WIND TUNNEL SIMULATION STUDY OF VEHICULAR EXHAUST DISPERSION

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ABSTRACT

Simulation experiments were carried out in the Environmental Wind Tunnel to understand the vertical spread of pollutants ($\sigma_z$) in simulated Atmospheric boundary layers. The vertical profiles of line source dispersion followed power law profile, the concentration of the tracer showed decreasing trend with increase in height above the tunnel floor and downwind distance. Twenty one hydrocarbon tracer experiments were performed to evaluate ($\sigma_z$) in simulated Atmospheric boundary layers corresponding to three different terrain roughness and approaching wind direction of 90°. It showed an increasing trend with the downwind distance. The observed values were compared with that of Rao and Keenan (1) field values. It is concluded that they were in same trend, but the observed values were higher than that of Rao and Keenan 1. This is due to fact that field experiments were done in low roughness conditions.

Key Words : Atmospheric boundary layer, Vertical dispersion, Simulation, Vehicular emissions, Environmental wind tunnel.

INTRODUCTION

Problem of atmospheric pollution in urban areas has highlighted the need for detailed investigation of atmospheric flow and dispersion of contaminants in the vicinity of buildings. Examination of flow and dispersion in the wake of isolated obstacles is very useful in identifying the effect of a building or any other construction on the behavior of plumes released in their vicinity. However, in real situations occurring in urban areas there is a complex interaction between plumes of pollutants and groups of buildings and other obstacles.

Conducting outdoor dispersion and meteorological field trials, both in large-scale idealized arrays, and even more so in real urban areas, is very costly, and a great challenge in terms of logistics and permitting. However, a greater diversity and quality of datasets is still required to serve as guidance in the development of more complex, physics-based models or urban dispersion, as well as in their validation.

A number of experimental studies of dispersion in large groups of regular obstacles have appeared in the past decade in the literature. Of particular relevance for the present study are the works by Davidson et al.4,5 and Macdonals et al.6,7. Davidson et al.5 compared some small-scale field investigations...
reported in Macdonald et al.\(^6\) with wind-tunnel simulations at a range of scales (1:20 and 1:200), with quantitative measurements only being undertaken in a staggered array of cubical obstacles. A range of mean and concentration fluctuation statistics were compared to ‘control plumes’, measured at the same site in the absence of obstacles. In a similar fashion, Macdonald et al.\(^7\) compared wind-tunnel simulations of a field experiment Macdonald et al.\(^6\) involving cubical obstacles, this time for a greater range of plan area densities, and larger obstacle arrays. Attention remained focused on mean concentrations and associated dispersion parameters in these investigations, although Macdonald et al.\(^7\) expanded the study to consider a range of wider obstacles \((W/H>1)\) with \(W\) the cross-stream obstacle width and \(H\) the obstacle height), similar to the array studies in the feature. In contrast to feature investigations, it is also worth noting that these previous studies mainly considered source positions upwind of the first row of obstacles (with the exception of Macdonald et al.\(^7\) which can influence the initial plume development differently.

**OBJECTIVES**

The main aim of this paper is to experimentally investigate the vehicular emissions (which are treated as line source) dispersion phenomenon in different simulated terrain conditions, to understand the dispersion pattern in different urban terrain conditions and to evaluate vertical dispersion parameter \((\sigma_z)\).

**MATERIAL AND METHODS**

**Experimental Setup**

Experiments have been carried out in an open circuit, low speed and suction type Environmental Wind Tunnel (EWT). The layout of the EWT facility meant for air pollution dispersion studies has been shown in Fig. 1. The overall length of EWT is 19.7 m, out of which 12 m length is the test section, with cross-section of 1.2 m \(\times\) 1.2 m. The height of the bottom surface of the test section is 145 cm above the general ground level. The EWT has been presently housed in a built up shed.

**Simulation of ABL Flow**

Artificially thickened Atmospheric boundary layers (ABLs) have been produced in the EWT by the combination of the passive devices such as Counihan’s spires, tripping barrier and roughness blocks on the wind tunnel.

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**Fig. 1**: Layout of Environmental Wind Tunnel.
floor. Three number of elliptic vortex generators (Counihan spires) of 940 mm height were placed symmetrically at the entrance of the test section of EWT. In addition, the entire floor of the EWT was covered with roughness elements of $23 \times 23 \times 23$ mm with a spacing of 70 mm. Further, a tripping barrier of 300 mm high was placed after the Counihan spires at 1.25 m from the Counihan spires. The design of cubical blocks has been carried out as per Counihan\(^8\), Gartshore De Cross\(^9\) and Gowda\(^10\).

**Mean Velocity Profile**

For the three cases of passive device arrangements in the EWT mentioned above, longitudinal (i.e., stream wise) mean velocities have been recorded at selected height above the tunnel floor by traversing single wire probe of hot-wire anemometer (HWA). The velocity recordings have been taken at 7.9 m from the entrance to the test section (i.e., at the turn table). The availability of personal computer (Pentium-IV) in the laboratory facilitated the digital recording of the measured data. The PC is equipped with data acquisition software (8-channel). The observed mean velocity profile in the simulated ABL is represented by the power-law given as below:

$$\frac{u}{U_\infty} = \left(\frac{Z}{\delta}\right)^\alpha$$

![Graphs showing mean velocity profile for simulated ABLs](image)

**Fig. 2:** Mean Velocity Profile for the Simulated ABLs

It can be observed that the observed mean longitudinal velocities were found to be in good agreement with the best fit curves. The power law index ($\alpha$) was found to be 0.3, 0.35 and 0.6 for the three simulated ABLs. These values are typically in the range quoted by Snyder\(^{11}\), Davenport\(^{12}\) and Counihan\(^8\) for urban terrain categories. The boundary layer depth $\delta$ (i.e., the point where $U/U_\infty = 0.995$) was observed to be 400 mm, 900 mm and 940 mm for ABLs. Matching the boundary layer height simulated in the wind tunnel with the Atmospheric Boundary Layer height seems to be rather difficult exercise. Counihan\(^8\) and
Snyder\textsuperscript{11} reported that the depth of the adiabatic boundary layer $\delta$ as 600 m for both rural and urban terrain. Hence matching boundary layer depths shall yield different scale factors. Counihan's recommends $\delta$ of 600 m, the simulated ABL-I, ABL-II and ABL-III represent to a scale of about 1 : 1500, 1 : 670 and 1 : 640, the urban ABLs respectively. Davenport\textsuperscript{12} has reported boundary layer depth $\delta$ as 457 m corresponding to $\alpha$ values of 0.333 (towns, suburbs, outskirts of large cities) and 550 m corresponding to $\alpha$ values of 0.4 to 0.66 (centre of large cities) for urban terrain categories. The values suggested by Davenport for boundary layer depth, $\delta$ are slightly lower than that of Counihan's value of 600 m.

The mean wind velocities is the lowest 10 - 15 % of the ABL (termed as the surface/canopy layer) further analyzed. In this layer, a steep wind profile is observed (eq.2),

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z - d_0}{z_0} \right)$$ (2)

The three parameters $u_*$, $z_0$ and $d_0$ has been evaluated using the least square analysis, based on quality of fit of observed velocity profiles as recommended by Schaudt\textsuperscript{13}. The evaluation of these parameters has been carried out within the logarithmic height range. The roughness parameters evaluated for the simulated ABL have been given in Table 1. It can be observed from the table of values that, the roughness length, $z_0$ and displacement height, $d_0$ are increasing with the increased value of power-law index, $\alpha$ for all ABLs. However, the friction velocity, $u_*$ is nearly same for ABL-I and ABL-II and slightly higher for ABL-III. This may be due to presence of same roughness blocks on the wind tunnel floor. Since $u_*$ is more related to nature of surface irregularities. The slightly higher value for ABL-III can be attributed due to presence of 300 mm high tripping barrier type of passive roughness placed at the floor level. This offers more resistance at the floor level in addition to inducing turbulence.

<table>
<thead>
<tr>
<th>ABL</th>
<th>$u_*$ m/s</th>
<th>$d_0$ mm</th>
<th>$z_0$ mm</th>
<th>$u_*/U_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABL - I</td>
<td>0.229</td>
<td>1.38</td>
<td>0.287</td>
<td>0.059</td>
</tr>
<tr>
<td>ABL - II</td>
<td>0.213</td>
<td>1.438</td>
<td>0.790</td>
<td>0.0905</td>
</tr>
<tr>
<td>ABL - III</td>
<td>0.268</td>
<td>1.84</td>
<td>0.993</td>
<td>0.0607</td>
</tr>
</tbody>
</table>

Comparison of Roughness Parameters with full scale data
The full-scale values of $z_0$ and $d_0$ have been compared with the recommended values of Environmental Protection Agency (EPA) and ESDU : 85020 values using scaling ratio based on Counihan's value of $\delta$ as 600 m and tabulated in Table 2. The value of $z_0$ representing outskirts of towns suburbs, centers of towns and centers of large cities for three simulated ABLs respectively. The values of $d_0$ suggested by ESDU are comparable with the values obtained for the simulated ABLs.

Turbulence Profile
The fluctuating velocities of longitudinal component were recorded at selected heights
Table 2: Comparison of Roughness Parameters with Recommended Values of EPA and ESDU

<table>
<thead>
<tr>
<th>Present Study</th>
<th>EPA Recommended Values</th>
<th>ESDU : 85020 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABL-1</td>
<td>0.430</td>
<td>2.07</td>
</tr>
<tr>
<td>ABL-II</td>
<td>0.529</td>
<td>0.963</td>
</tr>
<tr>
<td>ABL-III</td>
<td>0.636</td>
<td>1.177</td>
</tr>
</tbody>
</table>

above the tunnel floor. All the recordings were done by employing hot-wire anemometer using the single wire probe. From this data the intensities of longitudinal component of turbulence have been obtained from the digitised signal of the hot-wire anemometer. The variation of longitudinal component of turbulence with normalised height has been shown for three simulated terrain categories in Fig. 3.

The present data of the longitudinal component of turbulence has been compared with that reported by Snyder.  

Fig. 3: Longitudinal Component of Turbulence profile.
Tracer Gas sampling and Analysis

The schematic of tracer gas dispersion experimental set-up used for the present study has been shown in Fig. 4. The hydrocarbon tracer gas used was a mixture and it consisted of 5% Acetylene (C$_2$H$_2$) in grade-I Nitrogen. This tracer was obtained by mixing pre-calculated flow rate of laboratory grade 95.5% Acetylene and grade-I Nitrogen (99.9%) in to the mixing unit. After the mixer unit, the tracer gas mixture was fed to common multiple outlet container. From this container using two separate equal lengths (500 mm) and diameter (3 mm) connecting tubes, tracer gas was fed to two inlet ports of the line source system. The flow rate was maintained at 1 LPM to ensure a low discharge velocity at the tips of 1 mm diameter tubing of the line source.

![Fig. 4: Schematic View of Line Source Dispersion Experiment in the EWT](image)

For sampling of tracer gas at each desired locations was made by positioning five sampling probes which have been fixed on a 2D traverse mechanism. At each location, the lower probe tip was maintained at the tunnel floor. The sampling probes were made out of copper material and were connected by Poly Tetra Fluoro Ethylene (PTFE) tubing’s to suction pump of low flow rate (0-5 LPM) placed outside the EWT. At each sampling location the tracer samples were collected for a pre-selected time of 1 minute. The samples were collected from PTFE tubing was analyzed on-line by using gas chromatograph (GC) with flame ionization detector (FID). The GC was frequently calibrated using laboratory grade tracer gas (Acetylene) of known concentrations during course of tracer experiments.

RESULTS AND DISCUSSION

Experimental results describing the behaviour of vertical dispersion parameter simulated in different ABLs are discussed below:

Evaluation of vertical dispersion parameter

In order to find the dispersion profiles in vertical and downwind distance, twenty one experiments were conducted in the three simulated ABLs. For each simulated ABL,
seven experiments were conducted to measure vertical concentration profile distribution at downwind distances of 8 cm, 90 cm, 100 cm, 130 cm, 210 cm, 226 cm and 244 cm from simulated line source. The tracer experiments were done in each ABL for 90° orientation of wind in the present study.

Vertical mean concentration profiles have been measured at different downwind distances of a line source placed on the turntable. The vertical dispersion were drawn between normalised concentrations and height above tunnel floor (i.e. above roughness blocks) for simulated three ABLs. The concentration profiles are taken up to 80% of the boundary layer depth. The dispersions showed that with increase in height the concentration is decreasing. A best curve is fitted by drawing power law profile. The power law exponent showed a negative values (–2 to –3.5) indicating that with increase in height the concentration of the tracer decreased. The R-squared value is in the range of 0.9 to 0.98 for power law profile, fitting to the vertical concentration profiles for the simulated three ABLs.

As shown in Fig. 5 after certain height above ground level the dispersion profile in nearly linear this is due to the maximum pollutant has dispersed at the ground level and a small amount of pollutant is dispersed at certain level. This may be due to the fact that turbulence level is higher near to the ground level. Thus urban roughness conditions play vital role in dispersion near the ground or in the lower ABL. The power law exponents gradually decreased with increase in height. The R-squared value showed that power law profile is best fitted for the observed experimental values. The power law exponent showed a negative value showing that with increasing downwind distance from the source the tracer concentration is decreasing.

![Graph showing variation of σz in Downwind Distance for Simulated ABLs](image)

Fig. 5: Variation of σz in Downwind Distance for Simulated ABLs
Comparison of $\sigma_z$ Variation for different terrains

The experimental values of $\sigma_z$ obtained have been compared with field experimental data as reported by Rao and Keenan\(^1\). They were shown in Fig. 6. They were best fitted with power law profiles. The R-squared values for these profiles are above 0.96 it shows that they follow power law profile. The power law exponent values are positive it shows that with increase in the downwind distance from the line source the vertical dispersion parameter ($\sigma_z$) also increases. In comparison to field values reported by Rao and Keenan\(^1\) the experimentally observed values are above the field values. This may be due to different roughness conditions simulated from that of field roughness. The $\sigma_z$ field values reported by Rao and Keenan\(^1\) are for open terrain conditions having low roughness. However, the present $\sigma_z$ profile follows the same trend as that reported for filed values. Thus it can be concluded that present $\sigma_z$ values evaluated by simulation experiments are valid for field situations having different roughness conditions.

![Fig. 6 : Comparison of Experimental $\sigma_z$ values with the Field Values for ABLs](image)

CONCLUSIONS

Three ABLs are simulated with power law index of 0.3, 0.34 and 0.6, they are typically in the range of urban terrain categories to understand the vertical spread of pollutants ($\sigma_z$). The vertical profiles of line source dispersion followed power law profile, the concentration of the tracer showed decreasing trend with increase in height above the tunnel floor and downwind distance in corresponding to three different terrain roughness and approaching wind direction of 90°. The observed values were compared with that of Rao and Keenan\(^1\) it is concluded that they were in same trend, but the observed values were higher than that of Rao and Keenan\(^1\). This is
due to fact that field experiments were done in low roughness conditions. The above discussions revealed that the simulation experiments in EWT can be carried out for investigating dispersion phenomenon from line source for wide range of realistic situations prevailing in urban areas.

REFERENCES