VEHICULAR POLLUTION DISPERSION: CASE STUDY OF A TYPICAL STREET CANYON IN SURAT

[1]T.Banerjee, [2]R. A. Christian
[1]Ph. D. Scholar, CED, S.V.N.I.T, Surat, [2]Associate Professor, CED, S.V.N.I.T, Surat
Email:[1]tandara.banerjee@ckpcet.ac.in, [2]rac@ced.svnit.ac.in

Abstract— Vehicular pollutant dispersion in a typical street canyon in Surat city is analysed. For the street canyon under consideration the traffic volume count for a busy period of the day is measured along with the type of vehicle and average vehicular speed. Based on this count and using the emission data from CPCB, the total release in the 120 m long street is calculated. Based on this release data, calculations are carried out using OSPM to obtain the possible concentration level at the leeward and windward ground levels of the street. These calculations are then compared with 2D CFD simulations carried out for the road considering the source of release from the ground level.

***Index Terms*—CFD, Dispersion, OSPM, Vehicular Pollution**

I. INTRODUCTION

Pollutant from vehicular exhaust constitutes a major fraction of total pollutant dispersion in atmosphere. These pollutants has direct impact on human health. Atmospheric air flow plays an important role in distribution of pollutants released from the vehicle into the air. Significant increase in computer power makes it now possible to use advanced numerical models for air pollution studies. But numerical analysis is also computationally expensive in terms of time. For urban street pollution monitoring, a simplified model which includes most of the complexities of real flow as well requires fewer calculation steps are preferable. The Operational Street Pollution Model (OSPM) [1] belongs to this category of parameterized models. This model is basically a semi-empirical one having few assumptions about flow and dispersion conditions. In this paper, calculations are first carried out using OSPM model for a sample street canyon in Surat city. The vehicular traffic flow and the air flow rate and direction of air flow are measured. The rate of emission from light and medium vehicles is calculated as per CPCB norms [2] according to the average speed of the vehicle.

Some of the assumptions of OSPM are very simplistic and hence result in gross inaccuracy of prediction of pollutant by this model. With the advent in Computational Fluid Dynamic (CFD) tools it is possible to rigorously check these simplistic assumptions and use the CFD simulation results to augment the model so that complex features of flow can be incorporated in these models. This is the aim of this research.

II. THE OPERATIONAL STREET POLLUTION MODEL (OSPM)

OSPM is based on similar principles as the CPB-model by Yamartino and Wiegand [3]. Concentrations of exhaust gases are calculated using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street (Fig. 1). OSPM makes use of a very simplified parameterization of flow and dispersion conditions in a street canyon. This parameterization was deduced from extensive analysis of experimental data and model tests [4].

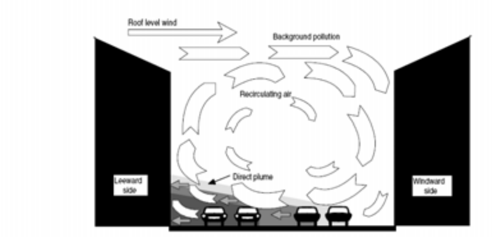

Fig. 1: Schematic of the basic principles in OSPM [1]

III DATA COLLECTION

A busy street of Surat city (near Bhagal Char Rasta) is selected as a case study (Fig. 2). The plan of the street is shown in Fig. 3.

Fig. 2: Bhagal Char Rasta

The street runs from east to west direction and the wind direction when measured was observed to be along north-west direction. The Street considered has the following dimensions and characteristics.

Width of street = 15.2 m
Height of the building = 15 m (approximate)
Length of street = 120 m
Ambient Temperature = 26.3^0 C
Average speed of vehicle = 10 km/hr =2.78 m/s
Wind direction = N-W
Angle of wind with reference to central line of the street is, $\Phi = 50^0$
Average roof top wind speed measured= 0.817 m/s

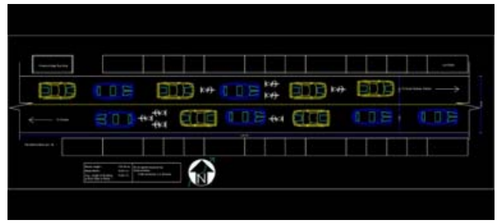

Fig. 3: Plan of the street under consideration

Measured vehicular traffic flow

Traffic volume count was carried out during peak traffic period. Table shows traffic count measured for 2-wheeler, 3-wheller and four wheelers in the street shown in fig. 3. This traffic count is used to generate the pollutant release in that period in the street under consideration. Based on this traffic count, the emission rate of Carbon monoxide (rate of release of CO) in the street is calculated as is discussed in the next section.

IV OSPM CALCULATIONS

Calculation of the emission rate of CO for the vehicular traffic

The emission factors for 2-wheeler, 3-wheeler, 4-wheeler vehicles are considered based on draft report. "Emission Factor development for Indian Vehicles" published by Central Pollution Control Board of India [5]. The values chosen are for Indian road conditions and considering the vehicle to have been manufactured after 2000. For 2-wheeler average emission factor is considered between scooter and motor cycle. For 3-wheeler average is taken between 2-stroke and 4-stroke engines of less than 200 cc capacity. Similarly for 4-wheelar average is considered between petrol, diesel and CNG driven vehicles. The average emission factors are shown in table II.

Calculation of dispersion of CO by Operational Street Pollution Model (OSPM)

The ground level concentration of pollutant established using OSPM as a sum of direct contribution (C_d), recirculation contribution (C_{rec}) and the background contribution (C_b) as shown below:

$$C = C_d + C_{rec} + C_b$$

Step 1: Calculation of direct contribution C_d

The direct contribution at any receptor point at the ground level is calculated as a sum total of discrete contribution due individual source of emission and is expressed as:

where Q_i is the emission strength from the vehicles of the ith traffic lane in g/ms, x_i is the corresponding horizontal distance from the source to the receptor in m, σ_w is the mechanical turbulence created by wind and traffic in the street in m/s, u_b is the wind speed at the street level in m/s,

h_0 is the initial dispersion in the wakes of the vehicles assumed as approximately equal to 2m. Thus in order to obtain the direct contribution at any receptor point in the ground level located at a horizontal distance x_i from the source of strength Q_i, it is required to estimate the following:

(i) Calculation of emission strength, Q_i

Q_i= (No. of vehicles/sec)×(emssion factor in g/m)

The calculation is carried with the assumption is that there is a single lane along the center of the street.

ii) Calculation of street level wind speed, u_b

$$u_b = u_t \frac{\ln(h_0 / z_0)}{\ln(H / z_0)}[1 - 0.2.p.\sin(\Phi)]$$

where u_t = 0.817 m/s, h_0 = 2m, H = 15m, p = 1, $\Phi = 50^0$ (wind angle with respect to street axis), Z_0 = 0.60m

(iii) Calculation of mechanical turbulence, σ_w

$$\sigma_w = \left[(\alpha u_b)^2 + \sigma_{w0}^2\right]^{1/2}$$

$$C_d = \sqrt{\frac{2}{\pi}}\frac{1}{u_b}\sum_i \frac{Q_i}{\left[h_0 + \left(\sigma_w / u_b\right)x_i\right]}$$

where $\alpha = 0.1$, u_b = 0.258 m/s, σ_{w0} = traffic induced turbulence and is given by

$$\sigma_{w0} = b\left(\frac{N_{veh}.V.S^2}{W}\right)^{1/2}$$

where b = 0.3,

S^2 = horizontal area occupied by a single vehicle
= 1.08 (2-Wheeler) [6]
= 3.64 (3-Wheeler) [6]
= 6.40 (4-Wheeler) [6]

(iv) Calculation of direct contribution, C_d

$$C_d = \sqrt{\frac{2}{\pi}}\frac{1}{u_b}\sum_i \frac{Q_i}{\left[h_0 + \left(\sigma_w / u_b\right)x_i\right]}$$

Thus the direct contribution is an inversely proportional to the distance of the source from the receptor.

Step 2: Calculation of recirculation contribution (C_{rec})

$$C_{rec} = \frac{Q.L_{rec}}{W\left(\sigma_{wt}L_t + u_t L_{s1} + u_b L_{s2}\right)}$$

Here Canyon ventilation, $\sigma_{wt} = \left[(\lambda u_t)^2 + 0.4\sigma_{w0}^2\right]^{1/2}$;

$L_{rec} = \min\left(W, L_{vortex}.\sin(\Phi)\right)$ and L_{vortex} is taken equal to twice the height of the upwind building for u_t = 2 m/s. For u_t < 2 m/s, a linear decrease in L_{vortex} is observed.

Table I: Vehicular traffic flow for different types of vehicles

TIME (pm) / VEHICLE TYPE	2 WHEELER	3 WHEELER	4 WHEELER
06:05-06:10	287	154	24
06:10-06:15	348	194	18
06:15-06:20	335	141	29
06:20-06:25	317	202	20
06:25-06:30	319	198	27
06:30-06:35	293	204	36
06:35-06:40	303	197	27
06:40-06:45	329	207	21
06:45-06:50	315	205	15
06:50-06:55	274	187	24
06:55-07:00	342	209	19

07:00-07:05	322	199	14
07:05-07:10	307	215	23
TOTAL	4091	2512	297

Table II: Emissions factor for CO [5]

Type of vehicle	Total nos. of vehicle/hr	Emission factor[g/km]
2 wheeler	4091	1.205
3 wheeler	**2512**	**2.92**
4 wheeler	297	1.12

Length of recirculation zone, L_{rec} is taken as either equal to street width W or length of the vortex L_{vortex} whichever is smaller. When L_{vortex} > W and for an oblique wind angle, L_{rec} as shown in fig. 4 is given as $L_{rec} = \min(W, L_{vortex}.Sin(\Phi))$.

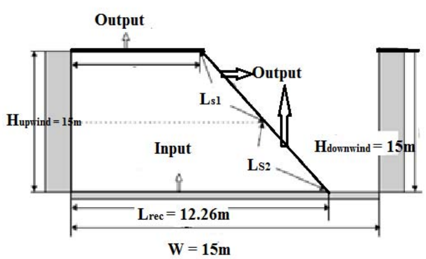

Fig. 4: Concept of top edge and slanting edge for escape of pollutant

The total concentration is made up of direct and the recirculation contributions. However, for a receptor on the leeward side, the direct contribution is calculated considering the emissions from traffic in the recirculation zone only. For a receptor on the windward side, only contributions from the emissions outside the recirculation zone are taken into account. If the recirculation zone extends through the whole canyon, no direct contribution s given for the receptor on the windward side. Thus the total concentration for the receptor on the leeward side is given as: $C_{Lee} = C_d + C_{rec}$

Since there is no source outside the recirculation zone in the present case, a receptor on windward side will only be influenced by the recirculation contribution.

The difference between the leeward and windward concentration is less in this case because the wind speed is very low which resembles the case of calm wind flow in the canyon. Only when the wind speed is more that 2m/s, there can be reasonable influence of wind. Thus a parametric variation of wind velocity is considered. The wind velocity is varied as 2m/s, 4m/s and 8m/s and the above calculations are repeated. Also the influences of wind angle for all these speed are calculated. The wind angle is varied from 0^0 (parallel to street axis) to 90^0 (perpendicular to street axis). These calculations are discussed below:

V PARAMETRIC INVESTIGATIONS

.

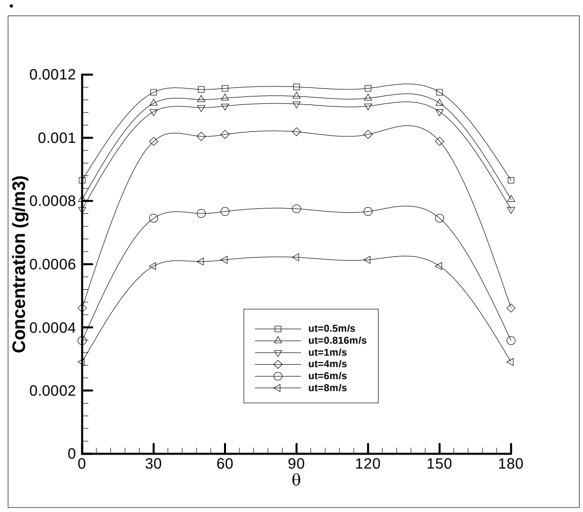

Fig. 5 Variation of leeward end ground level concentration as a function of wind angle and wind speed.

Fig. 5 shows the variation of leeward end ground level concentration as a function of wind angle and wind speed. It can be observed that the leeward concentration decreases with increase in wind speed. This is because of the increase in recirculation vortex with wind speed which results in more ventilation of pollutant from the roof top level. The influence of wind angle is significant at lower wind angles. When the wind flow is parallel to the street axis the contribution to windward and leeward side is same and is equal to the direct contribution due to the plume.

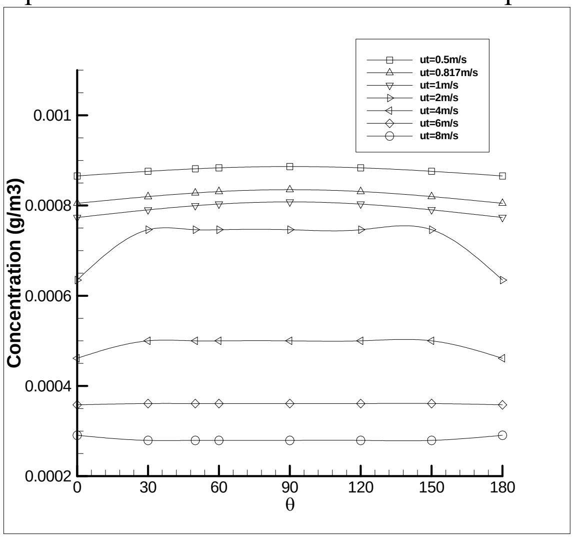

Fig. 6 Variation of windward end ground level concentration as a function of wind angle and wind speed.

Fig. 6 shows the variation of windward end ground level concentration as a function of wind angle and wind speed. For the windward side the direct contribution starts becoming important for wind speed less than 1m/s. For still lower wind speed the street vortex disappears and the wind direction dependence disappears too. Thus at vanishing ambient wind the concentration levels are solely determined by the traffic created turbulence. For higher wind speed the windward side concentration is due to recirculation component only.

VI CFD SIMULATION OF STREET CANYON

Two-dimensional simulations for flow inside the street canyon are developed by solving the Reynolds averaged Navier-Stokes (RANS) [7] equations with two equation k-ε model for turbulence being used as closure. The RANS equations are derived by Reynolds decomposition where the instantaneous flow variables are represented as sum of the mean value and the perturbations. The underlying assumption in the derivation of RANS equations are that the perturbation is velocity components do not significantly alter the average mass flow rate while the momentum equations are modified with extra stress terms called the Reynolds stresses. The Reynolds stresses in terms are represented in terms of eddy viscosity and gradient of mean velocity based on Boussinesq approximation. In k-ε model the eddy viscosity is obtained by solving the conservation equations of turbulent kinetic energy (k) and rate of decay of turbulent kinetic energy (ε) also called the eddy dissipation rate. The geometry of the canyon is generated in GAMBIT and is messed with structured rectangular grid structure. The mesh is then imported in FLUENT where the viscous model with standard k-ε option is enabled to solve the RANS equations. The convergence criteria for the mass, momentum, k and ε equations are kept as low as 10^{-5}. The pressure-velocity decoupling is solved using SIMPLE (Semi-Implicit Pressure Linked Equations) algorithm with first order upwind scheme being used for discretisation of advection terms. The results of simulations obtained for different wind speed at roof top level and different aspect ratio of the canyon are discussed here.

One of the most important feature of OSPM is the calculation of the recirculation component of the pollutant concentration. The calculation of the re-circulating component is based on the proposed length of the vortex in the street. The simplified linear approximation proposed in OSPM model may not be true. Also the OSPM model proposes that there is a single vortex responsible for recirculation in the street canyon for wind speed more than 2 m/s. However CFD simulations shows multiple vortices in the street particularly for deep streets with larger depth compared to the width of the canyon. Fig. 7 shows the vortex structure in street canyons for same aspect ratio for the three different wind speeds to highlight this feature.

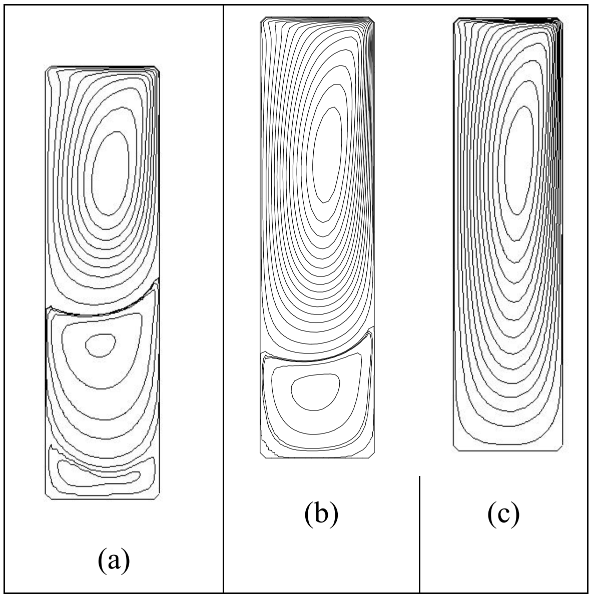

Fig 7 Vortex pattern in the street canyon for AR=0.25 and wind speed (a) 0.5 m/s (b) 1 m/s (c) 2 m/s

The other issue which needs to be addressed is the concept of vortex length for AR=1 as is demonstrated in Fig 8 It can be observed that the primary vortex occupies the entire street canyon even at wind velocities much lower than 2 m/s. However the OSPM predicts that the street will be completely occupied with the primary vortex only for wind speed above 2 m/s. and the length of the vortex as linearly decreases with the wind speed for values less than 2m/s. Accordingly the direct and recalculating components of pollutant distribution are calculated on the leeward and windward side. However if the CFD simulations are to be believed the windward side also receives the recirculating component of pollutant at much lower speeds than 2m/s.

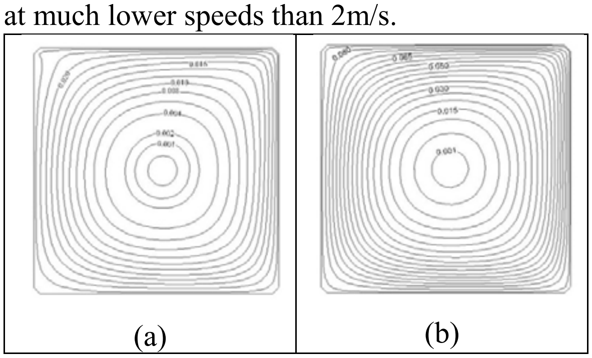

Fig 8 Vortex pattern in the street canyon for AR=1 and (a) wind speed =0.5 m/s (b) wind speed =2 m/s

Two dimensional CFD simulations of vehicular dispersion in street canyon

The multiphase model of FLUENT is enabled to generate the distribution of Carbon monoxide (CO) released from the vehicles in the street. The simulations shown in fig 9 are for AR=1 and wind speeds of 0.5 m/s and 1 m/s respectively. The volume fraction here represents the volume of CO per unit volume of air. It can be observed in both fig 9 (a) and (b) that the fluid current re-circulates the CO from the street level to the leeward wall and a part of this is flushed out from the rooftop level. A portion of this re-circulated concentration accumulates in the windward side as well. As the wind speed increases the amount of CO flushed out or ventilated from rooftop also increases thereby the deposition of the ground level concentration at both the leeward and windward level decreases.

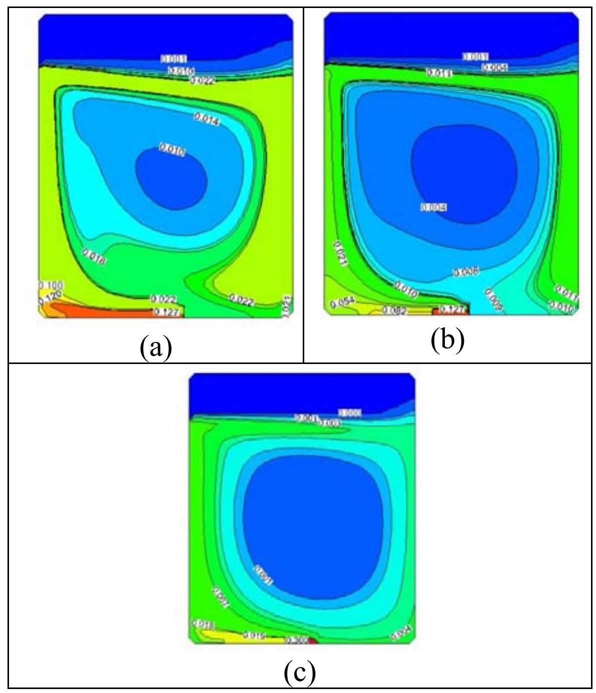

Fig. 9 Volume fraction distribution of CO in the street canyon for AR=1 and wind speed (a) 0.5 m/s (b) 1 m/s and (c) 2 m/s

Table III. Comparison of the ground level concentration predicted by CFD simulations with the OSPM calculations

Wind speed (m/s)	Leeward concentration obtained by OSPM	Leeward concentration obtained by CFD	Windward concentration obtained by OSPM	Windward concentration obtained by CFD
0.5	0.00122	0.001156	0.0002748	0.000421
0.817	0.00113	0.001101	0.0002963	0.000312
2	0.00143	0.001010	0.0007462	0.000674
4	0.00101	0.000912	0.0005000	0.0005612
6	0.00077	0.000662	0.0003610	0.0002814
8	0.00062	0.000521	0.0002793	

Table III shows the variation of ground level concentration at the leeward and windward end obtained by the OSPM and the CFD model for the street pollutant release conditions discussed in the previous chapter. It can be noted from the comparison that OSPM predicts larger deposition of concentration as compared to the results obtained by the CFD simulations. This is particularly true for higher wind speed. This is because the assumptions pertaining to OSPM allows reduced flush off from the roof top level as is calculated by the CFD simulations. Actually OSPM under predicts the strength of the recirculation vortex which is responsible for this flush out. The windward concentration predicted by the CFD model is slightly more than the OSPM calculation because of the re-circulating component which accumulated on the windward end for wind flow perpendicular to street axis.

REFERENCES

[1] Berkowicz R., OSPM-Aparametrised street pollution model, Environmental monitoring and assesment, 65, 323-331, 2000.

[2] CPCB, Status of the vehicular pollution control programme in India, New Delhi, March 2010.

[3] Yamartino R.J. and Wiegand G., Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon, Atmospheric Environment, 20(11):2137–2156, 1986.

[4] Berkowicz R., OSPM-Aparametrised street pollution model, Environmental monitoring and assesment, 65, 323-331, 2000.

[5] CPCB/ MOEF, Draft report on “Emission Factor development for Indian Vehicles ,“Project Rep No.: AFL/2006-07/IOCL/Emission Factor Project/Final Rep dt. August 17, 2007One

[6] Joshi G, Sinha V, Patel J, Heterogeneous Traffic Characterisation and Flow Behaviour Modeling for Metropolitan Arterial in India, Journal of the Eastern Asia Society for Transportation Studies,Vol.9,2011

[7] Ferziger H J and Peric M, Computational Methods for Fluid Dynamics, Springer-Verlag, Berlin, 2002.