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A two-dimensional air quality model in an urban street canyon: evaluation and sensitivity analysis

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Abstract

In order to predict the air quality impact by vehicle emissions within an urban street canyon, a two-dimensional air quality numerical model was developed based on atmospheric convection diffusion equations and a k–ε turbulent model. The numerical model has been evaluated using the database from a set of street canyon air tracer experiments carried out near the crossing of Aoyama ichome, Minato-ku, Tokyo in December 1980, by the Japan Environmental Management Association of Industry (JEMAI). Twenty-four cases have been studied for the sensitivity analysis, including more practical cases when the inflow wind has an inclination with the horizontal road and the two buildings have different heights. As a result, it has been shown that the concentration distributions of pollutants emitted from the street are governed by both the inflow wind and the street canyon geometry. A stable vortex was formed within the street canyon, which agrees with other researchers. Pollutant concentrations were predicted to have higher values on the leeward side compared to the windward side. It was concluded that the released pollutants from street canyon become more diluted in the following cases: a lower height of the street canyon, a faster wind speed, a higher height of the leeward building than the windward building and an inflow wind direction towards the street. It is also suggested that the numerical model is useful for predicting the air quality within a typical urban street canyon.

Keywords: Street canyon two dimensional model; k–ε turbulent model; Transport and diffusion; Vehicle emissions; Wind and concentration distributions

1. Introduction

Motor vehicles are a major source of air pollution. In the United States, motor vehicles are currently estimated to be responsible for about 40–50% of the HC or VOC emissions, 50% of the NO_x emissions, and 80–90% of the CO emissions in urban areas. The relative contributions in other parts of the developed world such as in Europe and Japan are similar (Sher, 1998). These emissions contribute to the formation of secondary pollutants like ozone and other oxidants through complex photochemistry in the atmosphere near ground level. Many of these pollutants are very harmful to the health of human beings and other creatures, and can generally affect global climates. How to predict and decrease motor vehicle emissions continue to be a major environmental challenge to our society due to the increase in vehicles.

Motor emissions have a significant effect on the air quality on an urban and global scale. It also has important impacts on a local scale, such as road where the emissions can more directly and quickly harm human beings. In urban area where motor vehicles have high traffic loads, street canyons which refer to a relatively narrow street between tall buildings (Nicholson, 1975) can be thought to have severe air pollution due to motor vehicles emissions. The prediction of pollutant concentrations within urban street canyons is very important for human beings using the streets and working in the vicinity.

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Many approaches have been developed to predict the pollutant concentrations. More powerful computers provide the tools to use finer scale refined models. Many air quality numerical models have been done in street canyons, including empirical models based on field data and a full simulation of the flow field and pollutant transport (Hassan and Crowther, 1998). Johnson et al. (1973) developed an empirical model based on full-scale field observation data. The pollutant concentrations near the leeward sides of buildings were considerably higher than those near the windward sides. Lee and Park (1994) developed a two-dimensional, time-dependent flow model and found that two contra-rotating vortices may be formed: an upper and a lower one. However, it obviously lacked experimental evaluation. Okamoto et al. (1996) evaluated a two-dimensional numerical particle model (Lin et al., 1993). However it lacked a detail model analysis. Guido and Matteo (1995) presented a new microscale Lagrangian particle model. A comparison was done with the profiles of the concentration fields calculated by CPBM (Yamartino et al., 1989) and CANYON (Johnson et al., 1973).

Thus the common results from all these studies can be summarized as follows. A vortex can be formed within a street canyon. Higher concentrations are found on the leeward side than on the windward side. The wind and concentration distributions depend on the canyon geometry and the wind speed above the street canyon. However, in almost all of these studies, ideal conditions including buildings with the same height and a horizontal wind direction were used. In this study, a two dimensional air quality numerical model in an urban street canyon based on the k–ε turbulent model and atmospheric convection diffusion equation was developed. After an atmospheric tracer experiment evaluation, a detailed sensitivity analysis has also been done with the change in wind speed, the canyon geometry including changing the height of the buildings and wind direction.

2. Model description

The air quality model for an urban street canyon contains two submodels: one is a wind-distribution model, and the other is a concentration diffusion model. The wind distribution within street canyon will be first solved, then it is taken into the concentration diffusion model to get the concentration distribution within the street canyon.

The flow of air in an urban street canyon is thought to be incompressible turbulent flow according to the valid assumption at low subsonic speeds. The air is assumed to have a varying pressure and a constant density ρ. The two-equation, k–ε turbulent model is used to solve the wind distribution. The governing equations of the model are shown below

Continuity equation:

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0.$$

Momentum equations:

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \bar{U}_i}{\partial x_j} - \overline{u_i u_j}\right).$$

k-transport equation:

$$\frac{\partial k}{\partial t} + \bar{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + \upsilon_t\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\frac{\partial \bar{U}_i}{\partial x_j} - \varepsilon.$$

ε-transport equation:

$$\frac{\partial \varepsilon}{\partial t} + \bar{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + \frac{\varepsilon}{k}\left(C_{\varepsilon 1}\upsilon_t\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\frac{\partial \bar{U}_i}{\partial x_j} - C_{\varepsilon 2}\varepsilon\right),$$

where $\overline{u_i u_j} = \frac{2}{3}k\delta_{ij} - \upsilon_t(\bar{U}_i/\partial x_j + \partial \bar{U}_j/\partial x_i)$, $\upsilon_t = C_\mu(k^2/\varepsilon)$, $C_\mu = 0.09$; $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 1} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, V_t is the turbulent dynamic viscosity of air, k is the turbulent energy and ε is the turbulent dissipation.

Pollutant concentrations are predicted based on the atmospheric convection diffusion equation including meteorological data, transport diffusion, and the relevant emissions (S_i). It can be written as

$$\frac{\partial C_i}{\partial t} + \frac{\partial (u_j C_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(K\frac{\partial C_i}{\partial x_j}\right) + S_i,$$

where C_i denotes the concentration of the chemical species and K is the diffusivity. Different values have been considered for different species. The Schmit number ($\mathrm{Sc} = v/K$) was considered here. v is the viscosity, K is the diffusivity. Studies have been done (Moriguchi et al., 1995; Yoshikawa et al., 1997) to change the Schmit number in street canyon models to regress the observed data, and found that $\mathrm{Sc} < 1$ has better regression. In this study, $\mathrm{Sc} = 0.5$ was selected, and assumed to be constant.

In general, the diffusion and convection of emissions from vehicles along streets can be thought to be a linear source when the street is straight. When the ambient winds are perpendicular to the street, the air quality model can become a two-dimensional model. For this study, the street canyons under ambient winds perpendicular to the street were studied, and a two dimensional model was solved.

Table 1
Boundary condition used in this study

	Open surface			
	Inflow	Top	Outflow	Solid surface
Velocity	Fixed gradient	Zero gradient	Zero gradient	Logarithmic law
Concentration	Zero gradient	Zero gradient	Zero groadint	Zero gradient

The solution of the equations was based on a finite-volume method (Patankar, 1980). A staggered grid is employed for the vector (**u** and **w**) and scalar (C, P, k and ε) quantities. The scalar quantities are defined at the centers of the grid cells, while the wind vectors are defined at the midpoints of the cell boundaries. The studied street canyons were divided into proper grid systems depending on the geometry of the street canyons. The boundary conditions based on Aragawa (Aragawa, 1994) are shown in Table 1.

3. Evaluation

The air quality model was evaluated using the database from the NO_2 Environmental Concentration Monitoring Stations Research Program (JEMAI, 1980). The program was conducted by the Japan Environmental Management Association of Industry (JEMAI) in 1980 in order to clarify the characteristics of NO_x monitoring stations and provide methods to deal with the situation when encountering high concentrations of pollutants. The program investigated many aspects including NO_x environmental concentration measurements, meteorological observations and diffusion experiments.

The air tracer dispersion experiment data, which was carried out near the crossing of Aoyama ichome, Minato-ku, Tokyo, in December 1980, was selected to evaluate the two-dimensional numerical model. The schematic diagram of the air tracer experiment is shown in Fig. 1. It is an urban street canyon between two buildings, one is 50.9 m high and the other 30.5 m high. The width of the road is 40.0 m, and the pavement is 5.0 m at both sides. The velocity of the wind was measured at the top of the buildings. SF_6 and $CBrF_3$ were used as tracer gases and constantly released from a pipe on the center divider of the road. The concentrations were measured on the both sides and on the top of the building and around the road lamps.

Figs. 2 and 3 show the comparison between the calculated and observed concentration of SF_6 and $CBrF_3$. The correction coefficients for the SF_6 and $CBrF_3$ data were obtained using a regression analysis. The results show a good prediction of the concentration distributions within the urban street canyon using this numerical model, and they show a higher concentration distribution on the leeward side.

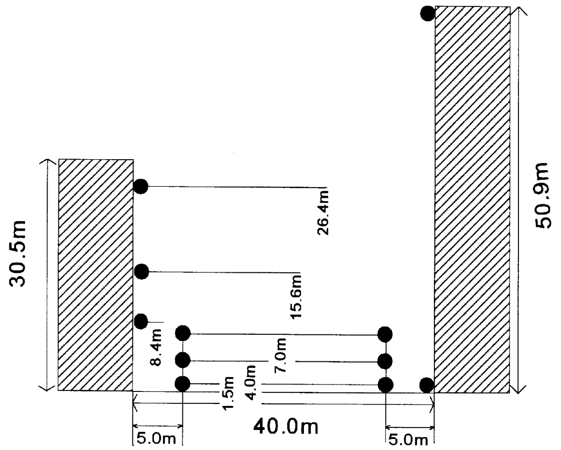

Fig. 1. Schematic diagram of the air tracer experiment including sampling cites.

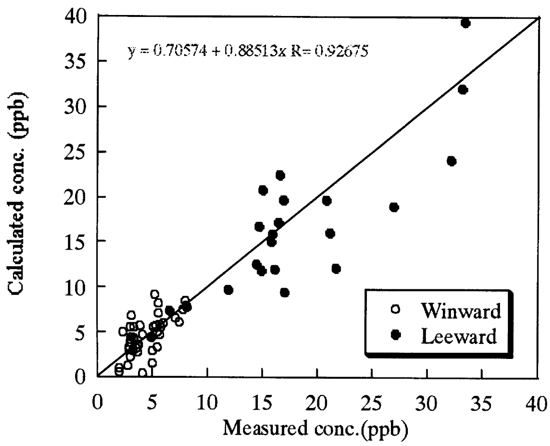

Fig. 2. Comparison of observed and calculated concentration of SF_6.

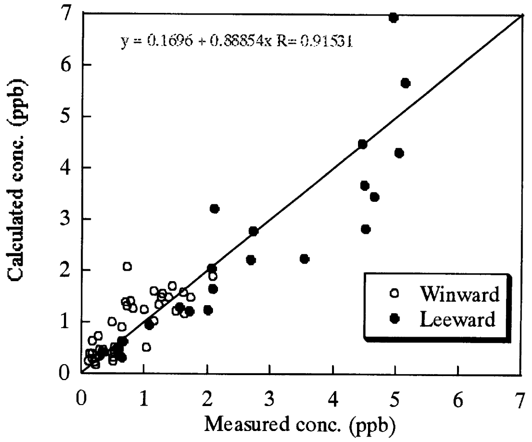

Fig. 3. Comparison of observed and calculated concentration of $CBrF_3$.

4. Sensitivity analysis

It has been known that the flow of air in a street canyon is decided by both the meteorological conditions and the geometry of the street canyon. In order to examine the flow and dispersion properties within an urban street canyon, 24 cases, which are shown in Table 2, have been done according to different meteorological conditions and street canyon geometry.

As has been previously stated, it is clear that the previous studies were all limited to the horizontal wind speed and the same height for both buildings. It is obviously a very ideal condition. In order to simulate more practical conditions, cases were selected that included the inflow wind having an inclination with the horizontal ground and both buildings have different heights. The pavement was set to be 5.0 m in all simulations.

4.1. Wind distribution

The wind distributions of cases 6, 13 and 14 are shown in Figs. 4–6. They show the change in wind with a decreasing street canyon height when the perpendicular wind speed is 5 m s^{-1}. We can clearly see that a vortex is formed within the street canyon, the center being about the middle of the height. With a decreasing building height, the vortex becomes closer to the leeward building. The vortex turns from circular to elliptical.

Table 2
Summary of the street canyon studies

Case	Road width (m)	Building height (m) Left, right	Inflow wind speed (m s^{-1}) u	v	Concentration calculation time (s)
1	40.0	40.0, 40.0	3.0	0.0	3600
2	40.0	40.0, 40.0	5.0	0.0	300
3	40.0	40.0, 40.0	5.0	0.0	600
4	40.0	40.0, 40.0	5.0	0.0	1200
5	40.0	40.0, 40.0	5.0	0.0	2400
6	40.0	40.0, 40.0	5.0	0.0	3600
7	40.0	40.0, 40.0	5.0	0.0	4800
8	40.0	40.0, 40.0	5.0	3.0	3600
9	40.0	40.0, 40.0	3.0	4.0	3600
10	40.0	40.0, 40.0	5.0	5.0	3600
11	40.0	40.0, 40.0	7.0	0.0	3600
12	40.0	30.0, 30.0	5.0	0.0	3600
13	40.0	20.0, 20.0	5.0	0.0	3600
14	40.0	10.0, 10.0	5.0	0.0	3600
15	40.0	40.0, 40.0	5.0	0.0	3600
16	40.0	40.0, 40.0	5.0	0.0	3600
17	40.0	30.0, 40.0	0.3	0.0	3600
18	40.0	30.0, 40.0	1.0	0.0	3600
19	40.0	30.0, 40.0	2.0	0.0	3600
20	40.0	30.0, 40.0	5.0	0.0	3600
21	40.0	40.0, 30.0	0.3	0.0	3600
22	40.0	40.0, 30.0	0.6	0.0	3600
23	40.0	40.0, 30.0	1.0	0.0	3600
24	40.0	40.0, 30.0	5.0	0.0	3600

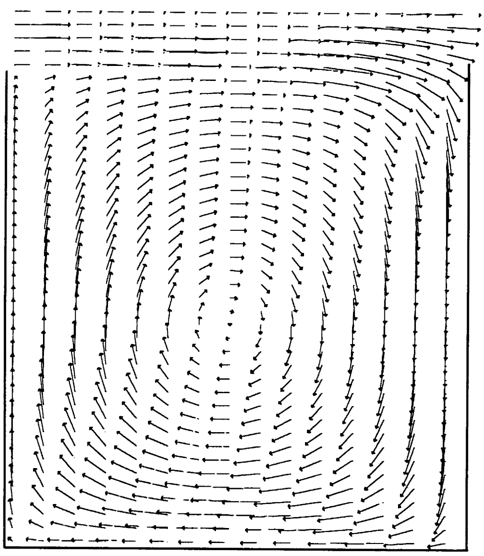

Fig. 4. Wind distribution for $W = 40$ m, $H = 40$ m, $u = 5$ m s^{-1}.

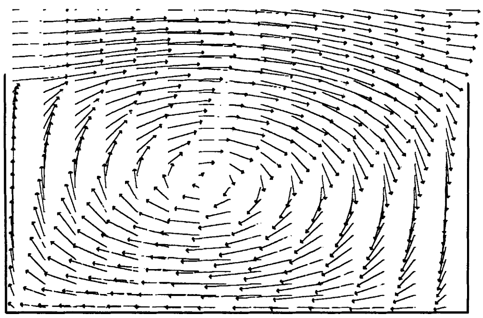

Fig. 5. Wind distribution for $W = 40$ m, $H = 20$ m, $u = 5$ m s^{-1}.

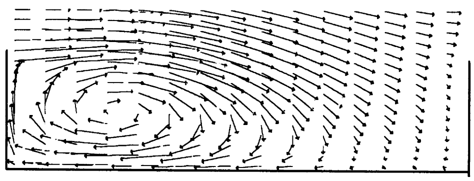

Fig. 6. Wind distribution for $W = 40$ m, $H = 10$ m, $u = 5$ m s^{-1}.

Figs. 7 and 8 show the horizontal and vertical wind speeds of the leeward, windward and the vortex center, respectively, for the inflow wind speed of 5 m s^{-1} and a street canyon height 40 m. We set the downward direction of the vertical wind speed and the right direction of the horizontal wind speed to be positive. We can conclude that the center of the vortex is at a 20 m height according to the change in the wind speed. The horizon-

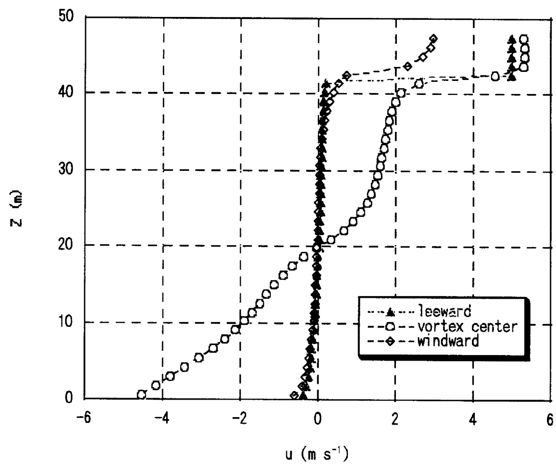

Fig. 7. Horixontal wind speed, u.

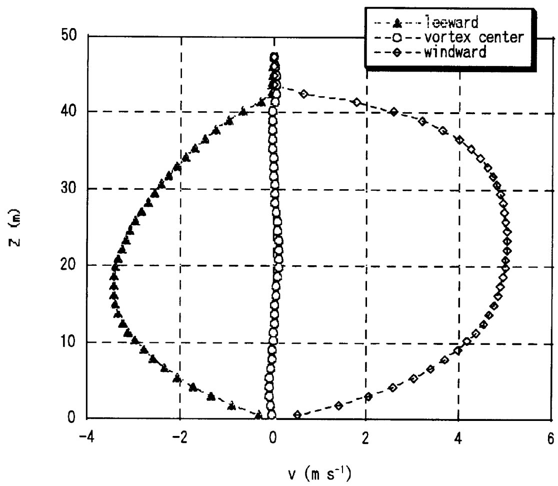

Fig. 8. Vertical wind speed, v.

tal wind speed at the vortex center is much faster than the leeward and windward sides. On the other hand, the vertical wind speed of the leeward and windward sides is much faster than that at the center. The windward speed is also faster than the leeward. As the vertical wind speed is very small at the center of the vortex, we made an enlarged figure of the wind speed at the center including two distributions at the position which are closest to the center and shown in Fig. 9. Based on Figs. 8 and 9, the wind speed at the left of the vortex is negative and the other side is positive. The maximum at the 20 m height also shows the position of the vortex.

It is usual that the inflow wind is not parallel to the horizontal direction. We gave a value to the vertical

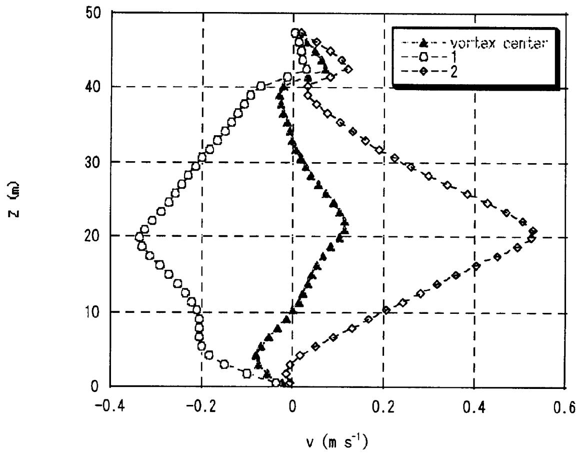

Fig. 9. Vertical wind speed, v. 1. The left closest site near the center, 2. The right closest site near the center.

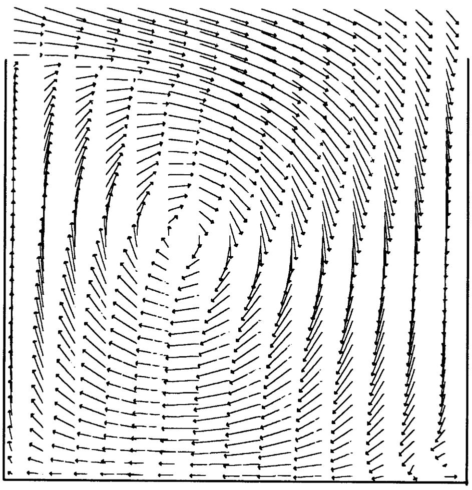

Fig. 10. Wind distribution for $W = 40$ m, $H = 40$ m, $u = 5\ \mathrm{m\,s^{-1}}$, $v = 3\ \mathrm{m\,s^{-1}}$.

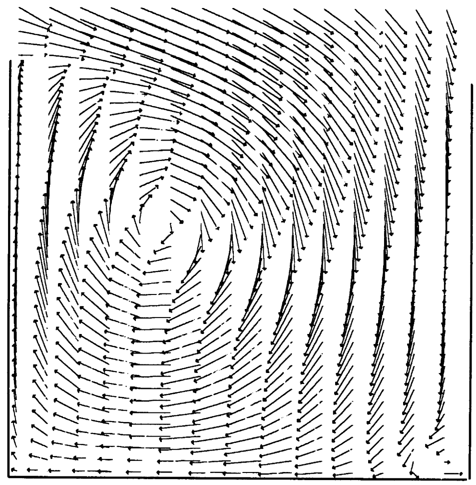

Fig. 11. Wind distribution for $W = 40$ m, $H = 40$ m, $u = 5\ \mathrm{m\,s^{-1}}$, $v = 5\ \mathrm{m\,s^{-1}}$.

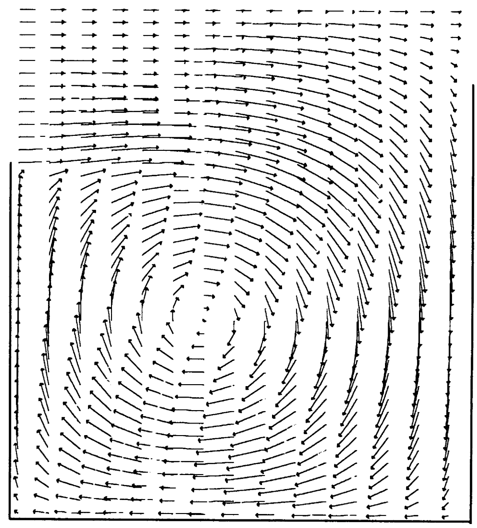

Fig. 12. Wind distribution for $W = 40$ m, $H(l) = 30$ m, $H(r) = 3$ m, $u = 1.0\ \mathrm{m\,s^{-1}}$.

wind, v, to make the wind have an inclination when entering the street canyons. Figs. 10 and 11 show the wind distribution for two different vertical wind speeds of 3 and $5\ \mathrm{m\,s^{-1}}$. With an increase in the vertical wind speed, the vortex approaches the leeward building. A little vortex can be found at the bottom near the windward building, and the vortex becomes larger with an increase in the wind speed.

Figs. 12 and 13 show the wind distribution when the two buildings have different heights. When the leeward building is lower than the windward building, the vortex moves towards the leeward building. On the other hand, when the leeward building is higher than the windward building, the vortex moves towards the outlet of the street canyon with an increase in the wind speed. It is also found that the wind speed, which can develop a vortex, is very small. According to the calculation, the vortex will disappear when the wind speed is faster than $1.5\ \mathrm{m\,s^{-1}}$.

4.2. Pollutant concentration distribution

The distribution of pollutant within the street canyon is determined by the wind field. In order to analyze the pollutant concentration distributions, the distribution of NO_2 within an urban street canyon was studied. The NO_x emission factors were assumed to be $0.41\ \mathrm{g\,km^{-1}}$

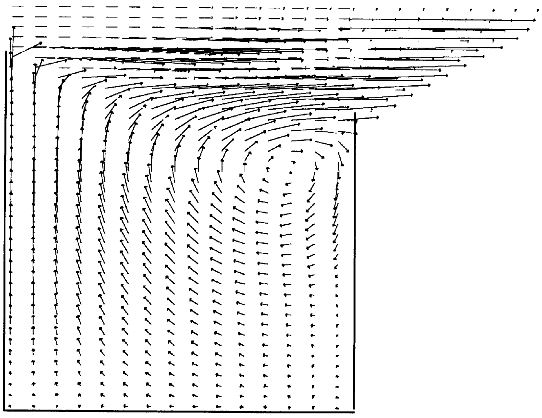

Fig. 13. Wind distribution for $W = 40$ m, $H(l) = 40$ m, $H(r) = 30$ m, $u = 0.6\ \mathrm{m\,s^{-1}}$.

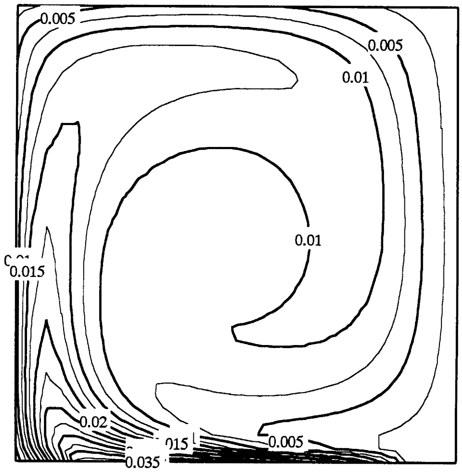

Fig. 15. Concentration districution for $W = 40$ m, $H = 40$ m, $u = 3\ \mathrm{m\,s^{-1}}$.

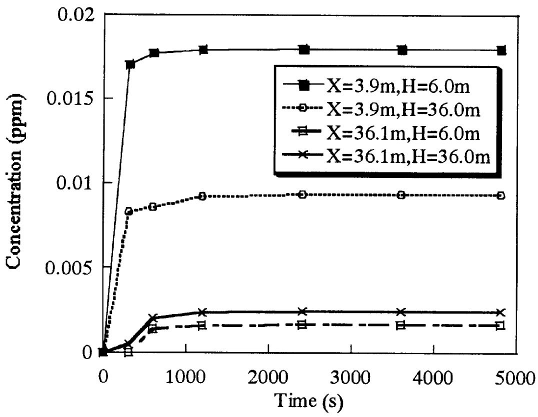

Fig. 14. Evolution of concentration for $W = 40$ m, $H = 40$ m, $u = 5\ \mathrm{m\,s^{-1}}$.

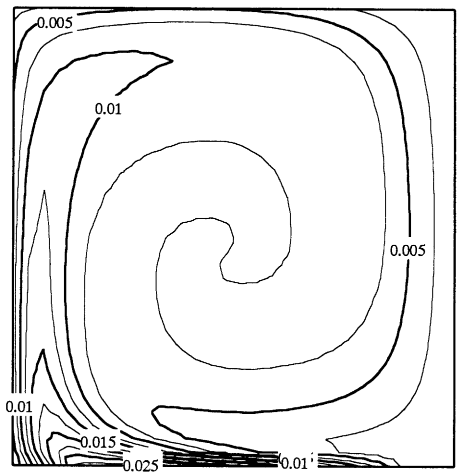

Fig. 16. Concentration distribution for $W = 40$ m, $H = 40$ m, $u = 5\ \mathrm{m\,s^{-1}}$.

(Sher, 1998), and NO/NO_2 was assumed to be 9. The road consists of four lanes, and the traffic is assumed to be 1200 vehicles $\mathrm{h^{-1}}$. Fig. 14 shows the concentration evolution with time. It can be seen that the concentration can quickly reach a stationary value. The leeward concentration reaches more quickly than the windward one. In this simulation, the concentration distribution of a sufficient evolution time of 3600 s was used.

Figs. 15–17 show the concentration distribution when the wind speed is 5 $\mathrm{m\,s^{-1}}$ and the height of both building is 40 m. The results show that the pollutant emitted from the bottom of the street canyon tends to follow the course of the wind field moving circularly. We can see that the accumulation occurs not only on the road, but also on the leeward sides. There are higher pollutant concentrations on the leeward side than on the windward side, which agreed with the experimental observations (Leisen and Sobottka, 1980; Hoydysh and Dabberdt, 1988). With an increase in the wind speed, the concentration decreases. This means that the higher the wind speed, the more easily pollutants can move out of the street canyon during the same time interval.

Figs. 18 and 19 show the leeward and windward vertical concentrations for three different wind speeds. A maximum can be found along the vertical direction. The concentration quickly decreases out of the street canyon. They also show the decreasing concentration with increasing wind speed. Fig. 20 shows the center vertical concentration for three different wind speeds. The maximum is at ground level, and quickly decreases along the height. We can see a lower and uniform concentration distribution in the vortex. Fig. 21 shows the horizontal

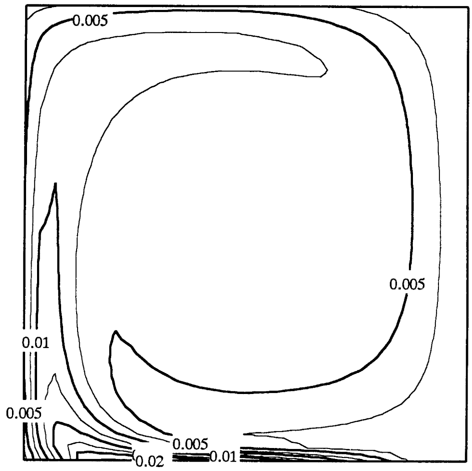

Fig. 17. Concentration distribution for $W = 40$ m, $H = 40$ m, $u = 7$ m s^{-1}.

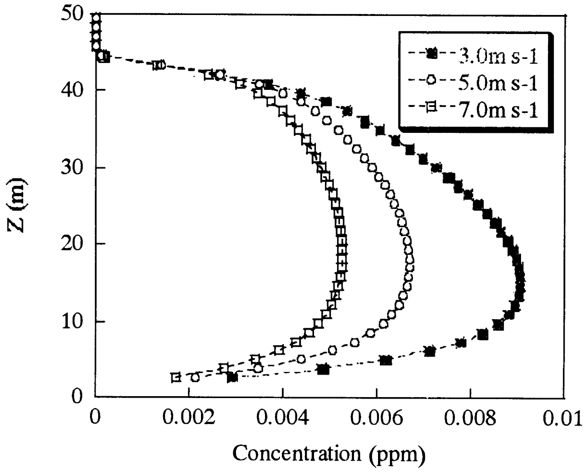

Fig. 18. Leeward vertical concentration $W = 40$ m, $H = 40$ m.

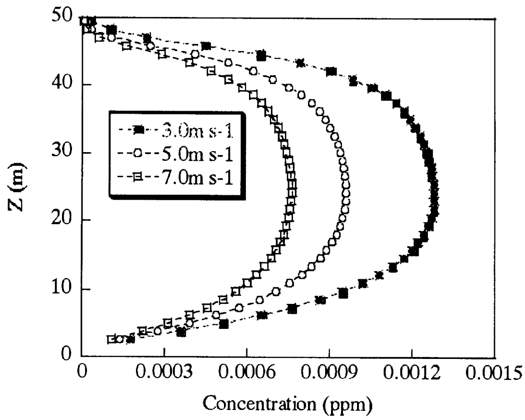

Fig. 19. Windward vertical concentration for $W = 40$ m, $H = 40$ m.

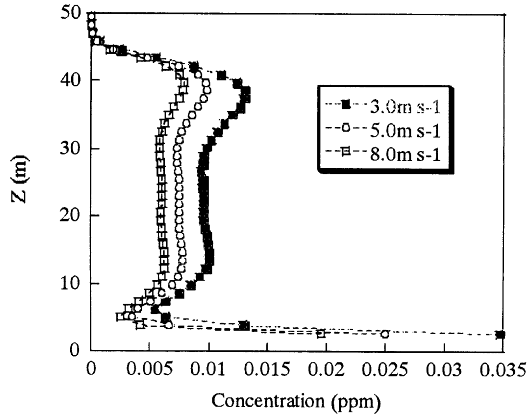

Fig. 20. Center vertical concentration for $W = 40$ m, $H = 40$ m.

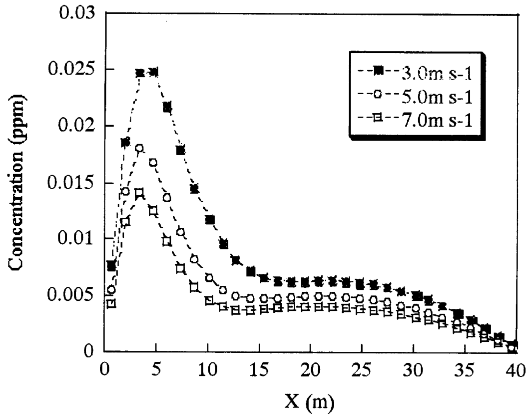

Fig. 21. Horizontal concentration profiles at $H = 6$ m for three different wind speeds.

concentration profiles for three different wind speeds. It also shows that the windward concentration is lower than the leeward one. There is a maximum at the leeward side. Fig. 22 shows the leeward concentration for three different street canyon heights. The higher the height of the street canyon, the more pollutants will be accumulated within the street canyon.

The concentration distributions have also been studied when the two buildings have different heights and the inflow wind has an inclination with the horizontal line. Fig. 23 shows a leeward concentration distribution for five different conditions for the same inflow wind speed of 5 m s^{-1}. It is very difficult for the pollutants released from the street canyon when the two buildings have the same height of 40 m. It becomes very easy when the leeward building is higher than the windward building. The concentration when the leeward building is lower than the windward building is a little smaller than that when the two buildings have the same height as the

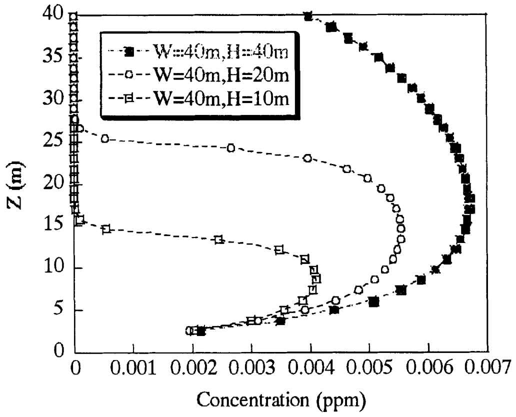

Fig. 22. Leeward vertical concetnration for different building heights.

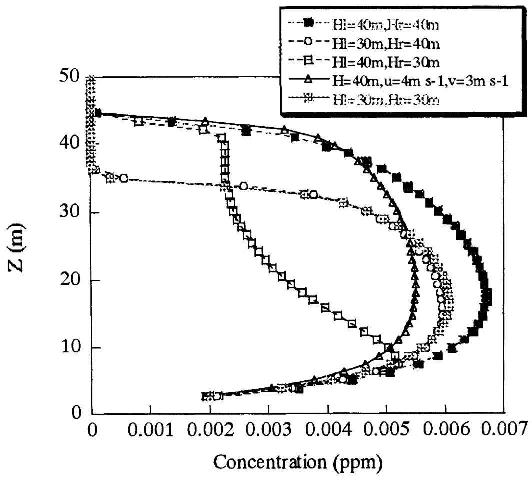

Fig. 23. Leeward concentrations for five different conditions.

leeward building. It is also rather easy for pollutant release from the street canyon when the inflow wind has an inclination towards the street. This suggests that the concentration distribution within a street canyon is governed by both the inflow wind and street canyon geometry.

5. Conclusion

In this paper, a two-dimensional air quality numerical model is developed based on the atmospheric convection diffusion equation and k–ε turbulent model to predict the pollutant concentration distributions within an urban street canyon. A full evaluation of the numerical model has been done using the database from a set of street canyon air tracer experiments. The good agreement between the calculated and observed concentrations make it possible to use this numerical model to analyze the pollutant distributions emitted by vehicle within an urban street canyon.

Twenty-four cases have been studied for the sensitivity analysis, including more practical cases that the inflow wind has an inclination with the horizontal road and the two buildings have different heights. The results show that a vortex can form within a street canyon and higher concentration at the leeward side than those at the windward side, which agrees with other research. The concentration distributions of pollutants emitted from the road are governed by both the inflow wind and the street canyon geometry. It is found that the released pollutants from a street canyon become more diluted in the following cases: the lower the height of the street canyon, the higher wind speed, the higher height of the leeward building than the windward building and an inflow wind direction towards the street.

It is difficult to apply the two-dimensional model to the cases where wind directions are other than that perpendicular to the street canyon, therefore, work will be continued on a full three-dimensional model involving wind directions other than that perpendicular to the street canyon.

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