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Micrometeorological and atmospheric diffusion studies at nuclear power station sites in India
Part II : Atmospheric diffusion studies

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ABSTRACT. The results of diffusion experiments, using smoke as a tracer, performed at Tarapur and Rajasthan, two of the nuclear power station sites in India are described in this (Part II) paper. The values of Sutton's diffusion coefficients C_y and C_z are related with easily measurable meteorological parameters like, stability parameter n, standard deviation of wind direction σ_θ etc. The measurements at Tarapur, a plain site on the sea coast, show regularity of variation of C_y and C_z with all such parameters. In particular, C_y and C_z are expressed in terms of n, which, though without sound physical basis, are useful for field applications. Such a regularity is not observed in Rajasthan site, which is uneven. The wind direction variability at this site is very high, with the result that in a 4-min time exposure photograph as many as three distinct plumes are obtained.

The graphs of σ_z *versus* travel distance obtained from Gifford's opacity method show very high rate of vertical diffusion even under stable conditions at Rajasthan.

1. Introduction

In connection with environmental radiation safety from nuclear power stations, a set of micrometeorological studies were conducted at Tarapur and Rajasthan Atomic Power Station sites. These experiments consisted of simultaneous measurements of wind and temperature profile, smoke diffusion runs and atmospheric turbulence characteristics. The analysis of wind profile have been reported in Part I of this paper. The purpose of the second part of the study reported here is to obtain workable diffusion parameters and to relate them to meteorological observables especially to Sutton's stability parameter n and wind direction fluctuation statistics, for future prediction purposes and routine applications.

2. Site description

The Tarapur site has been described in Part I of this paper (Shirvaikar *et al.* 1970) and will not be repeated here.

The Rajasthan site is located in a hilly terrain covered by sparse forest on the banks of the *Chambal* River about 50 km from the Kota City in Rajasthan State.

The meteorological station is equipped with a 24-m open-framed tower with platforms at every 3.3 m. Contact type Wilh Lambrecht anemometers with 1 km wind run contacts are mounted at 6 and 24-m levels. Potentiometric type wind vanes are also mounted at these levels. Air temperatures are measured at five heights using shielded bead-in-glass type thermistors. The air temperatures are recorded on a strip chart recorder. Wind directions are recorded continuously on 0-1 ma Esterline Angus recorders with a chart speed of 3″ per hour and wind run contacts by chronograph pens in the same recorders. All recorders are housed in a laboratory building 75 m away from the tower.

3. Experimental technique

(*a*) *Smoke Photography*—Smoke was generated by using Army Smoke Generators which on ignition emit dense white Smoke for about 15 minutes. Smoke release was made at ground level at Tarapur and at ground level as well as from 21-m platform on the tower at Rajasthan site. The ground level experiments at Rajasthan site are too few to draw any conclusion and are not reported here. It is well known that instantaneous plume photographs, because of the ragged edge are not amenable to analysis. It is necessary to either average over a large number of such photographs or take time exposure photographs

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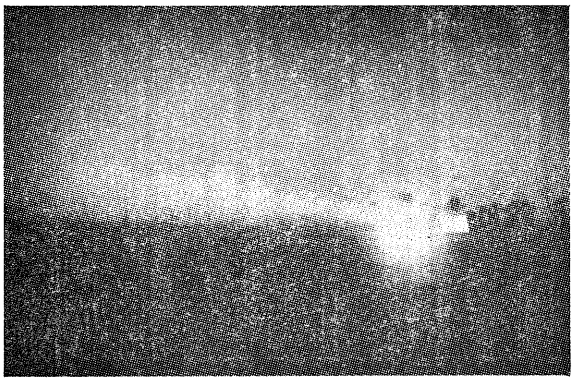

Fig. 1

with exposure periods long enough to average the ragged edge.

In these experiments time exposure (2·5 min or more) photographs were taken using neutral density filters for daytime runs. Night time experiments were done on moonlit nights. Here, the photographs were necessarily time exposure even without filter. An improvised filter made out of welding glass was used for most of the daytime exposure photographs taken at Tarapur. The plume outline was obtained by superposition of instantaneous photographs whenever time exposure photographs were not satisfactory.

For the Rajasthan site an EXAKTA Varex IIb camera with Flektogon 20 mm wide angle lens (Field of view 93 degrees) was available and in most of the smoke photographs complete visible plume could be covered. At this site smoke photographs were taken by three cameras positioned at different places and with different times of exposures. During the exposures the axes of cameras were placed perpendicular to the plumes as judged from the mean wind direction.

(*b*) *Meteorological measurement*—For wind and temperature profile measurements a temporary steel mast of 10 m was erected at Tarapur. Its instrumentation has been described in Part I. The wind direction was recorded on a EA recorder at a chart speed of 3″/min during smoke runs.

At Rajasthan site, during smoke runs, wind profile measurements were made with Casella anemometers mounted on the tower, when smoke was released from the tower and on a mast 3 m high when the release was made at ground level. The azimuth and elevation wind direction fluctuations were recorded using a Gelman make bivane on a pair of 0-1 mA EA recorder at a fast speed of 3″/ min.

4. Theory

(*a*) *Evaluation of Diffusion Coefficients using smoke as tracer* —Gifford (1959) gives a quantitative method of practical estimation of diffusion parameters from time exposure smoke photographs. The method generally called the 'opacity method' follows from the fact that smoke particles obscure the background thereby defining the cloud outline depending upon the threshold number of particles in the line of sight. If uniformity of background and hence constancy of threshold is assumed, it can be shown that the diffusion parameters are related to the geometry of the smoke plume which on time exposure gives a somewhat elliptical pattern (*see* Fig. 1).

From the photographs the following distances can be measured by enlarging the photographs or projecting them on screen.

(*i*) Z_m, the maximum half width of the plume,

(*ii*) X_m, the distance from the source, at which Z_m occurs,

(*iii*) X_T, the total length of the visible plume measured from the source.

The plot of standard deviation $\sigma_z(x)$ *versus* x can be drawn for each time exposure photograph for a distance upto X_T using the relations given by Gifford (*loc cit.*).

$$\ln p = ap, \qquad (1a)$$

where a and p are found from the relations,

$$a = \frac{1}{e}\ (Z^2/Z_m^2) \qquad (1b)$$

$$p = e\, Z_m^2/\sigma_z^2(x) \qquad (1c)$$

If Sutton's form of σ is assumed, then stability parameter n and virtual diffusion coefficient C_z can be computed from a plot of σ versus x on a log-log scale, since —

$$\sigma_z^2 = \tfrac{1}{2} C_z^2\, X^{2-n} \qquad (2)$$

which implies a straight line on the above plot.

An alternate method for obtaining C_z is from the relation

$$C_z^2 = 2\, X_m^n\, (Z_m/X_m)^2 \qquad (3)$$

and n can also be obtained through measurement of velocity profile using the relation—

$$\frac{\bar{u}_1}{\bar{u}_2} = \left(\frac{Z_1}{Z_2}\right)^{n/(2-n)} \qquad (4)$$

where $\bar{u}_1$, and $\bar{u}_2$ are the mean wind speed at heights Z_1 and Z_2 respectively.

For the cases where due to short length of photographs, values of X_m and Z_m cannot be measured, the value of C_z may be computed from the relation—

$$C_z^2 = \left(\frac{Z_2^2}{X_2^{2-n}} - \frac{Z_1^2}{X_1^{2-n}}\right)\Big/\left(1-\frac{n}{2}\right) \ln (x_2/x_1) \quad (5)$$

If on the other hand, it is assumed that the outline is given by 1/10th of the centre line concentration, the value of C_z is given by—

$$C_z^2 = \frac{1}{2.303} (Z^2/X^{2-n}) \quad (6)$$

A graph of log Z *versus* log x therefore gives both C_z and n. We shall refer this last method as "slope method".

Similarly C_y can also be computed for the time exposure photograph of the plume in horizontal plane.

(*b*) *Evaluation of Diffusion Coefficients from wind measurements* —It is well known that since the mechanism of atmospheric diffusion occurs through turbulent air motions, the information about diffusion is implicitly stored in the record of wind speed or direction fluctuations.

The virtual diffusion coefficients C_y and C_z can be computed from the Sutton's relations—

$$C_y^2 = \frac{4\nu^n}{(1-n)\ (2-n)\bar{u}^n} \left[\frac{\overline{v'^2}}{\bar{u}^2}\right]^{2(1-n)} \quad (7a)$$

$$C_z^2 = \frac{4\nu^n}{(1-n)\ (2-n)\bar{u}^n} \left[\frac{\overline{w'^2}}{\bar{u}^2}\right]^{2(1-n)} \quad (7b)$$

where ν is the microviscosity of air, $\overline{v'^2}$ and $\overline{w'^2}$ are the variances of cross and vertical components of wind repectively.

Holland (1953) showed that the term in square brackets can be related to the wind direction fluctuations by writing it as $\sigma^2(\tan\theta)$ which for small angles equals $\sigma^2(\theta)$. For calculation of $\sigma^2(\tan\theta)$ for larger angles, following expression has been derived—

$$\sigma^2 \tan\theta = \sigma\theta^2 + 2\sigma\theta^4 + \frac{17}{3}\sigma\theta^6 + \ldots\ldots\ldots \quad (8)$$

a series converging for $\sigma\theta < 1$ radian. Similarly, $\sigma^2(\tan\phi)$ can be found from $\sigma\phi$, where $\sigma\theta$ and $\sigma\phi$ are the standard deviation of azimuth and elevation angles of wind direction, which are computed from the fast record of bivane.

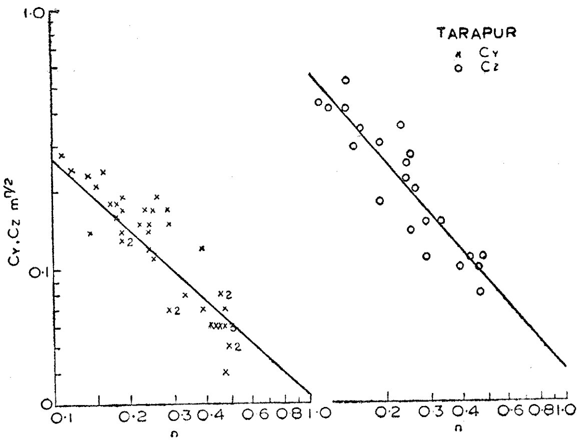

Fig. 2. Variation of Cy, C_z with n (The number against a point shows number of overlapping observations)

Sutton also suggested that for flow over rough ground, the microviscosity ν should be replaced by macroviscosity $N = U_* Z_o$, where U_* is the friction velocity given by $(\tau/\rho)^{1/2}$ and Z_o is the ground roughness parameter, defined in Part I of the paper.

5. Results and Discussions

(*a*) *Tarapur Experiments* —The smoke photographs taken at Tarapur site were analysed using Eqs. (5) and (6), since the range of photographs did not cover completely the visible end of the plume. Fig. 1 shows a typical photograph in the night time. In this case the time of exposure used was over the entire period of release (11min).

Table 1 summarises the values of C_y, C_z and n. The value of n used here were computed from Eq. (4). Since the experiments were conducted with ground level smoke release, only C_z was obtained by smoke photographs, and C_y from wind data using relation 7 (a). Fig. 2 shows a plot of C_y and C_z *versus* n on a log-log scale. Empirical relations were fitted for C_y and C_z with respect to n, using least square method, and are as follows,

$$C_y = 0.03 \quad n^{-0.92}, \quad (9)$$

$$C_z = 0.04 \quad n^{-1.15} \quad (10)$$

Whereas no physical basis appears to exist for these relations, such a plot is very useful for obtaining C_y and C_z from simple wind profile measurements. The variation of C_y and C_z with R_i is shown in Fig. 3. The correlation here is also very good. As expected the values of C_y and C_z are higher in day time than those in night time,

TABLE 1

Summary of micrometeorological and diffusion parameters at Tarapur Atomic Power Project

Run No.	Time (hrs)	$\bar{u}_{2m}$ (m/sec)	n	Ri	Cy (meters)$^{n/2}$	Cz (meters)$^{n/2}$
			22-12-1961			
A1	1730	3·68	0·17	—0·055	—	—
A2	2130	1·76	0·33	0·188	0·08	0·15
			23-12-1961			
A3	0000	1·83	0·29	0·262	0·07	0·11
A4	0310	1·47	0·43	0·298	0·06	0·11
A5	0505	1·58	0·47	0·223	..	0·08
A6	0810	2·85	0·24	—0·072	0·14	0·22
A7	0950	2·94	0·16	—0·585	0·24	0·34
A8	1245	3·32	0·06	—4·603	0·23	—
			18-2-1962			
B1	2200	1·79	0·48	0·158	0·06	0·11
B2	2300	1·73	0·46	0·237	0·08	—
			19-12-1962			
B3	0000	3·59	0·22	0·168	0·15	—
B4	0100	3·57	0·24	0·120	0·12	—
B5	0200	3·85	0·25	0·096	0·11	0·14
B6	0330	3·71	0·17	0·423	—	—
B7	0511	3·01	0·27	0·195	—	—
B8	0710	2·23	0·43	0·131	—	0·22
B9	0800	2·47	0·25	0·086	0·17	0·27
B10	1000	2·82	0·14	—0·797	0·23	0·52
B11	1200	3·66	0·11	—1·115	0·28	0·43
B12	1400	5·07	0·14	—	0·14	0·41
B13	1515	5·14	0·19	—	0·13	—
B14	1600	5·11	0·19	—0·105	0·13	0·19
B15	1700	4·42	0·19	0·002	0·19	0·30
			21-3-1962			
C1	1750	3·55	0·23	—0·099	0·17	0·35
C2	2105	2·39	0·29	0·062	0·15	—
			22-3-1962			
C3	0500	1·45	0·47	0·252	0·07	—
C4	0655	1·46	0·46	0·273	0·08	0·10
C5	0730	1·74	0·26	0·163	0·19	0·20
C6	1200	4·75	0·18	—0·263	0·18	0·70
			19-4-1962			
D1	2200	3·30	0·24	0·026	0·15	0·25
			20-4-1962			
D2	0400	1·35	0·29	0·040	0·17	0·15
D4	0600	1·44	0·39	0·277	0·12	0·10
D5	1000	3·14	0·15	—0·875	0·21	0·29
D6	1200	3·75	0·12	—1·024	0·24	0·41
E2	2230	1·63	0·46	0·234	0·06	—
E3	2300	1·38	0·47	0·485	0·06	—
E4	2335	1·43	0·47	0·559	0·04	—
			4-11-1963			
E5	0005	1·59	0·49	0·330	0·05	—
E6	0037	1·54	0·49	0·358	0·05	—
E7	0107	1·46	0·48	0·448	0·06	—
E8	0142	1·57	0·44	0·432	0·06	—
E9	0211	1·28	0·29	2·428	0·07	—
E10	0214	2·09	0·39	0·299	0·07	—
E11	1400	2·63	0·17	—0·464	0·18	—
E12	1432	3·15	0·18	—0·196	0·16	—
E13	1503	3·00	0·19	—0·368	0·17	—
E14	1534	3·21	0·19	—0·172	0·14	—

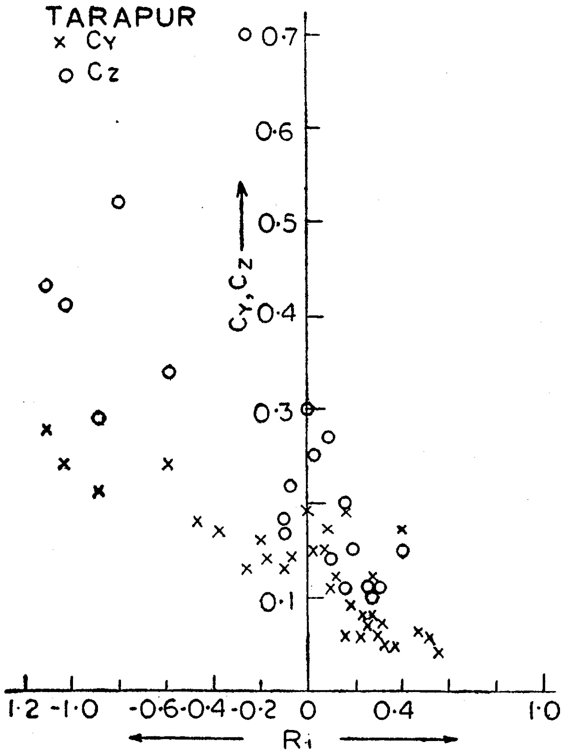

Fig. 3. Variation of Cy, C_z with Ri

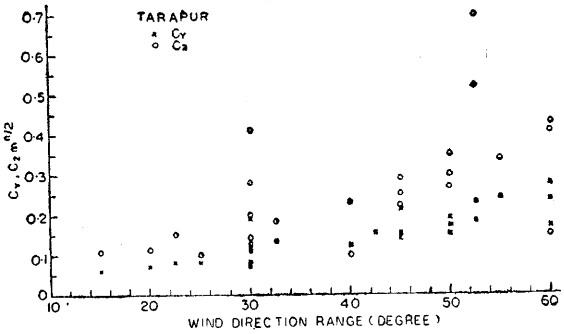

Fig. 4. Variation of Cy, C_z with wind direction range

Fig. 6

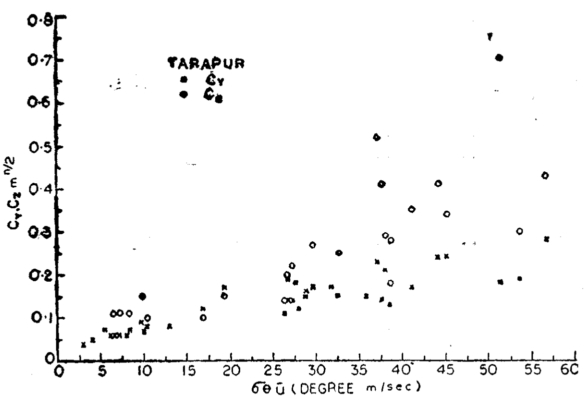

Fig. 5. Variation of Cy, C_z with $\sigma_\theta \bar{u}$

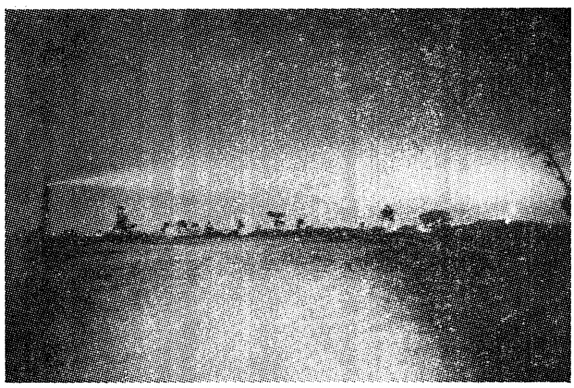

Fig. 7

Fig. 4 shows the plot of C_y and C_z with wind direction range $\triangle\,\theta$. The values of C_y and C_z are found to increase with the increase in wind direction range. The multiplicity of points for given $\triangle\,\theta$ in Fig. 4 is because the range could not be read better than 4·5 degrees on the chart. Fig. 5 shows the plot of C and C_z with $\sigma\,\theta\,\bar{u}$. Both Figs. 4 and 5 show a similar behaviour.

(*b*) *Rajasthan Experiments* —In most of the smoke photographs for these experiments, complete visible plume could be covered. Figs. 6 and 7 give the vertical cross-section of the plume under typical lapse and inversion conditions. Plume photographs in the Y-direction could be taken only for elevated release during moon lit nights. Fig. 8 shows such a photograph. Fig. 9 gives a photograph which shows characteristically three different distinct plumes. The exposure period of this was four minutes. The occurrence of a triple plume indicates distinct low frequency oscillations in the wind direction. Since the period of oscillations appears to be less than 4 minutes (the exposure period) and the phenomenon is found

TABLE 2

Summary of micro meteorological and diffusion parameters at Rajasthan Atomic Power Project

Run No.		Period of exposure (min)	$\bar{u}_{2m}$ (m/sec)	n	$\Delta\theta$ (degrees)	$\sigma\theta$ (degrees)	$\sigma\phi$ (degrees)	$C_y\ m^{n/2}$ Gifford	$C_y\ m^{n/2}$ Slope	$C_y\ m^{n/2}$ Wind	$C_z\ m^{n/2}$ Slope	$C_z\ m^{n/2}$ Gifford	$C_z\ m^{n/2}$ Wind
5-12-1965													
I1	1213	2·5	1·37	0·04	108	11·3	40·2	..	..	0·29	0·91	0·28	..
I2	1655	3·5	3·51	0·22	29	3·3	7·1	..	..	0·13	0·14	0·12	0·23
I2	1659	5·0	3·56	0·27	32	5·4	7·3	..	..	0·21	0·16	0·15	0·26
I2	1655	0·5	3·51	0·22	29	1·1	5·7	0·11	..	0·05	..	..	0·19
I3	1855	3·5	3·84	0·49	14	2·5	4·1	..	..	0·19	..	0·33	0·25
I3	1854	7·0	3·84	0·49	14	2·7	4·3	0·55	0·15	0·20	0·16	..	0·25
I4	2008	15·0	2·71	0·49	36	6·7	9·0	..	..	0·31	0·14	0·24	0·36
I5	2255	7·0	3·49	0·60	22	4·4	4·6	0·89	0·19	0·30	..	..	0·31
I5	2300	10·0	3·23	0·57	22	6·1	3·9	..	..	0·33	0·15	0·43	0·27
I5	2310	2·5	3·23	0·57	18	3·0	3·3	..	..	0·24	..	0·22	0·25
I6	2342	12·5	3·96	0·32	36	6·7	8·0	..	..	0·25	0·12	0·31	0·28
6-12-1965													
I7	1945	15·0	3·86	0·36	43	6·9	11·6	..	..	0·27	0·11	0·35	0·38
I7	2000	5·0	3·86	0·36	36	5·9	10·7	..	..	0·25	0·25	0·40	0·36
I8	2210	14·5	7·03	0·37	36	6·8	11·7	..	..	0.27	0·37	0·35	0·38
7-12-1965													
I9	1055	4·0	4·78	0·26	68	12·7	23·0	..	..	0·38	0·25	0·27	0·59
I9	1059	5·0	5·48	0·25	58	12·2	15·8	..	..	0·37	0·23	0·24	0·44
I11	1557	5·0	2·35	0·22	..	..	24·8	..	..	0·48	0·33	0·42	0·62
I11	1602	5·5	2·26	0·24	..	..	21·2	..	..	0·48	0·51	0·26	0·55
8-12-1965													
I13	1645	5·0	3·70	0·22	43	7·9	15·4	..	..	0·25	0·18	0·24	0·42
I14	1722	7·0	3·19	0·33	47	8·2	14·6	..	..	0·29	0·09	0·21	0·44
9-12-1965													
I20	0346	15·0	3·85	0·56	18	3·9	3·5	..	..	0·27	0·09	0·19	0·26
10-12-1965													
I21	1150	5·0	2·79	0·05	108	16·1	26·5	..	..	0·41	..	0·21	0·66
I21	1150	5·0	2·79	0·05	108	16·1	26·5	..	..	0·41	0·30	0·20	0·66
I21	1146	4·0	2·79	0·05	108	15·2	26·3	..	..	0·39	0·09	0·23	0·65
I21	1146	4·0	2·79	0·05	108	15·2	26·3	..	..	0·39	0·37	0·18	0·65
I21	1146	4·0	2·79	0·05	108	15·2	26·3	..	..	0·39	0·33	0·10	0·65
4-5-1966													
II11	2036	11·0	0·68	0·60	83	17·0	7·1	0·67	..	0·52	..	..	0·37
II12	2230	10·0	7·16	0·33	11	1·9	2·7	..	..	0·11	0·12	0·03	0·14
II12	2230	11·0	7·16	0·33	11	1·9	2·7	0·31	0·18	0·11	..	..	0·14
5-5-1966													
II13	0057	10·0	2·85	0·33	40	10·3	6·6	0·28	0·18	0·34	..	..	0·26
II13	0107	4·0	3·60	0·34	47	8·9	6·4	0·21	0·11	0·32	..	..	0·25
II13	0058	10·0	2·85	0·33	40	10·3	6·6	..	..	0·34	0·23	0·28	0·26
II14	0252	11·5	3·25	0·32	65	10·2	4·0	0·17	0·15	0·34	..	..	0·18
II14	0252	11·5	3·25	0·32	65	10·2	4·0	0·25	0·13	0·34	..	..	0·18
II14	0252	11·5	3·25	0·32	65	10·2	4·0	0·23	0·14	0·34	..	..	0·18
II15	0406	14·0	4·61	0·59	32	5·4	2·7	..	..	0·32	0·12	0·30	0·25
II15	0406	12·0	4·61	0·59	32	5·4	2·7	0·41	0·11	0·32	..	..	0·25
II15	0418	4·0	3·07	0·34	..	..	2·6	0·20	..	0·20	..	..	0·14
II15	0418	4·0	3·07	0·34	..	..	2·6	0·18	0·65	0·20	..	..	0·14

Fig. 8

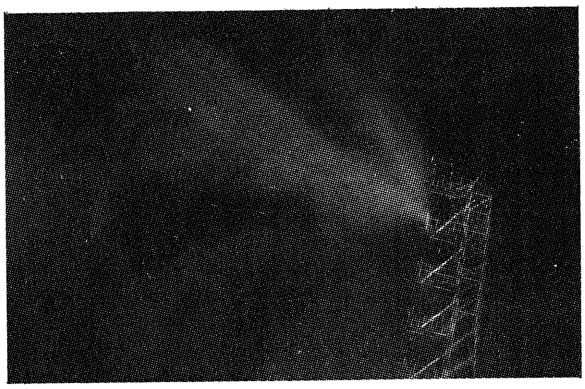

Fig. 9

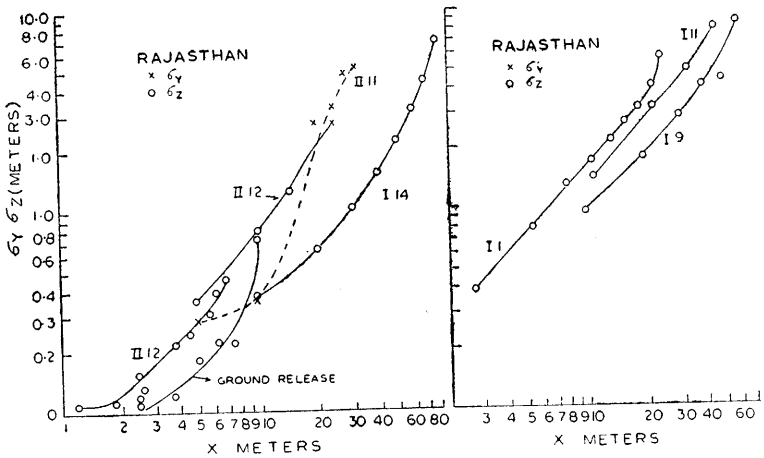

Fig. 10. Variation of σ_y, σ_z with X

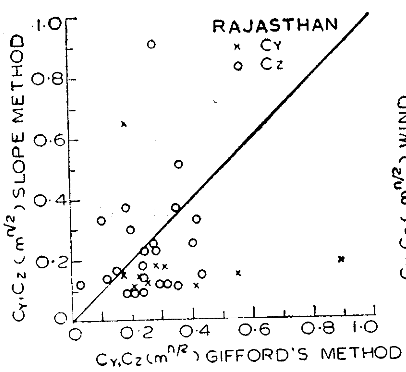

Fig. 11 (a)

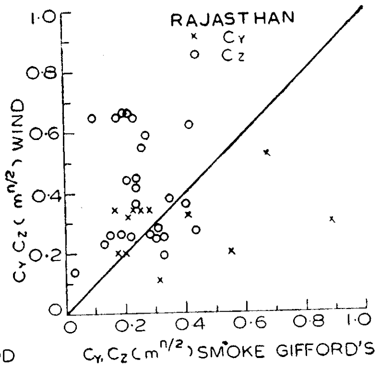

Fig. 11 (b)

(a) Comparison of C_y, and C_z (smoke) by Gifford's and Slope method
(b) Comparison of C_y and C_z obtained from smoke (Gifford's) and wind
(Smoke release 21 metres)

to occur in day time only, one can preclude the existence of gravity waves at the time of these experiments. Such behaviour was not observed at Tarapur where the release was at ground level. Low frequency oscillations of this nature in horizontal wind direction are frequently found at Rajasthan site during day time (Kapoor 1968).

Fig. 10 shows variation of σ with downwind distance as obtained from plume photographs and Eq. (1). It is clear from these graphs that stability parameter n would have to be very large and negative to explain the slopes on Sutton's model. Such large negative values have been reported by Haugen *et al.* (1961) for a downwind

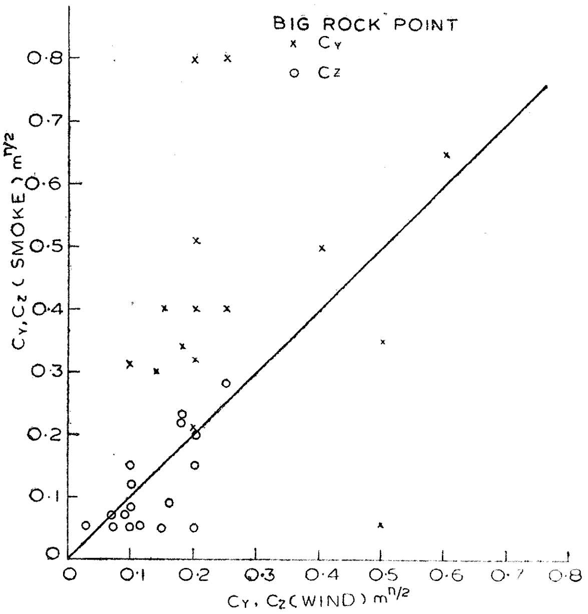

Fig. 12. Comparison of C_y and C_z values from wind and smoke

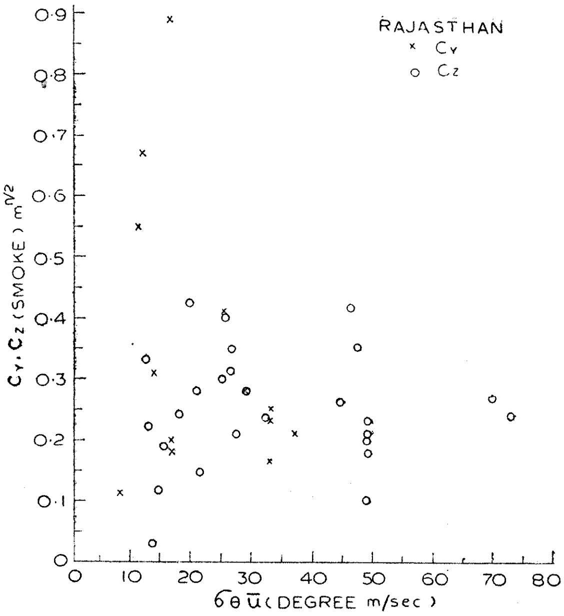

Fig. 14. Variation of C_y, C_z (smoke) with $\sigma\theta\bar{u}$ (21m)

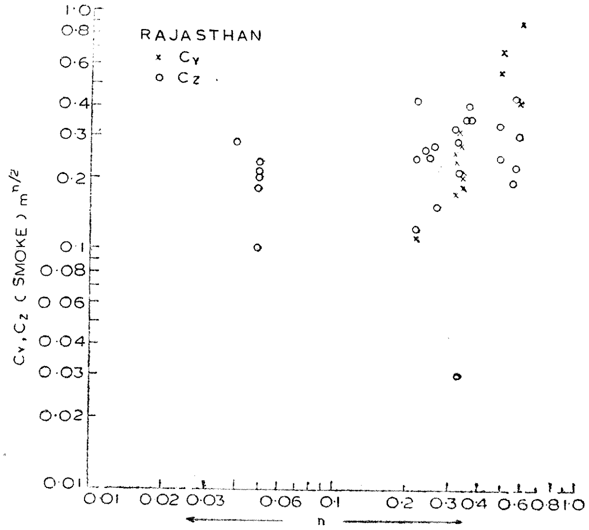

Fig. 13. Variation of C_y, C_z (smoke) with n

distance of 100 m. The data of SO_2 experiments carried by Cramer *et al.* (1958) also show the variation of σ with distance which is consistent with a negative value of n numerically increasing with downwind distance. However to reduce the data to some what standard form, following method was used for calculating C_y and C_z and n. Table 2 gives the values of C_y and C_z obtained from smoke and wind along with other meteorological parameters.

The diffusion parameters were calculated both from Eqs. (3) and (6). For Eq. (3), the value of n was computed from Eq. (4), whereas for Eq. (6), the value of n was obtained from the graphs Z versus x, which were in general different from that obtained from wind profile Eq. (4).

Values of C_y and C_z were also computed from $\sigma\,\theta$ and $\sigma\,\phi$ using Eq. (7). The values of n were computed from wind profile measurements.

Fig. 11(a) shows the comparison of C_y and C_z obtained from the slope method and Gifford's method Eq. (3). The scatter is very high and correlation is not satisfactory. In Fig. 11(b), comparison is made between the value of C_y and C_z

obtained from wind and smoke (Gifford's method) for the same time of sampling or exposure. The correlation between the two is slightly better though it is seen that values obtained from wind are higher than those from smoke. (Henceforth the reference to the values obtained from the smoke will imply that they are obtained using Gifford's method.)

This kind of behaviour is also observed for the results of smoke experiments conducted by Hewson *et al.* (1963) at Big Rock point. Plume lengths of the order of few kilometers were photographed in their experiment by means of aerial photography and average plume section is obtained by superposition of time lapse photographs. Their results are shown for comparison in Fig. 12.

Fig. 13 gives plot of C_y and C_z *versus* n for smoke experiments. Fig. 14 shows the plot of C_y and C_z obtained from smoke *versus* $n\sigma\theta\ \bar{u}$. The regularity of trend observed at Tarapur is absent at Rajasthan site. The scatter is also very high. The same parameters obtained from wind (bivane) are shown in Figs. 15 and 16. Fig. 16 shows a somewhat better regularity in the behaviour of the parameters. Here the sampling period for bivane data was 10 minutes. The reason for the difference in behaviour of parameters obtained from smoke and wind is not very clear. Terrain and differences in sampling times appear to be two principal reasons. Unlike Tarapur, the regularity of behaviour of diffusion parameters with n (Fig. 15) is also absent at Rajasthan site.

The values of C_y and C_z given earlier and which refer to σ at X_m are therefore to be judged more for application and operational stand point rather than as parameters describing diffusion for extended distance. The irregularity of behaviour of the computed diffusion parameters with the observed wind and stability parameters at Rajasthan site and the comparative regularity of the same at Tarapur, brings out to the fore the inapplicability of current diffusion theories developed for plain uniform terrains to the sites of complicated terrains.

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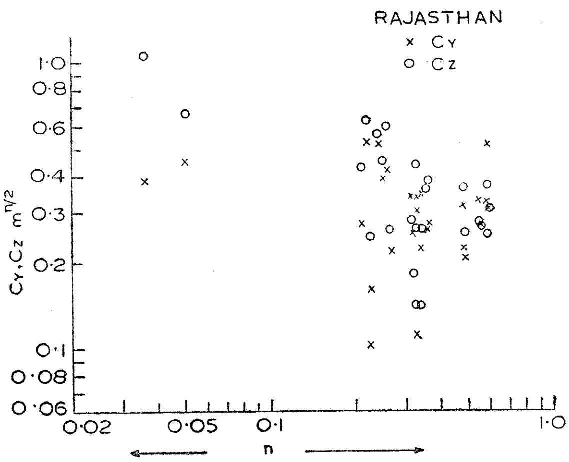

Fig 15. Variation of C_y, C_z (bivane 21 m) with n

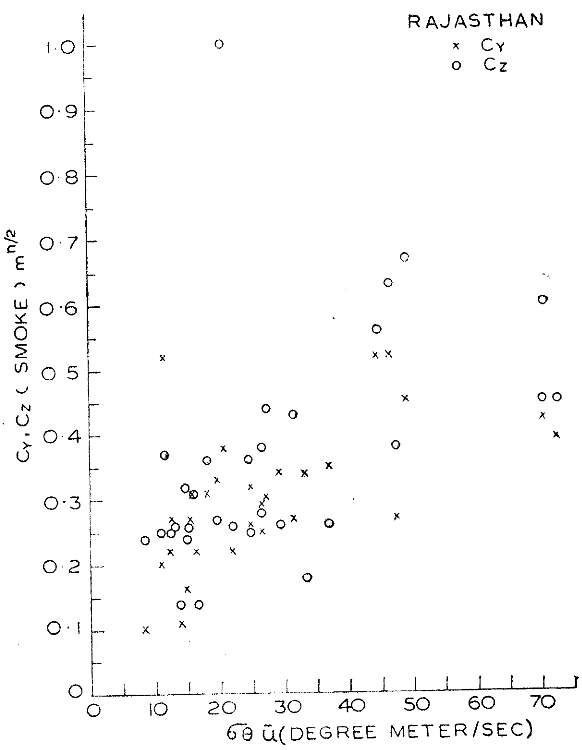

Fig. 16. Variation of C_y, C_z with $\sigma\theta\bar{u}$ (21m)

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