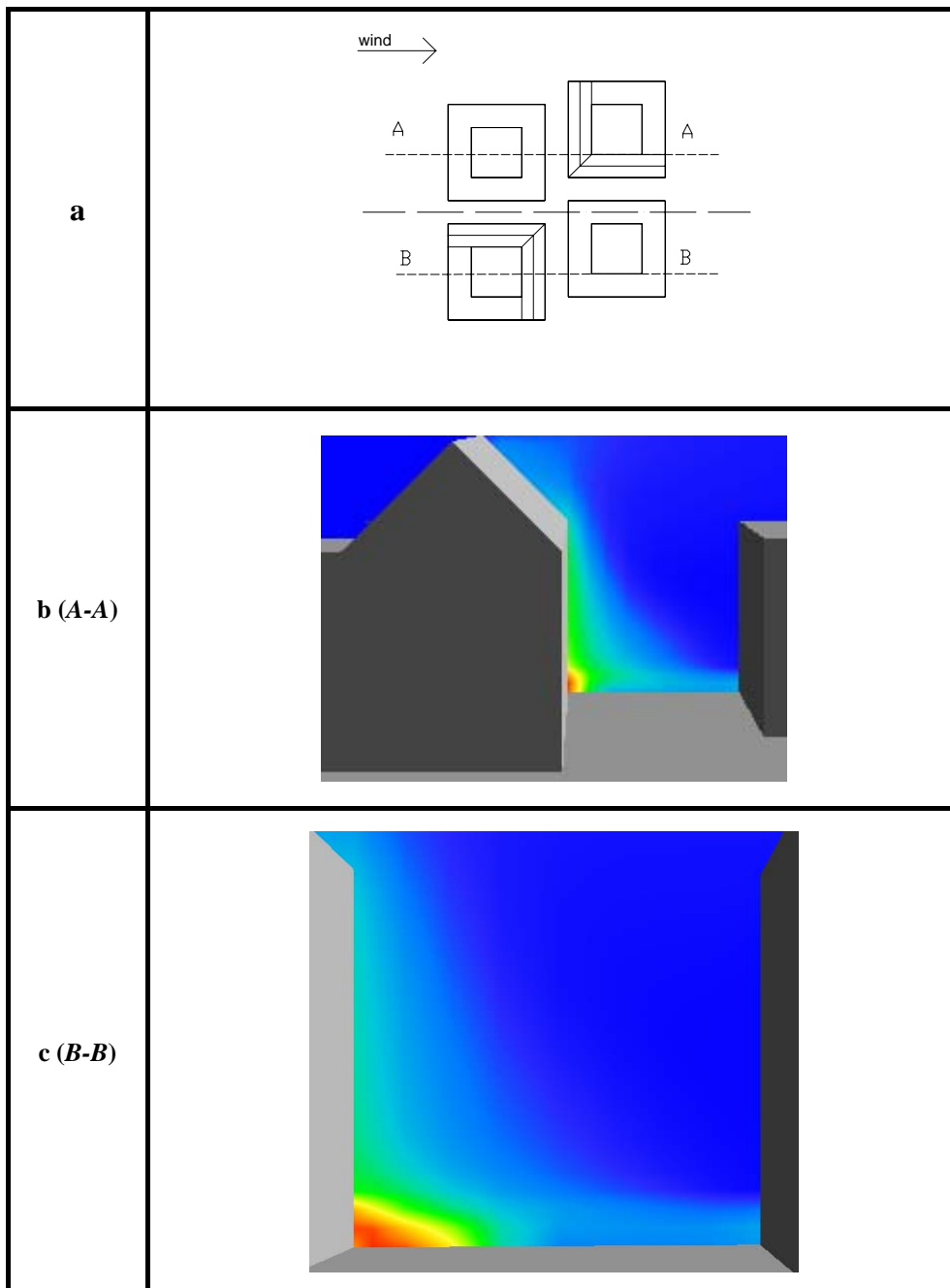


Figure 3: (a) Geometry of the tested model; (b) results obtained at the $A-A$ cross section plane; (c) results obtained at the $B-B$ cross section plane;

5. TEST CASE THREE: A REAL COMPLEX CONFIGURATION OF STREET CANYONS

An analysis of numerically-modelled, local concentration gradients, taking into account an idealised, but geometrically much more complex built environment, will be done using the test case of 3 x 7 arrays of obstacles, using the RNG k- ε only. (Crowther, *et al.*, 2003a). By positioning additional obstacles just upstream and downstream, and also on both sides of the observed street canyon, the complexity is greatly increased. This is significant, in order to show that the very steep concentration and velocity gradients, occur not just in the test cross-section, but in all centrally located street canyons upstream of the tested one.

Figures 4 and 5 show the spatial distribution of concentration from the first, to the fifth centrally located street canyon. As has been shown (Crowther, *et al.*, 2003b), the position of centres of vertical vortices within the cavity depends on the number of street canyons located upstream of the tested one. Therefore, one has to analyse the influence of the upstream building configuration on the change of the vertical concentration gradients, $\partial C / \partial y$.

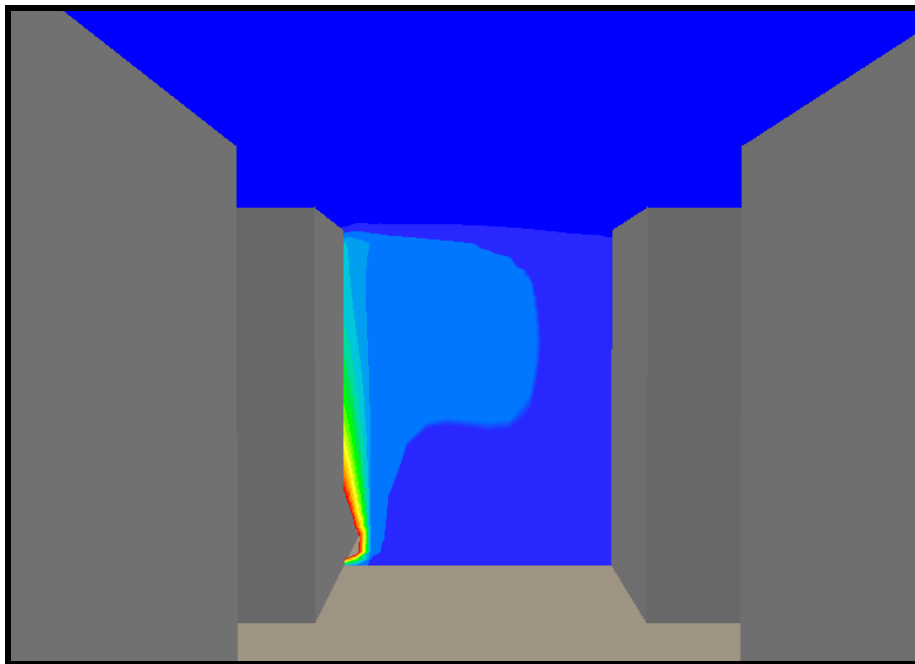


Figure 4. Concentration distribution in the vertical cross-section of 5th cavity

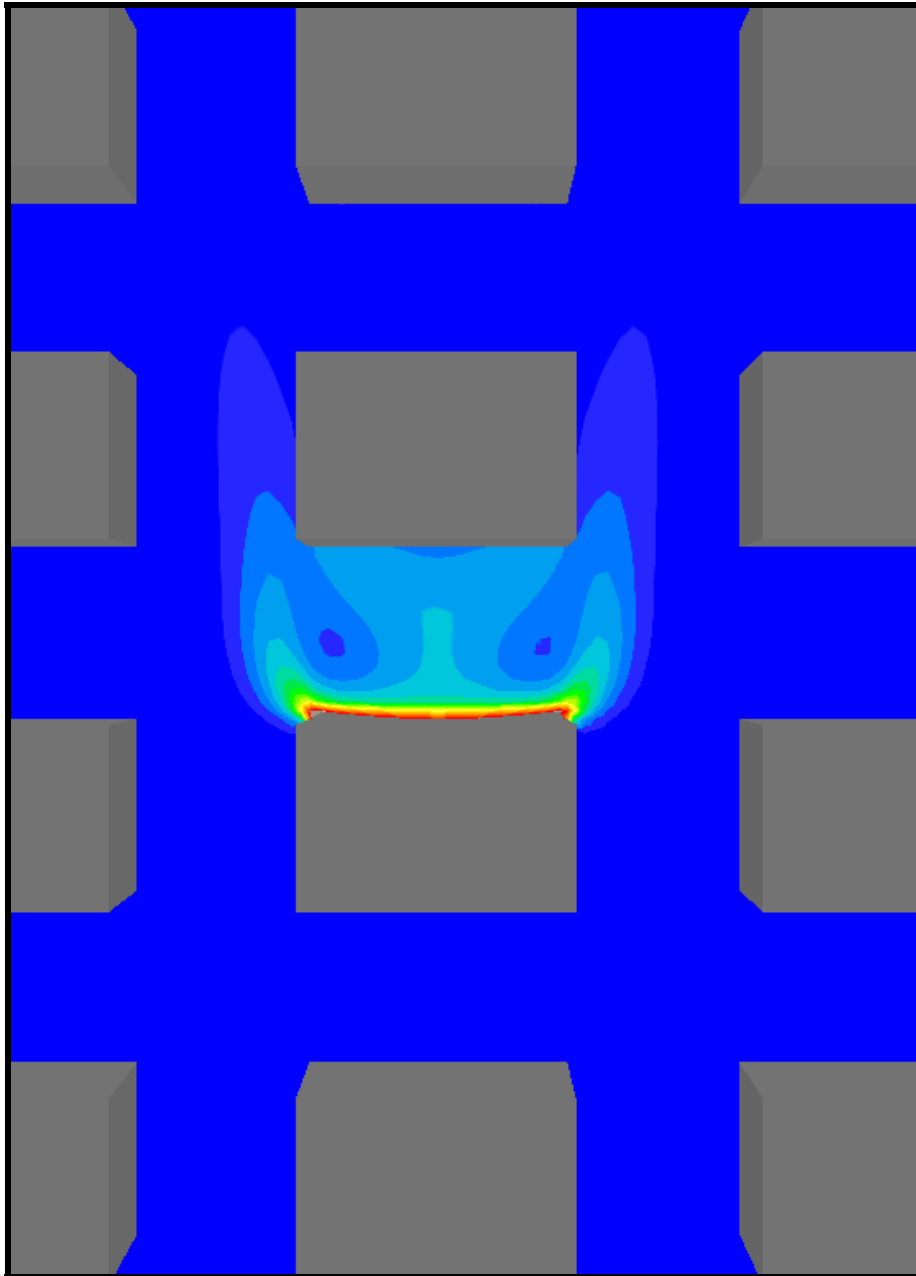


Figure 5. Concentration distribution in the horizontal cross-section of 5th cavity

These figures clearly show the formation of three regions of relatively smooth concentration gradients, as was observed in the previous sections:

1. in the vicinity of the vortex centre
2. in the lower corner of the windward side
3. in the upper part of the leeward wall

It has to be stressed that these results are obtained assuming the wind direction to be perpendicular to the street axis, and for the aspect ratio of the street canyon equal or close to one. Further numerical investigations are required to examine the rate of change of local concentration gradients at the leeward side of a street canyon, when the wind direction is oblique to the street. Unfortunately, there is a lack of available, detailed wind tunnel measurements with which to compare the results.

However, using the numerical results shown in the figure above, the following conclusions can be drawn:

1. In the upper part of the street canyon, iso-concentration lines are almost parallel. This probably means that the approaching wind is strong enough to enforce the formation and existence of the main vortex within the cavity. These results are obtained in all five cavities of the tested geometry.
2. Although quantitatively not so large as in the fifth cavity, the concentration gradients have a significant meaning. They still show that small differences in monitoring equipment positioning may lead to large variations in measured concentrations, especially in the lower part of the leeward side of the street canyon.
3. In the upper middle part of the street canyons, the longitudinal gradient, $\partial C / \partial z$, is approaching zero, which means that the velocity vector is mainly orientated in the z-direction (along the wind).
4. In the upper middle part of the street canyon, the vertical gradients, $\partial C / \partial y$, are considerably larger.
5. Analysing the last two statements, one can assume that the small-scale turbulence plays the most significant role in the dispersion of the air pollutants. The advection may not play the most significant role due to strong interaction between scales of turbulence within the cavities, and the lower surface sub-layer. However, it has to be stressed that this is just an assumption, based on this numerical modelling study. As already stated, a lack of available experimental results is the main obstacle to resolving physical mechanisms of the dispersion of air pollutants within street canyons.

6. CONCLUSIONS

Summarising the results, there are three different zones of the street canyon which appear to offer very convenient locations to monitor air quality. These locations are listed in *Table 5*.

There are three different issues, which have to be considered when deciding whether a location is suitable for air quality monitoring: (a) local concentration gradient, (b) practicality of the location in the real physical domain, (c) level of turbulence intensity at the chosen location. Satisfying all three requirements may determine an appropriate location for positioning of air quality monitoring equipment.

It must be emphasised that locating the monitoring stations in the region of highest expected concentration, i.e. in the lower part of leeward side of the street canyon may not be the best option available.

Table 5. Assessment of local concentration gradients

wind incident	Local concentration gradients	
	small	large/medium
perpendicular	upper leeward side vortex centre lower windward side	lower leeward side (large) bottom of the canyon (large)
oblique	upper leeward side vortex centre lower windward side	lower leeward side (medium) bottom of the canyon (medium)

Although the numerical results have been validated using both wind tunnel experiments and field measurements, only simultaneous measurements of fluctuations of velocities and concentrations can lead to complete understanding of physical processes within a street canyon built environment.

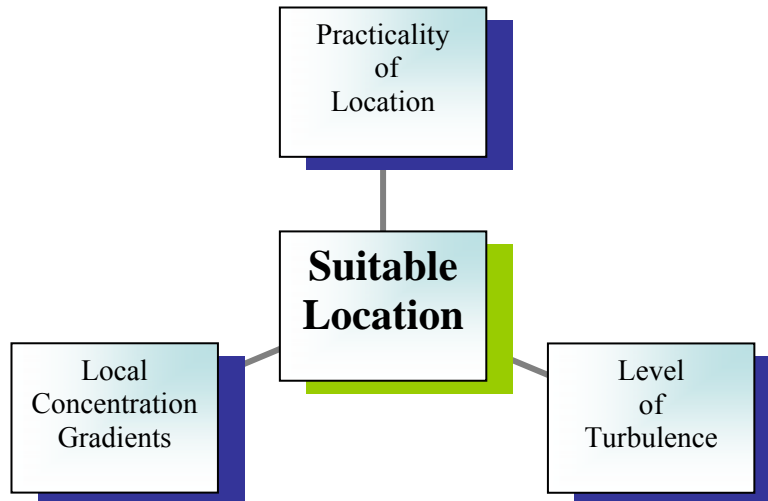


Figure 6. Different factors which have to be included when positioning air quality monitoring equipment in urban street canyons

When comparing the numerical modelling results and field measurements in urban street canyons, it has to be stressed that the controlled approach flow conditions assumed in the model, and to some extent simplified geometry provide modelled flows with strong gradients. However, the wind flow disturbances in a real complex configuration of street canyons caused by the variation of wind direction might have a smoothing effect on the flow irregularities. Therefore, a smaller spatial variability of mean flow, turbulence field, and consequently of pollutant concentration may be observed if measured within a real urban built environment.

The work described in this paper will be continued and extended to the analysis of available field measurements within real street canyons, and to the modelling of the dispersion of the air pollutants within real configurations of street canyons.

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