Three Dimensional Analysis of Pollution Dispersion in Street Canyon

T. Banerjee and R. A. Christian

Abstract**—**Three dimensional simulations are carried out to estimate the effect of wind direction, wind speed and geometry on the flow and dispersion of vehicular pollutant in a street canyon. The pollutant sources are motor vehicles passing between the two buildings. Suitable emission factors for petrol and diesel vehicles at varying vehicle speed are used for the estimation of the rate of emission from the streets. The dispersion of automobile pollutant released from the street is simulated by introducing vehicular emission source term as a fixed-flux boundary condition at the ground level over the road. The emission source term is suitably calculated by adopting emission factors from literature for varying conditions of street traffic. It is observed that increase in wind angle disturbs the symmetric pattern of pollution distribution along the street length. The concentration increases in the far end of the street as compared to the near end.

Keywords**—** Street canyon, Pollution dispersion, Vehicular emission, Numerical simulation

I. Introduction

AIR pollutants from motor vehicle exhausts in urban areas are confined between buildings under unfavorable wind conditions. The wind flow over the urban canopy drives localized flow patterns in the space between the buildings and street. These localized flows can create significant spatial variations of air pollution concentrations near the streets. A classic example of such dispersion effects in urban areas are those associated with street canyons. The street canyon domain is a region where large amounts of pollutants are released near the ground from motor vehicle exhausts and near the roof level from domestic (or industrial) chimneys [1]. One of the most important issues leading to popular street canyon pollution research is thus the large amount of vehicular pollutants emitted at the ground level of urban street canyons, which considerably deteriorates the local air quality and imposes direct impact on human health. It is of paramount importance from the point of view of an urban planner to find out how these pollutants are transported and distributed in street canyon. A planner can thus decide whether modifying some design parameters or planning strategies, the air pollution problems at pedestrian level and along the building wall can be reduced or eased. The transport of gaseous pollutants in street canyon depends generally on the rate at which the street exchanges air vertically with the atmosphere above the roof level and laterally with the connecting streets. Liu et al. [2] introduced the concept of Air Exchange Rate (ACH) and Pollutant Exchange Rate (PCH) to represent the pollutant dilution capabilities of a street canyon. Most of the studies focus on the SF (Skimming Flow) regime because it provides minimal ventilation and is relatively ineffective in removing pollutants. Many metropolises like Hong Kong and New York suffer from this flow situation which leads to poor air quality within the street canyon.

Analysis of dispersion of automobile pollutants in street canyon is reported in this paper. Three dimensional simulations are carried out using FLUENT for various aspect ratios of the street canyons. The pollutant sources are motor vehicles passing between the two buildings. Since carbon monoxide is the most significant pollutant released from the motor vehicles, dispersion of carbon monoxide from the motor vehicles is only considered for the present simulations. Suitable emission factors for petrol and diesel vehicles at varying vehicle speed are used for the estimation of the rate of emission from the streets.

Three dimensional simulations are carried out to analyze pollution dispersion in the street canyon. The dispersion of automobile pollutant released from the street is simulated by introducing vehicular emission source term as a fixed-flux boundary condition at the ground level over the road. No pavement area is considered for this analysis assuming that pavements are almost negligible. The emission source term is suitably calculated by adopting emission factors from literature for varying conditions of street traffic. The influence of street geometry in the form of aspect ratio on dispersion of a fixed vehicular emission flux and fixed wind speed from the roof level is observed. The simulations are carried out for varying aspect ratios, wind speed, wind direction and street length. The velocity profile and concentration distribution are compared for varying wind direction also.

II. Geometric Model

Fig.1 shows the physical model of the street canyon domain considered for three dimensional simulations presented in this chapter. The model of the domain is created in GAMBIT by sweeping in the third dimension by required depth (Z direction), the faces of the two-dimensional canyon (X-Y

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plane) described in the previous chapter. Air (with or without pollutant) enters the street through the inlet (X-Z) plane shown in figure and flows over the roofs of the building and gets transported into the street. The street is formed by the two buildings represented by the forward and backward facing steps. W and H are the width and height of the building while L represents the length of the building. Simulations are carried out for a street length (L) of 40m, 100m and 180m. The height of the inlet channel is taken as 100m and the height of the building is 20m. The width of the channel varies for different aspect ratio of the canyon geometry. The automobile pollutants are released by motor vehicles plying in the street formed by the two buildings.

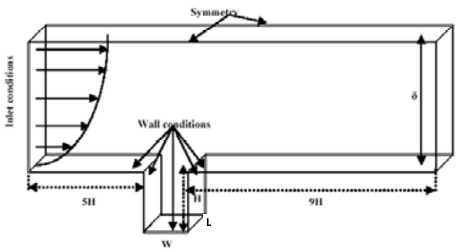

Fig. 1 Geometric model of the street canyon domain for three dimensional simulations[1]

A. Governing Equations

Three dimensional Navier-stokes equations (conservation of mass and three directional momentum equations) for incompressible, Newtonian fluids are solved in conjunction with standard k-ε model for turbulence. The Eulerian mixture model is selected for two-phase (Air and Carbon monoxide) mixing and transport. Mixture model solves the mixture momentum equation and prescribes relative velocities to describe the secondary phase. Mixture model solves the transport equation of volume fraction for the secondary phase. Volume fraction of the secondary phase in a control volume is the ratio of the volume of the phase in the cell to the total volume of the cell.

B. Boundary Conditions

The inlet boundary condition is prescribed as a constant velocity boundary while the outlet is a pressure outlet boundary condition. The top surface of the domain along with the near and far faces is assigned free boundary conditions. The walls of the building are assigned no slip boundary conditions. The vehicular exhaust emission source term is added as a fixed-flux boundary condition at the street level over the road. No pavement width is considered for the present simulations. The eddy diffusivities are assumed to be isotropic and equal to effective kinematic viscosity. The main source of emission, carbon monoxide is assumed to be non-reactive gas in the atmosphere.

C. Estimation of Vehicular Pollutant Emission Rate

In the present work the vehicular pollution emission rate has been calculated based on the guidelines suggested by Tsai and Chen [3]. They assumed vehicular emission as line source and defined a term called emission factor of the pollutant in g/km. The pollutant emission factors in g/km for Light Duty Gas Vehicle (LDGV), Heavy Duty Diesel Truck (HDDT) and Motor Cycle (MC) are tabulated in Table 1 [3]. Only one- fifth of the values for emission factor of SO2 given in the Table 5.1 should be used since the sulfur content of mobile fuel was about 0.1gl-1 in 1991 but 0.018 gl-1 in 2002, corresponding to a five fold reduction.

The expression for the rate of emission qik by traffic in the kth lane of species i is given by

$$q_{ik}(t) = \frac{EF_{ik}(t) \times N_k(t)}{A_k \times 1000} \quad (1)$$

where EF_{ik} is the emission factor of pollutant i and N_k is the average traffic flow rate or number of vehicles per unit time. The subscript k refers to the kth lane. A_k in the above equation is cross sectional of the kth line source.

$$A_k = h_k \times w_k \quad (2)$$

h_k and w_k are the height and band width of the line source. The typical values of h_1=1.2m and w_1=1.9m for a passenger car and h_2 = 1.5m and w_2 = 0.8m for motor cycle are adopted in the present work. Separate lanes are considered in the entire canyon width with passenger cars and motor cycles plying in different lanes [4]. The rate of traffic considered is around 3000 vehicles per hour. The rate of emission q_{ik} obtained in kg/m^3-s is then provided as mass source term from the ground level.

D. Numerical Scheme

The mesh structure used for the three dimensional simulations on the present domain is shown in Fig. 2. The physical domain is discretized using structured, uniform hexahedral mesh. Implicit pressure based (segregated) solver is used for the steady state computations. All terms are approximated using first order upwind scheme except for pressure term which is approximated by central difference scheme. The coupling between the velocity and pressure is solved using the semi-implicit method for pressure linked equation (SIMPLE) procedure [5]. The computational time required for three dimensional simulations are approximately 30 times those for two dimensional simulations.

E. Validation

To ensure the accuracy of the three dimensional simulations presented here, the concentration contours obtained by Crowther *et al.* [6] are compared with present results and a close comparison is observed for the carbon dioxide concentration in ppm.

TABLE I
POLLUTANT EMISSION FACTORS IN G/KM [3]

Speed	LDGV			HDDV			MC		
(km/hr)	CO	NO_x	SO_2	CO	NO_x	SO_2	CO	NO_x	SO_2
10	-	-	-	-	-	-	20.73	0.0976	0.074
20	-	-	-	-	-	-	15.84	0.1063	0.074
30	17.14	1.355	0.25	7.5	14	4.25	11.77	0.1101	0.074
40	12.59	1.369	0.25.	5.5	13.5	4.25	8.65	0.1115	0.074
50	8.95	1.437	0.25	4.0	13.5	4.25	6.15	0.1145	0.074
60	6.52	1.588	0.25	3.2	14.2	4.25	-	-	-
70	5.01	1.821	0.25	3.0	15.5	4.25	-	-	-

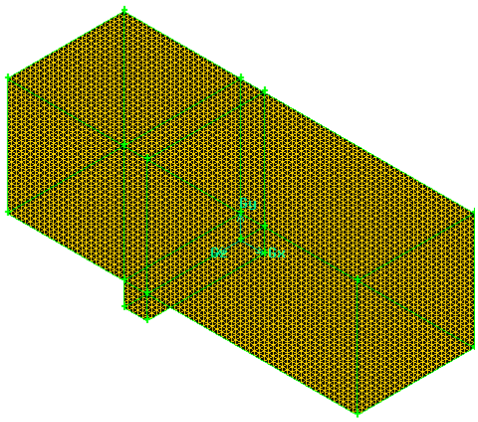

Fig. 2 Mesh structure (grids) used for the three dimensional computations

III. Results And Discussions

To investigate the dispersion of vehicular pollution released from the street the street canyon model is created in three dimensions. A three dimensional simulation is required for simulations when the wind direction is not parallel to the width of the street [7]. Three dimensional simulations are carried out to establish the influence of aspect ratio, wind direction and street length on dispersion of vehicular emission in the street canyon are discussed in this section. Results are depicted in the form of velocity vectors and concentration distribution over a transverse vertical plane at the mid of the street length (XY plane at Z=L/2) and near the edge of the street length (XY plane at Z=0.1×L). Concentration distributions are also plotted at various heights of the street canyon (bottom pedestrian level Y=1.3 m, top pedestrian level Y=2.6m and mid-height of the canyon Y=10m) in a transverse vertical plane (YZ plane) near leeward wall (X=0.05×W), mid of the canyon (X=0.5×W) and near windward wall (X=0.95×W). For all the plots the linear dimensions are non-dimensionalized with respect to the height of the street canyon (H = 20m).

A. Influence of Aspect Ratio

The results discussed in this section are for simulations where the street canyon is of length L=100m and wind direction parallel to the axis of the street width. The wind speed and vehicular emission rate are kept constant for these simulations. The concentration distribution inside the street canyon for varying aspect ratio is analyzed. Three different aspect ratios W/H =0.33, 1.0 and 2.99 are considered for the present study. The concentration distribution is represented in terms of the volume fraction of carbon monoxide which depicts the partial volume of carbon monoxide per unit volume of air.

Fig. 3 shows the concentration contours for different aspect ratio over the transverse vertical plane (XY plane) at the mid of the street length (Z=L/2) and at edge of the street length (XY plane at Z=0.1×L). The filled arrow in each figure shows the direction of wind flow. The colored legend represents the non-dimensional volume fraction of carbon monoxide released by the vehicular emission. Fig. 4 shows the variation of volume fraction of carbon monoxide along the street width at different vertical levels in these two vertical (XY) planes. Three different vertical heights are considered, one at the mid section of the pedestrian level (Y=1.3 m), one at the top of the pedestrian level (Y=2.6 m) and one at the mid height of the canyon (Y=10m).

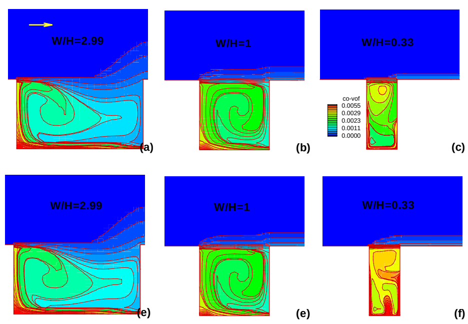

Fig.3 Concentration contours for different aspect ratio over the transverse vertical (XY) planes; (a, b, c) at the mid of the street length, Z=L/2 and (d, e, f) at edge of the street length, Z=0.1×L.

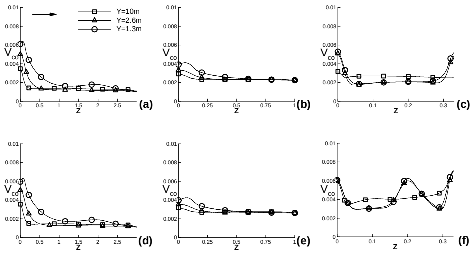

Fig. 4 Variation of volume fraction of carbon monoxide along the width of the street canyon for varying aspect ratio (a,d) W/H = 2.99, (b, e) W/H = 1.0, (c,f) W/H = 0.33 at two different transverse vertical XY planes (a,b,c) Z=L/2, (d,e,f) Z=0.1×L.

For all aspect ratios being considered it is observed that there is an accumulation of pollutant concentration towards the leeward end of the canyon. This is due to the formation of wind flow vortex characterized by updraft near the leeward wall and down draft near the windward building. This vortex facilitates the ventilation of vehicular emission through the roof level as the aspect ratio increases. The average concentration level in the canyon is however observed to decrease as the aspect ratio increases. This is because at low aspect ratio formation of multiple counter-rotating vortices in the canyon reduces the ventilation of carbon monoxide released from roof level. These multiple vortices are also responsible for pollutant accumulation in the windward end (Fig. 4 c, f) for canyons with lower aspect ratio. The accumulation at the mid block of pedestrian level (Fig. 3d and 4 f) for vertical (XY) plane nearer to the edge of the street length suggests two counter-rotating vortex at the pedestrian level.

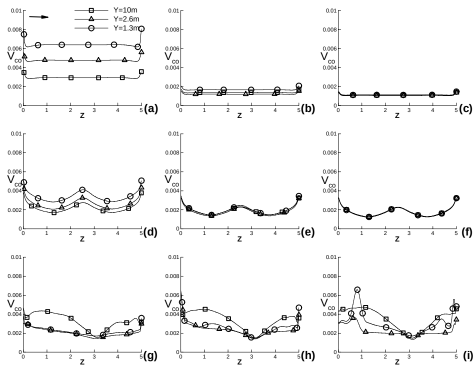

Fig. 5 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying aspect ratio (a,b,c) W/H=2.99, (d,e,f) W/H=1.0, (g,h,i) W/H=0.33 and at three different longitudinal vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall.

Fig. 5 shows the concentration variation along the street length in terms of volume fraction of carbon monoxide. The variations at three different canyon heights (Y=1.3 m, 2.6m and 10m) are plotted at three longitudinal vertical planes, one near the leeward wall, one at the mid width of the canyon (X=W/2) and one near the windward wall. The arrow shows the direction of wind flow. It is observed that at very low aspect ratio (Fig. 5 g,h,i) the average concentration at the mid height of the canyon is more than that at the pedestrian level. This is because of the intersection of the primary vortex from the roof top main flow and secondary vortices from the ground level near the mid height of the canyon. The primary vortex doesn't allow the vehicular emissions carried by the secondary vortices from the ground level to rise beyond the mid canyon height. The average pollutant concentration however is higher at the pedestrian level for higher aspect ratios. This is contrary to the popular belief that higher aspect ratio canyon provides lesser concentration level at the pedestrian level. At higher aspect ratios (Fig.5 d-e) the pollutant concentrations at the leeward and windward faces along the street are characterized by higher concentration at the mid-block, with the street level gradient directed from the end of the street to the mid block. Also the concentration levels at the leeward face are greater than at the windward face. At the ends of the street the pollutants are mixed with cleaner air and expelled, resulting in lower concentration in these regions.

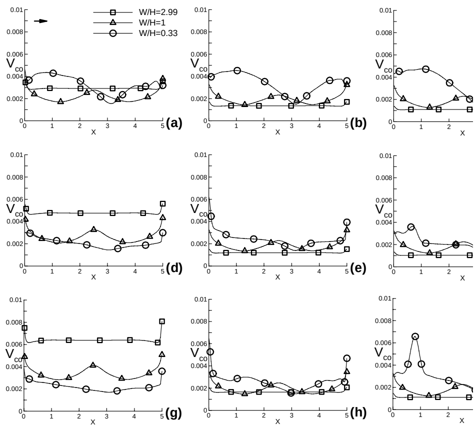

Fig. 6 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying aspect ratio at different heights (a,b,c) Y=10m, (d,e,f) Y=2.6m, (g,h,i) Y=1.3m and at three different longitudinal vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall.

Fig. 6 summarizes the influence of aspect ratio at three different vertical heights of the canyon. Three different longitudinal (YZ) planes are considered for comparison, one near the leeward end, one at the mid of the canyon (X=W/2) and one near the windward end. At all heights of the canyon, the concentration level of carbon monoxide is observed to decrease drastically from leeward plane to the mid and windward plane (Fig. 6 a,b,c) for higher aspect ratio of 2.99. For other aspect ratios, the variation of concentration however is less significant. For higher aspect ratio of 2.99 and 1 the concentration level is more at the pedestrian height as compared to mid height of the canyon. However for very low aspect ratio of 0.33, the concentration level at the mid height of the canyon is more than the pedestrian level. This means that though narrower streets reduce the ventilation of vehicular pollution, the pedestrian zone is safer so far as pollutant accumulation is concerned.

B. Influence of Street Length

Simulation results presented in this section are for cases where the aspect ratio and wind direction are kept fixed while varying the length of the street. Three different street lengths L=40m, L=100m and L=180m are considered for these simulations. The wind velocity is fixed at 5m/s parallel to the width of the canyon and concentration contours are depicted in term of the volume fraction of carbon monoxide with respect to air. Fig. 7 shows the contours of concentration at the transverse vertical planes of the canyon for three different street lengths. The contours are plotted at two different XY planes at mid of the street length (Z=L/2) and at end of the street (Z=0.1×L). The average concentration accumulation in the street is observed to be more for longer streets. This is because for smaller streets the fresh air flowing along the street ends produces jet effect flushing away the concentration from the canyon inside.

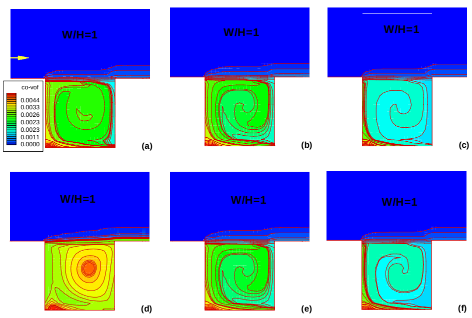

Fig. 7 Concentration contours at the transverse vertical XY planes of the canyon (a,b,c) at Z=L/2 and (d,e,f) Z=0.1×L for street lengths of (a,d) L=180m, (b,e) L=100m and (c,f) L=40m

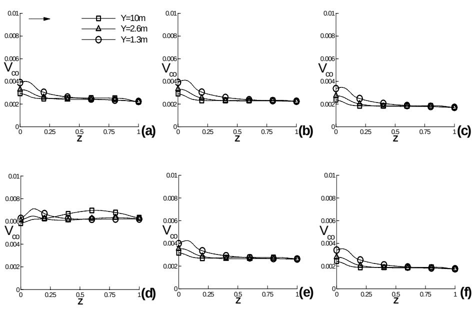

Fig. 8 Variation of volume fraction of carbon monoxide along the width of the street canyon for varying street length (a,d) L=180m, (b,e) L=100m, (c,f) L=40m and two different transverse vertical XY planes (a,b,c) Z=L/2, (d,e,f) Z=0.1×L

Fig. 8 shows the variation of concentration along the width of the canyon at pedestrian level and vertical mid height at the two transverse vertical planes considered here. The concentration levels at the leeward face are greater and remain almost constant from the midsection to the windward wall for all the street lengths under consideration. Also the concentration at the pedestrian level is more than at the mid canyon height

Fig. 9 shows the concentration variation along the street length for three longitudinal vertical planes, one near the leeward face, one near the mid canyon (X=W/2) and the other near the windward face. The variations are shown at three vertical heights, one at the mid of pedestrian level (Y=1.3m), one at the top of pedestrian level (Y=2.6m) and one at the mid height of the canyon (Y=10m). For longer street length (L=180 m) the concentration levels are more near the ends of the street than the central region. This is due to the low pressure draft created by the wind blowing at the end of the street length which facilitates the drawing of pollutants from the mid level to the ends of the street length. For moderate street length though the average concentration in the canyon is lower, there is an accumulation at the mid block as well as at the ends. For lower street length the low pressure draft created by the wind blowing at the ends of street produces almost uniform distribution of concentration along the street length. The concentration level near the leeward wall however is always more than other planes. At the mid vertical plane and near the windward wall the concentration distribution at all vertical heights are almost similar and equal.

Fig. 10 shows a comparison of concentration distribution at pedestrian levels and mid height of the canyon as the street length varies. Vertical heights at three different longitudinal planes are considered, one near the leeward end, one at the mid width (X=L/2) of the canyon and one near the windward end. It is observed that the concentration distribution is uniform along the street length at all vertical heights for small length of the street (L=40).

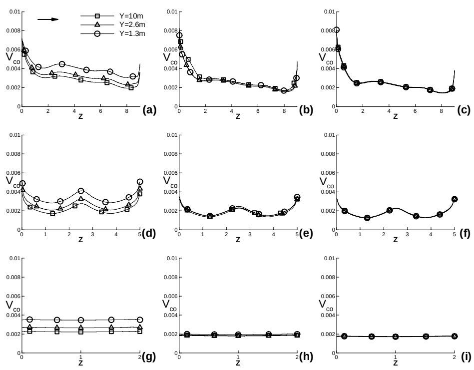

Fig. 9 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying street length (a,b,c) L=180m, (d,e,f) L=100m, (g,h,i) L=40m and at three different longitudinal vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall.

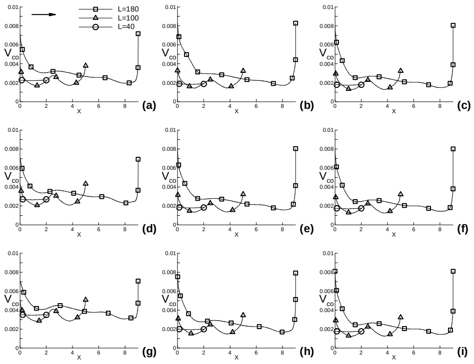

Fig. 10 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying street length at different heights (a,b,c) Y=10m, (d,e,f) Y=2.6m, (g,h,i) Y=1.3m and at three different transverse vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall

C. Influence of Wind Direction

Pollutant dispersion is also significantly affected by the variability in wind direction. For all results presented in this section the street geometry (L W and H) are held to be constant 100m, 20 m and 20m, respectively, and the roof top wind speed is held at 5 m/s. The wind directions are varied from parallel to width (θ=0°) to θ=30° and θ= 60° to the target street.

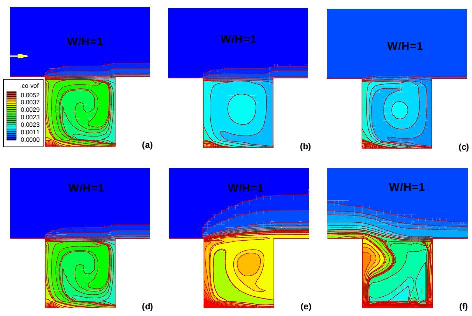

Fig. 11 Concentration contours at the transverse vertical XY planes of the canyon (a,b,c) at Z=L/2 and (d,e,f) Z=0.1×L for different wind direction of (a,d) θ=0°, (b,e) θ=30°and (c,f) θ=60°

Fig. 11 shows the contours of volume fraction of carbon monoxide at transverse vertical planes at the mid of the canyon length (Z=L/2) and end of the canyon length (Z=0.1×L) for all the wind directions under consideration. It is observed that the average concentration decreases in the mid canyon plane as the wind angle increases from 0^o to 30^o. This is because more pollutants are flushed out to the ends of the street as the wind angle increases. This also increases the average concentration at the street ends for this increase in wind angle. A further increase in wind angle to 60^o doesn't significantly affect the concentration contours at the mid plane. At the ends of the street however significant difference in concentration contours are observed.

Fig. 12 shows the variation of concentration along the width of the canyon for all the wind angles under consideration. The variation is shown at the mid pedestrian level (Y=1.3m), top of pedestrian level (Y=2.6m) and mid height of the canyon (Y=10m). As the wind angle increase from 0^o to 30^o the average concentration level is observed to drop at all the heights the mid transverse plane. However there is an increase in concentration level at the plane near the end of the street length. Further increase in wind angle, doesn't show significant change at the mid transverse plane. Near the end of the street length, however the concentration level is observed to be lower at the top of the pedestrian level.

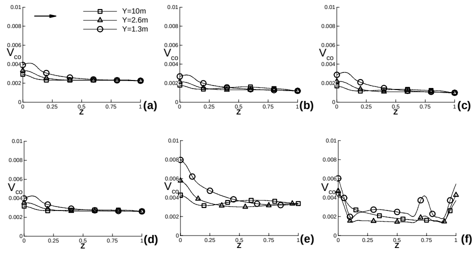

Fig. 12 Variation of volume fraction of carbon monoxide along the width of the street canyon for varying wind direction (a,d) θ=0°, (b,e) θ=30°, (c,f) θ=60° and two different transverse vertical XY planes (a,b,c) Z=L/2, (d,e,f) Z=0.1×L.

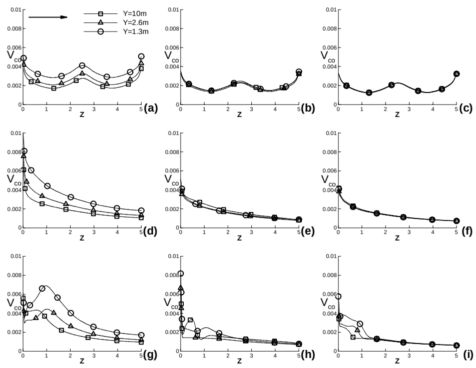

Fig. 13 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying wind direction (a,b,c) θ=0°, (d,e,f) θ=30°, (g,h,i) θ=60° and at three different transverse vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall.

Fig. 13 shows the variation of concentration at three vertical heights along the street length as the wind direction varies. The analysis with wind direction parallel to the street width has already shown that the Carbon monoxide concentrations along the street at the two ends of the street are identical with a higher concentration at the middle of the street. The symmetric pattern of distribution however disappears as the angle is varied. An increase of 30^o wind angle produces higher concentration at the near end and lowers at the far end. Further increase to 60^o produces local maxima near the far end street length.

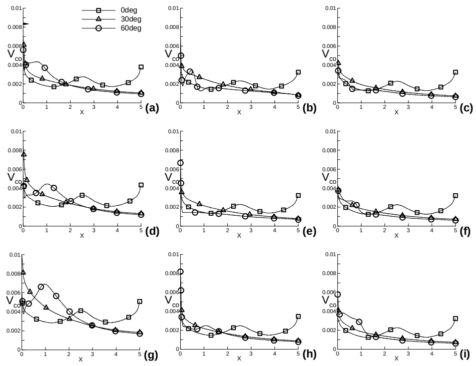

Fig. 14 Variation of volume fraction of carbon monoxide along the length of the street canyon for varying street length at different heights (a,b,c) Y=10m, (d,e,f) Y=2.6m, (g,h,i) Y=1.3m and at three different transverse vertical YZ planes (a,d,g) near leeward wall, (b,e,h) at the mid section of the width of the canyon and (c,f,i) near windward wall

Fig. 14 shows the influence of wind angle at various heights of the street canyon for longitudinal vertical planes near the leeward end, at mid width of the canyon and near the windward end. It is observed that an increase in wind angle from 0^o to 30^o causes drastic variation of concentration from one end to the other end of the street particularly at pedestrian height. With further increase in wind angle the maxima shifts from the street end and the point of inflexion shifts inside the street length at pedestrian level.

IV. Conclusions

Computational Fluid Dynamics (CFD) software package FLUENT is used with a standard κ-ε turbulence model to simulate the three-dimensional dispersion of air pollutants in an urban street canyon. Carbon monoxide is considered as the only vehicular emissions for all the simulations. The rate of emission of carbon monoxide from the ground level is calculated in kg/m3-s based on the traffic rate and composition of traffic. This is then provided as a mass source term from the ground level in the present computations.In all cases, a vortex was formed within the street canyon characterized by updrafts near the leeward building and downdrafts near the windward buildings. Contours of pollution concentration over a transverse vertical plane at mid canyon show pollutants circulating within the vortex, with higher concentrations at leeward face than the windward faces. Longitudinal distribution of pollutant concentrations at leeward and windward faces are characterized by higher concentrations at mid blocks and lower concentration at the end. Parametric variations are carried to estimate the influence of aspect ratio, street length and wind direction on concentration distribution in the canyon. The concentration distribution is depicted in terms of volume fraction of carbon monoxide. The average concentration in the canyon, particularly in the pedestrian level is observed to decrease with increase in aspect ratio. The shorter length of the street canyon facilitates in creating uniform concentration distribution in the entire canyon length. Also for short street length the concentration of pollutant reduces from leeward plane to wind ward plane with maximum change in the pedestrian plane. There is negligible variation for longer street lengths. The increase in wind angle disturbs the symmetric pattern of pollution distribution along the street length. The concentration increases in the far end of the street as compared to the near end.

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