IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)
e-ISSN: 2319-2402,p- ISSN: 2319-2399.Volume 10, Issue 7 Ver. III (July 2016), PP 10-16
www.iosrjournals.org

A Wind Tunnel Study on Concentration Variation for Single Storied Staggered Array Configuration with Downwind Distance

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Abstract: *Physical modeling dispersion experiments were carriedout under simulated Atmospheric Boundary Layers, which represents the center of large city, in the near-field of roadway in the Environmental Wind Tunnel for single storied buildings model arrangement. Experiments were carried out for a geometric model scale of 1:100, which represents a real building's height of 3.5 m ie single storied buildings. Staggered array buildings model configurations were adopted, and the results have been discussed. The particular effect of obstacle width-to - height ratio (S/H) was examined for a fixed obstacle plan area density. Normalized concentration variation has been plotted at selected downwind distances of 119H, 179H, 238H, 298H and 357H from the centre of the line source for selected lateral widths of Y=8H, Y=16H and Y=24H. The normalized concentration variation profile C/C_0 versus selected downwind distances X/H for the single storied buildings model of staggered array configuration was plotted. It is evident that downwind tracer concentration is maximum near the line source (at X=119H) and concentration decreases as downwind distances increase (at X=357H). Also, it was clear that downwind concentration decreases with downwind distance.*

Keywords: *Atmospheric Boundary Layers, Vehicular emission dispersion, Array of building Obstacles, Downwind distances, and Wind tunnel study.*

I. Introduction

Plume dispersion in the urban environment is quite complex and involves the details of the interaction of the plume and the flow field with several obstacles. This type problem is not generally solvable by computational means and thus physical modeling is the best way to obtain sensible results and to study the influence of the various parameters relevant to the problem. While using any line source model for prediction of pollutants in any urban/suburban area, it is imperative that the model should be capable of accounting for building effects. There is greater scope to understand systematically the influences of important varying parameters on dispersion mechanisms through arrays of obstacles. For the study of these types of local parametric influences, a boundary layer wind tunnel is a convenient tool to investigate the effects of these potential parameters.

The dispersion is dependent on various source parameters and surface layer micro-meteorological parameters such as wind speed, wind direction, roughness conditions etc. In addition, the influence of the nearby buildings and other structures of varying terrain categories cause further complexity in the dispersion phenomenon. Hosker (1984), Hunt (1975) and Meroney (1995) have discussed the complex diffusion mechanisms in the wake of building arrays. Until fairly recently the literature on this topic has been quite sparse; for example the review by Hosker (1984) was mainly concern with flow and dispersion around individual or small groups of obstacles, with only handful of relevant field and wind tunnel experiments have appeared.

Meroney (1995) and Hosker (1984) provided excellent reviews on the main characteristics of flow and dispersion around single or small groups of obstacles. Several experiments have been carried out in model and real urban canopies and wind tunnel using tracer gases. Davidson et al. [1995], Theurer et al. (1996), and Macdonald et al. (1998) investigated diffusion around a building in field experiment in suburban area in Sapporo. They found that high concentrations were observed both upwind and downwind of the source on the roof. Macdonald et al. (1998) confirmed that at short distances from the source, concentration profiles in the obstacle arrays are quite variable. Mavroidis and Griffiths (1996) examined the flow and dispersion through arrays of obstacles. The results suggested that enhanced mixing and dispersion occur within array. Recently, dispersion of atmospheric pollutants in the vicinity of isolated obstacles of different shape and orientation with respect to the mean wind direction has been examined in scaled field and wind tunnel experiments. It has been found that the presence of taller obstacles results in a reduction of ground level concentrations. It is now widely acknowledged that the greatest damage to human health is caused in the near- field of toxic releases from line sources within the urban region. Complex flows around the obstacles in urban canopy pose difficult challenges to research. Thus, it is essential to address these challenges and develop methods to model the impact of contaminants at short distance from the source within urban region. The main aim of the present paper is to investigate experimentally, the vehicular emission (which are treated as line source) dispersion phenomenon in simulated terrain conditions. And to understand the normalized concentration variation at selected downwind distances from the center of the line source for selected lateral widths through single storied staggered array building model configurations in the near- field of roadway.

II. Experimental Setup

2.1. Simulation of ABL Flow

Artificially thickened Atmospheric Boundary Layers (ABLs) have been produced in the Environmental Wind Tunnel (EWT) by the combination of the passive devices such as Counihan's spires, tripping barrier and roughness blocks on the wind tunnel floor. The entire floor of the EWT was covered with roughness elements of 23 x 23 x 23 mm with a spacing of 70 mm (ABL-I). Three number of elliptic vortex generators (Counihan spires) of 940 mm height were placed symmetrically at the entrance of the test section of EWT with roughness elements (ABL-II). Further, a tripping barrier of 300 mm high was placed after the Counihan spires at 1.25 m from the Counihan spires with roughness elements (ABL-III). The design of cubical blocks has been carried out as per Counihan (1969), Gartshore and De Cross (1977) Gowda (1999).

2.2. Details of physical modelling dispersion experiments

In the present study a near-field terrain buildings model arrangements have been selected. The set of experiments were carried for a geometric model scale of 1:100, which represent a real buildings height of 3.5 m (single storied buildings). For this study staggered buildings model configuration were selected. Physical modelling dispersion experiments were carried out one of the simulated ABL-III which represent centre of large city in the near field of roadway in the EWT. Measurements were taken to obtain vertical tracer gas concentration profiles for single storied building at pre-selected downwind distances of 119H, 179H, 238H, 298H and 357H from centre of the line source as per the scheme shown in Fig. 1. These measurements were observed at selected vertical height of (Z) 2.9H, 5.7H and 8.6H for single storied buildings model for selected lateral width of tunnel from the tunnel floor. For this tracer experiments were carried out for 90^{o}. Lateral concentration measurements (along width of the test section) for pre selected lateral width of 8H, 16H, and 24H for single storied buildings model for all the downwind distances on either sides of the centreline. Further repeatability checks were carried out for all the experimental observations.

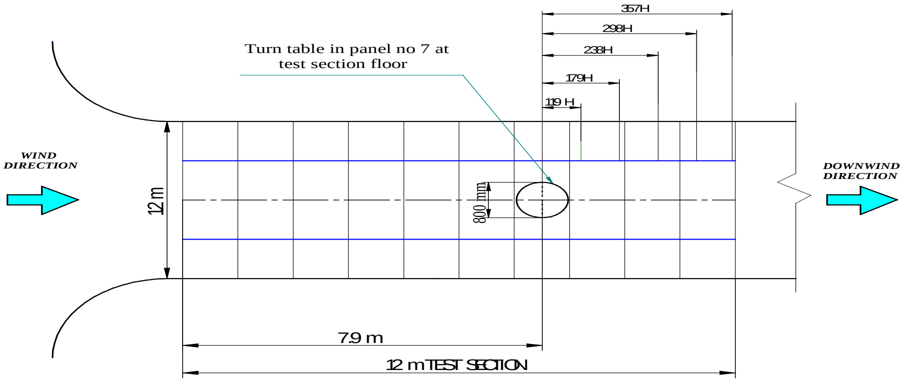


Figure 1: Schematic showing downwind distances for tracer gas concentration measurement in the E WT

2.3. Experimental configuration in the wind tunnel

For the present study, buildings model made of wood cubical in shape had been arranged on the floor of the tunnel from line source to entire downwind section of the tunnel. The buildings model had been arranged downwind direction of the line source such that the row of buildings was at 35 mm (1H) for single storied buildings. This arrangement ensured that the line source was located in amidst of the buildings model.

Macdonald et al. (1997) characterised the buildings arrangement for arrays of cubical elements by plan area density, λ_{ar}. For regular arrays of cubic elements, the plan area density λ_{ar} is related to the gaps between cubes S and their height H by (eq 1)

$$\lambda_{ar} = \frac{1}{\left(1 + S/H\right)^{2}} . \qquad (1)$$

Where, S= Space between two consecutive array element

Based on plan area density different flow regimes have been defined for arrayed cubical blocks arrangement. The characteristics of these main flow regimes are presented in Table.1. The present studies have been conducted an isolated roughness flow regime for single storied buildings for the plan area density as per the Table 2.

Table. 1. Characteristic of the flow regime (Macdonald et al. [1997])

Flow regime	**Array spacing**	**Plan Area density (%)**
Isolated Roughness flow	S/H>2.0-2.5	λ<8-11
Wake Interference Flow	1.0-1.5<S/H<2.0-2.5	8-11< λ <16-25
Skimming Flow	S/H<1.0-1.5	16-25< λ

Table. 2. Characteristic of the flow regime for single storied buildings model

Sl. No.	**Average building height in (m)**	**Scale**	**S/H (S/H>2.0-2.5)**	**□ar (%) (□ar<8-11)**	**Width**	**Prototype cubical model H(mm)**
1	3.5	1:100	2.40	8.5	W=2H	35

In single storied buildings, cubical model having height (H) 35 mm with spacing (S) 85 mm between elements the plan area density was found to be 8.5 % (or S/H = 2.4). As per the flow regime suggested by Macdonald (1997) in Table 2, the Prototype cubical models used for the experiment are made of wood at a geometric model scale of 1:100, which represent a real buildings height of 3.5 m. Dimensions of the models are 35 mm (L) x 35 mm (W) x 35 mm (H). The size of staggered array configuration was 8 x 10 arrays. Fig 2 shows plan view of experimental buildings arrangement in staggered array for single storied.

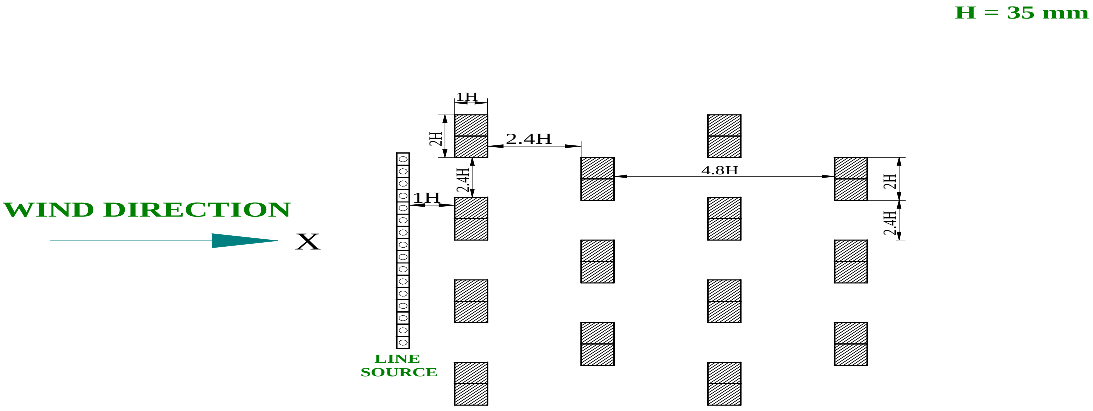


Figure 2: Plan view of experimental buildings model staggered array arrangement for single storied

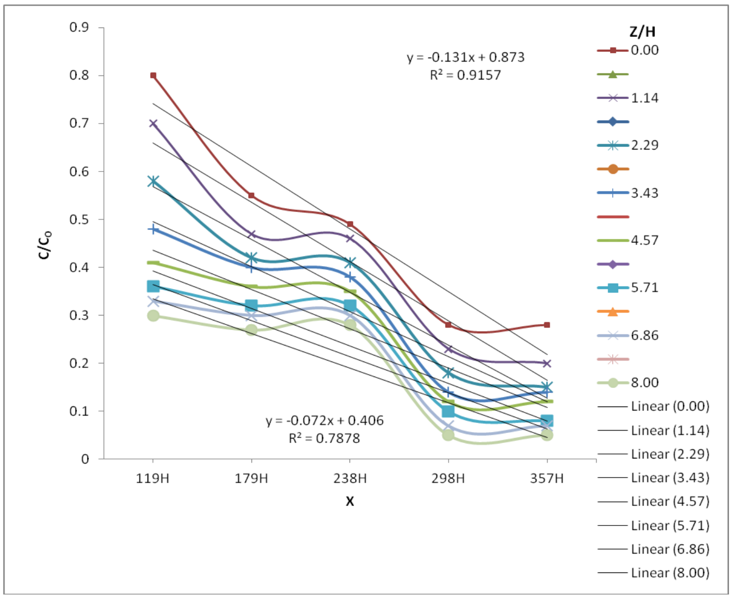
III. Results And .Discussions

3.1Concentration variation with downwind distance for single storied staggered array configuration

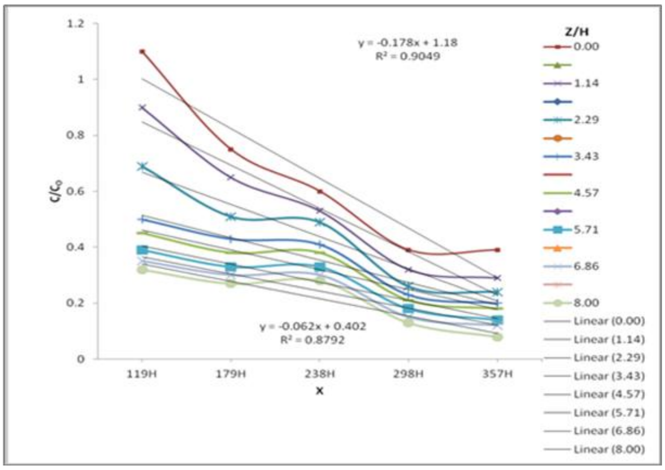
Normalized concentration variation has been plotted at selected downwind distances of 119*H*, 179*H*, 238*H*, 298*H* and 357*H* from the center of the line source for selected lateral widths of *Y*=8*H*, *Y*=16*H* and *Y*=24*H* for the single storied buildings model of staggered array configurations as per the scheme shown in Fig. 1. Figs. 3 depict the normalized concentration variation profile C/C_0 versus selected downwind distances *X*/*H* for the single storied buildings model of staggered array configuration. From the figures, it is observed that tracer concentration is maximum near the line source (at *X*=119*H*) and concentration decreases as downwind distances increase (at *X*=357*H*). Also, it was clear from the figures (see trend line) that downwind concentration decreases with downwind distance. A similar tracer concentration trend was reported by Macdonald and Griffiths [1997] in their work.

Tables 3-5 present the normalized downwind concentration variation for selected downwind distance of single storied staggered array configuration at *Y*=8*H*, 16*H* and 24*H*. From the tables, it is revealed that (see Table 3), at a lateral width of *Y*=8*H*, percentage reduction of concentration observed between 119*H* and 357*H* near the tunnel floor is 53.3% and it is 57.5% at measured elevated height of the tunnel. From Table 4 , it can be seen that, at a lateral width of *Y*=16*H*, percentage reduction of concentration observed between 119*H* and 357*H* near the tunnel floor is 58.3% and it is 61.9% at measured elevated height of the tunnel. From Table 5, it can be observed that, at a lateral width of *Y*=24*H*, percentage reduction of concentration observed between 119*H* and 357*H* near the tunnel floor is 57.4% and it is 64.1% at measured elevated height of the tunnel. It is evident from the tables and figures that centerline concentration is relatively higher for the single storied buildings model of staggered array configuration at all the downwind distances. Thus, it can be concluded that tracer concentration is maximum near the line source, and it decreases with downwind distances similar to that observed for inline configuration *Krishna, and Gowda [2015]*, but quantitatively differs.

Y=8H



Y=16H



Y=24H

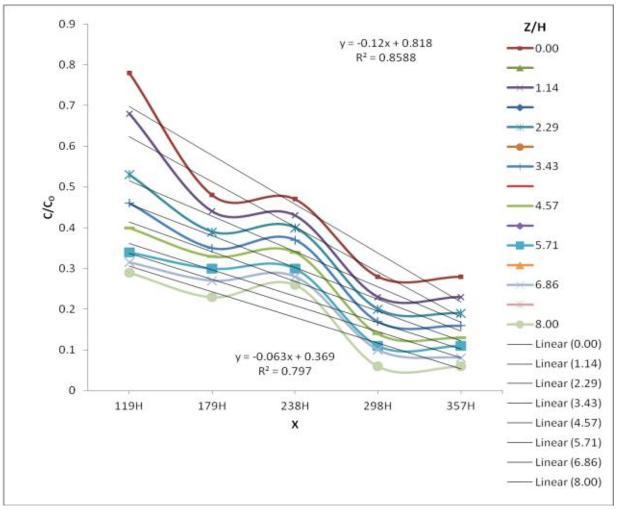


Fig. 3. Concentration variation at selected downwind distance for single storied staggered array configuration at different lateral width

Table.3. Normalized vertical concentration (C/C_0) variation at selected downwind distance for single storied staggered array configuration at Y=8H

Z*/*H	**Downwind distances**					**Percentage reduction between 119*H* and 357*H***
	X*=119*H	***X*=179*H***	***X*=238*H***	***X*=298*H***	***X*=357*H***	
0.00	0.90	0.65	0.59	0.49	0.42	53.3
0.57	0.85	0.58	0.57	0.45	0.39	54.1
1.14	0.80	0.57	0.56	0.44	0.37	53.7
1.71	0.70	0.55	0.54	0.42	0.32	54.3
2.28	0.68	0.52	0.51	0.43	0.33	51.0
2.85	0.62	0.51	0.50	0.40	0.30	51.6
3.43	0.58	0.50	0.48	0.38	0.28	51.7
4.00	0.55	0.47	0.46	0.35	0.25	54.5
4.57	0.51	0.46	0.45	0.34	0.24	52.9
5.14	0.48	0.44	0.43	0.31	0.22	54.1
5.71	0.46	0.42	0.42	0.31	0.21	54.3
6.82	0.44	0.41	0.41	0.30	0.20	54.5
6.86	0.43	0.40	0.40	0.26	0.16	62.7
7.42	0.42	0.38	0.39	0.28	0.18	57.6
8.00	0.40	0.37	0.38	0.26	0.17	57.5

Table.4 Normalized vertical concentration (C/C_0) variation at selected downwind distance for single storied staggered array configuration at Y=16H

Z*/*H	**Downwind distances**					**Percentage reduction between 119*H* and 357*H***
	X*=119*H	***X*=179*H***	***X*=238*H***	***X*=298*H***	***X*=357*H***	
0.00	1.20	0.85	0.80	0.60	0.50	58.3
0.57	1.10	0.80	0.64	0.56	0.46	58.1
1.14	1.00	0.75	0.63	0.58	0.48	52.0
1.71	0.89	0.65	0.62	0.52	0.42	52.8
2.28	0.79	0.61	0.59	0.47	0.37	53.1
2.85	0.68	0.55	0.55	0.45	0.35	48.5
3.43	0.60	0.53	0.52	0.42	0.32	46.0
4.00	0.59	0.50	0.50	0.40	0.30	49.1
4.57	0.55	0.48	0.48	0.38	0.28	49.1
5.14	0.51	0.45	0.46	0.36	0.26	49.0
5.71	0.49	0.43	0.43	0.33	0.22	55.1
6.82	0.47	0.42	0.41	0.32	0.21	55.3
6.86	0.45	0.40	0.40	0.30	0.20	55.5
7.42	0.43	0.39	0.39	0.28	0.18	58.1
8.00	0.42	0.37	0.38	0.26	0.16	61.9

Table.5 Normalized vertical concentration (C/C_0) variation at selected downwind distance for single storied staggered array configuration at Y=24H

Z*/*H	**Downwind distances**					**Percentage reduction between 119*H* and 357*H***
	X*=119*H	***X*=179*H***	***X*=238*H***	***X*=298*H***	***X*=357*H***	
0.00	0.87	0.58	0.57	0.47	0.37	57.4
0.57	0.83	0.56	0.55	0.45	0.35	57.8
1.14	0.78	0.54	0.53	0.43	0.33	57.6
1.71	0.71	0.53	0.52	0.42	0.30	57.7
2.28	0.63	0.49	0.50	0.41	0.29	53.9
2.85	0.60	0.47	0.48	0.39	0.27	55.0
3.43	0.56	0.45	0.47	0.38	0.25	55.3
4.00	0.52	0.44	0.45	0.36	0.26	50.0
4.57	0.50	0.43	0.44	0.35	0.23	54.0
5.14	0.46	0.42	0.42	0.33	0.21	54.3
5.71	0.44	0.40	0.40	0.30	0.20	54.5
6.82	0.42	0.39	0.39	0.29	0.19	54.7
6.86	0.41	0.37	0.38	0.27	0.17	59.0
7.42	0.40	0.35	0.37	0.26	0.16	60.0
8.00	0.39	0.33	0.36	0.25	0.14	64.1

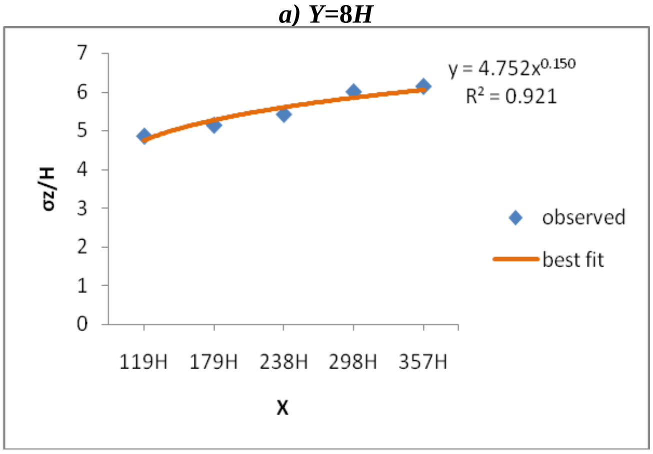
3.2Variation of vertical dispersion parameter (σ_z) with downwind distance

Experiments were carried out for evaluating σ_z at various downwind distances of 119*H*, 179*H*, 238*H*, 298*H* and 357*H* for selected lateral widths of *Y*=8*H*, *Y*=16*H* and *Y*=24*H* for the single storied buildings model from line tracer source. The σ_z values were obtained from the given observed concentration value after cubic spline interpolation of the data by the method of integration of the concentration and the height product.

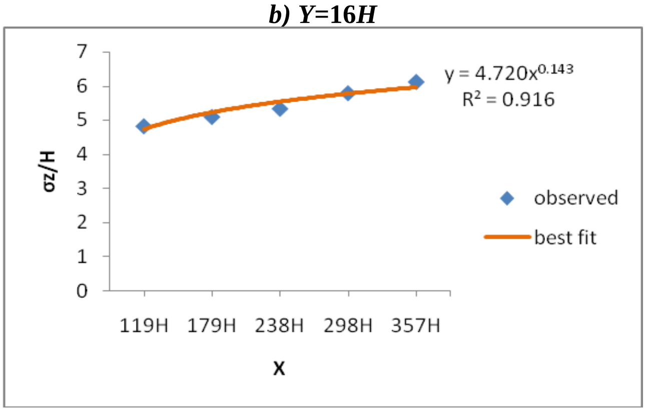
3.2.1Vertical dispersion parameter ($\square_z$) for single storied staggered array configuration

Fig.4.depict the vertical dispersion parameter for single storied staggered array configuration for selected downwind distances. Experimentally obtained $\sigma_{z/H}$ value was plotted against downwind distances (*X*). The power-law profile is best described the variation of σ_z with downwind distance. In all the three lateral widths for staggered array configuration, σ_z behaved in a similar trend. They showed an increasing trend with the downwind distances. They were best fitted with power-law profiles. *R*-squared values were in the range of 0.891–0.921 for staggered array configuration of the single storied buildings model

a) Y=8H



b) Y=16H



c) *Y=24H*

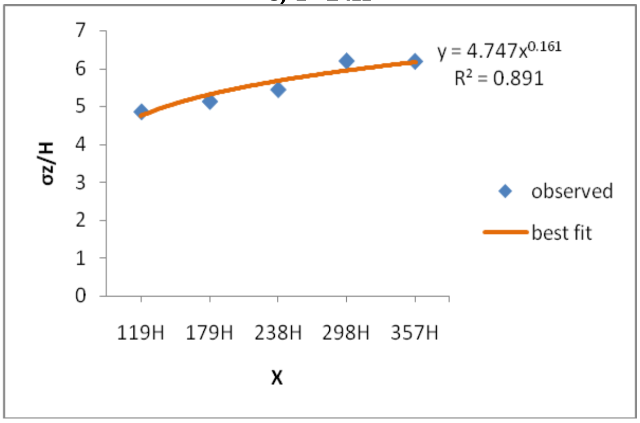


Fig. 4. Variation of σ_z with downwind distance for the staggered array single storied buildings model

IV. Conclusions

There were significant differences between non-dimensional concentrations measured in the downwind of the obstacles in staggered array. Even with quantitative differences, the staggered array configuration of single storied buildings model results showed the same general trend. Downwind tracer concentration maximum near to line source (at X=119H) and it decreases with downwind distances increases (at X=357H) for single storied buildings model of staggered array configuration. Also, it was clear that downwind concentration decreases with downwind distance. A similar tracer concentration trend was reported by Macdonald and Griffiths [1998] in their work. Vertical spread parameter (σ_z) for single storied buildings model of staggered array configuration behaved in more or less similar trend with quantitative difference between centreline and either side of centerline at lateral locations. Thus, it can be concluded that tracer concentration is maximum near the line source, and it decreases with downwind distances similar to that observed for inline configuration *Krishna, and Gowda [2015].*, but quantitatively differs.

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