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Atmospheric pollution due to improper industrial siting : A meteorological approach for abatement

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ABSTRACT. A simple method utilising the conventional meteorological data to advise on (*a*) optimum stack height of any proposed industry to limit the pollutant concentrations within their lethal values and (*b*) optimum emission with the existing stack height of an operating industry to control the concentrations within the standard limits is presented. In developing this methodology a comparison was also made of the stability classification of Pasquill-Turner, critical values of Richardson's number and limits of standard deviation of wind directions. Of these the best classification was found to be by using wind direction traces. Plume rise by Briggs, Tennessee Valley Authority, Holland, Whaley, Morton, CONCAWE and Lucas methods were compared and the study points out that Lucas formula could be employed with minimum data without losing much accuracy as often claimed by sophisticated formulae. Coefficients for vertical variation of wind were derived from continuous records over a tower at two levels. Temperature variation in the vertical under daylight conditions is assumed to be dry adiabatic. During night time inversions a mathematical model derived from screen temperature data is used.

Maximum concentration and its distance were obtained for 03 and 12 GMT for every month from climatological data. Where these concentrations were found to be lower than United States Environmental Protection Agency (EPA) secondary standard the stack heights are considered to be safe provided the background pollution is negligible; otherwise the optimum stack heights were determined. Alternatively with the limit of EPA standard, existing stack height and meteorological parameters the optimum emission rate is determined. Those industries in the proposal stage can modify the stack design but for industries in production stage emission rate has to be limited.

1. Introduction

Increasing industrialization and consequent urbanization without due regard to the environmental meteorological conditions is leading to a deterioration of ambient air quality at several places. Realising the adverse effects of the poor air quality, it has become customary to probe into the precedent and antecedent meteorological conditions of the industrial area and seek solution to the pollution problems. The meteorological approach for proper air management is to limit the ambient air quality within the lethal values either by emission control or by alteration of stack heights utilising the dilution capacity of the atmosphere to a maximum. Elaborate analysis of meteorological data is both laborious and time consuming. Secondly sophisticated formulae for deriving several plant characteristics and parameters need either very accurate meteorological data or specialised meteorological measurements which may not be readily available. In the present paper a simple method utilising commonly available climatological data to advise on (*a*) optimum stack height of any proposed industry to limit the pollutant concentrations within their lethal values and (*b*) optimum emission with the existing stack height of an operating industry to control the concentrations within the standard limits is presented.

Studies on atmospheric pollutant dispersal from thermal power plants under Bongaigaon project at Borgolai (near Margherita) and Salakati were undertaken to advise on the stack height. Dispersal of sulphur dioxide from the stack of a fertilizer plant at Mathura was also determined to assess the propriety of their proposed stack height. The location map of these sites is shown in Fig. 1. Plant characteristics are given in Table 1.

2. Methodology

Ground level concentration along plume axis is :

$$\chi = \frac{Q}{\pi u \, \sigma_y \, \sigma_z} \; \exp \left\{ - \frac{h^2}{2 \, \sigma_z^2} \right\} \qquad (1)$$

where,

$\chi = $ Concentration of pollutant ($\mu g/m^3$)

$Q = $ Pollutant emission rate ($\mu g/sec$)

$u = $ Wind speed at stack height (m/sec)

σ_y and $\sigma_z = $ Standard deviations (m) of plume concentrations along y and z axes

$h = $ Effective stack height (m)

and $h = H + \triangle h$

where, $H = $ Physical stack height (m)

$\triangle h = $ Height of plume rise (m)
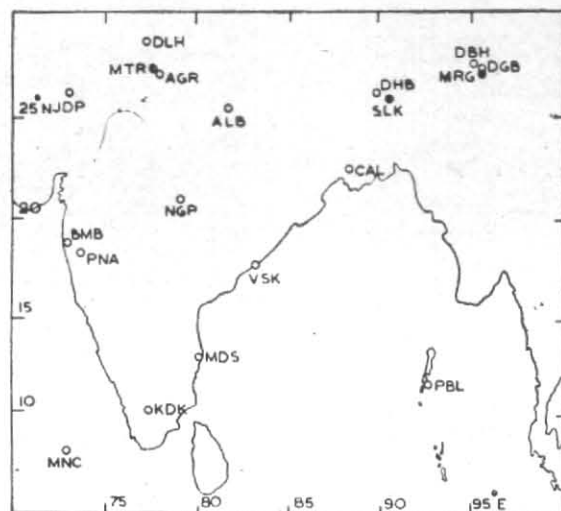
Fig. 1. Locator map

TABLE 1

Plant characteristics

Plant characteristics	Thermal power plant at		Fertilizer plant at Mathura
	Borgolai (near Margherita)	Salakati	
Capacity	2×60 MW	2×60 MW	—
Proposed ht. of stack	80 m	80 m	80 m
Source strength	3·0 ton/hr	3·0 ton/hr	0·342 ton/hr
Emission of heat from chimney	38·0 MW	38·0 MW	65·85 MW

On differentiating the Eqn. (1) w.r.t. x, the maximum concentration of pollutants from an elevated source can be obtained (Pasquill 1974, Smith 1968) with certain simplifying assumption.

$$X_{max} = \frac{2Q}{e \pi u h^2} \frac{\sigma_z}{\sigma_y}$$

where X_{max} = Maximum concentration of pollutant ($\mu g/m^3$)

$e = 2\cdot718$ (base of natural logarithm)

This maximum value occurs at a distance where $\sigma_z = \dfrac{h}{\sqrt{2}} = 0\cdot7h$, i.e., when the exponential term in the equation is unity.

In using the above equation, it is to be remembered that for each change in meteorological con-

ditions and wind speed, the ratio σ_z/σ_y changes and a new effective stack height must be obtained.

Computation of maximum concentration, therefore, necessitates determination of dispersion characteristics σ_y and σ_z, plume rise and wind speed at stack height. Climatological data in respect of temperature, wind and cloudiness for 03 and 12 GMT for the 12 months published by India Meteorological Department (1960) are made use of in the present study.

3. Dispersion characteristics

The dispersion characteristics σ_y and σ_z depend upon the turbulent structure of the atmosphere. From wind speed and cloudiness Pasquill (1961) estimated stability and computed σ_y and σ_z.

Pasquill classification has been made more objective by Turner (1964) by specifying the classes according to Net Radiation (NR) index and wind speed; for night time NR depends on cloudiness, for day time NR depends on solar altitude and cloudiness.

In the present model stability classification according to cloudiness, wind and solar altitude corresponding to the latitude of station culled out of Smithsonian Meteorological Tables (List 1951) is considered as standard. Wind direction fluctuations similar to Brookhaven National Laboratory (Slade 1968) are used to evaluate σ_θ and hence stability. This classification is standardized with reference to Pasquill type and is used in the present calculation. Industrialization and consequent urbanization leads to increased low level turbulence,

Hence McElroy's power laws as used in urban diffusion models are employed for evaluating σ_y and σ_z in the present study :

$$\sigma_y = a\,x^p, \qquad \sigma_z = b\,x^q$$

where σ_y, σ_z and x are in metres. Pasquill-Turner's six categories are also abridged to four classes adopted by McElroy as follows :

McElroy (1969)	Pasquill-Turner (1964)
Very unstable	A
Unstable	B, C
Neutral	D
Stable	E, F

The numerical values of a, b, p and q are given below. These are obtained from σ_y and σ_z curves (McElroy 1969).

Stability	a	p	b	q
Very unstable	1·459	0·714	·00555	1·54
Unstable	1·518	0·687	0·037	1·17
Neutral	1·358	·674	0·0944	·945
Stable	0·791	·667	0·4	·672

Plume rise

Plume rise can be calculated as a function of source parameters, such as buoyancy and meteorological conditions. Techniques for deriving this have been developed by several workers and organizations but hardly any of them agree, either with each other or with new observations, if they go outside the range of the original observations the techniques were made to fit (Briggs 1975, Guldberg 1975).

Of the several formulae in literature, Briggs model (1969, 1971, 1972) predicts best the observed plume rise during periods of low wind speed and at higher wind speeds the TVA 1972 model suggested by Montgomery *et al.* (1972) performed best. Both these formulae need vertical temperature distribution hence cannot be used in general. Holland's (1953) equation although physically sound, demands several parameters which also may not be readily available. Numerous empirical, semi-empirical formulae utilising heat emission and wind speed alone are developed both in Europe and United States (CONCAWE 1966, Whaley

1969, Lucas *et al.* 1963). Further, Moore (1974) after a comparison of plume rises recommended the use of Lucas formula with certain modifications. Morton *et al.* (1956) developed a simple formula under very stable and calm conditions. Therefore, in the present study a comparative study of plume rises computed by using the formulae of Holland, CONCAWE (1966), Whaley (1969), Lucas (1967), Briggs (1972), TVA Models 1971 and 1972 and Morton *et al.* (1956) was made. It is found that plume rise as determined by slightly modified Lucas formula is close to Brigg's model at low wind speeds and TVA 1972 model at higher wind speeds. Lucas formula for plume rise used in the present study is :

$$\triangle h = \frac{60 + 5H}{u}\,Q_H^{1/4}$$

(unstable and neutral conditions)

$$\triangle h = \frac{116\,Q_H^{1/4}}{u}$$

(stable and low wind speed)

$$\triangle h = \frac{160\,Q_H^{1/4}}{u}$$

(stable and high wind speed)

Wind at stack level

Wind speed at the stack level is obtained from ground value by employing power law as suggested by Sutton (1953).

$$u = u_1 \left(\frac{Z}{Z_1}\right)^p$$

where u_1 and u are wind speed at Z_1 (lower) and Z (higher) levels and

$p = 1/9$ (unstable, very unstable)

$p = 1/7$ (neutral)

$p = 1/3$ (stable)

Temperature at stack level

In unstable and neutral conditions air temperature at stack level was obtained by adopting dry adiabatic lapse rate. But in stable, calm, clear sky situations a mathematical model as given by Anfossi *et al.* (1976) was used.

Air quality criteria used and basis for advice

Environmental protection agency of U.S.A. has defined primary and secondary standards (EPA 1972). Primary standards are designed to protect human health. Secondary standards are design-

ed to protect against effects on soil, water, vegetation, minerals, animals, weather, visibility, personal comfort and well-being. U.S. EPA secondary standards are defined for 3 and 24 hours sampling time. The 3 hours value is reduced to one hour standard by :

$$X_s = X_k \left(\frac{t_k}{t_s} \right)^p$$

where X_s = Desired concentration estimate for sampling time t_s

X_k = Concentration estimate for shorter sampling time t_k and

$p = \cdot 185$

The value thus obtained was also compared with the method suggested by Lucas (1967) and it was found that the values are more or less the same.

U.S. Environmental protection agency standards

Primary   365 $\mu g/m^3$ 24-hr concentration
Secondary   1300 $\mu g/m^3$ 3-hr concentration
            1600 $\mu g/m^3$ 1-hr concentration
            (derived)

Maximum concentrations for 03 and 12 GMT for all the months were calculated together with their distances of occurrence. Concentrations at those distances were also computed employing the short term centre line equation.

$$X_{(x,0,0;\ H)} = \frac{Q}{\pi \sigma_y \sigma_z u} \ \exp \left(- \frac{h^2}{2 \sigma_z{}^2} \right)$$

It was found that the concentrations computed by the two methods agreed confirming the correctness of the computations. When the concentrations at any observation time did not exceed the U.S. EPA secondary standard it was considered that the existing/proposed stack height is satisfactory. In case the concentrations exceed, the secondary standard is used in place of X_{max} and the effective stack height computed keeping all the other parameters the same. From the effective stack height, the plume rise is deducted thus yielding the physical stack height and the concerned industry is advised to raise the stack level to this optimum value.

Where the industry is in operation a different procedure is adopted. With the secondary standard as the maximum concentration and existing stack height, the optimum rate of emission is determined and the industry can be advised to limit their emissions to this optimum value.

4. Results

Maximum concentrations together with the distance of their occurrence at the three sites

TABLE 2

Maximum sulphur dioxide concentration ($\mu g/m^3$) at different stations

	Borgalai		Salakati		Mathura Fertilizer Plant	
	03	12 GMT	03	12 GMT	03	12 GMT
Jan	1215 (2·0)	72·3 (14·0)	1349 (1·4)	490 (29·8)	143 (1·6)	127 (2·3)
Feb	1229 (2·0)	843 (9·8)	1357 (1·8)	537 (25·2)	146 (1·5)	130 (2·2)
Mar	1319 (1·6)	932 (7·4)	1240 (·9)	931 (7·4)	148 (1·3)	138 (1·8)
Apr	1264 (1·8)	1200 (2·1)	1354 (1·0)	1344 (1·1)	148 (1·3)	141 (1·7)
May	1264 (1·8)	1337 (1·5)	998 (1·7)	1357 (1·2)	149 (1·2)	148 (1·2)
Jun	1299 (1·5)	1324 (1·5)	1041 (2·4)	1005 (2·9)	148 (1·1)	147 (1·1)
Jul	1306 (1·7)	1299 (1·7)	1044 (2·3)	1283 (1·7)	149 (1·2)	148 (1·3)
Aug	1638 (1·0)	1611 (1·0)	1037 (2·5)	1283 (1·7)	148 (1·3)	144 (1·6)
Sep	1312 (1·6)	1593 (1·1)	1041 (2·0)	1357 (1·3)	147 (1·4)	146 (1·5)
Oct	1313 (1·6)	1380 (1·5)	980 (3·5)	1344 (1·4)	106 (6·4)	176 (1·0)
Nov	751 (12·9)	1265 (1·8)	764 (2·4)	1319 (1·6)	100 (7·8)	164 (1·3)
Dec	723 (14·0)	1162 (2·1)	965 (3·3)	1638 (1·0)	104 (7·0)	164 (1·4)

Figures in parenthesis indicate distance in kilometres

are given in Table 2. From the table it can be seen that at Borgalai there is a tendency for the ambient air quality to deteriorate beyond the approved limits thrice but at Salakati only once. In the case of Mathura fertilizer plant the maximum concentrations are very much below the standards of EPA and hence there is no necessity to enhance the stack height or reduce emissions. To limit the maximum concentration to EPA values at either Borgalai or Salakati it was found that the stack height should be raised above 87 metres atleast.

5. Conclusion

The methodology described in this paper is simple and utilises the available climatological (normal) data and minimum plant characteristics. The conclusions arrived by the study and the recommendations made thereon would be very helpful to industrial and town planners in locating the stacks and zoning of urban complexes, recreation areas etc.

The suggested advice on optimum stack heights or emission rates is given on the assumption of a single source and negligible background pollution. For multiple sources, the concentrations could become additive and the optimum stack heights may correspondingly change. Similarly, if there is background pollution, this may also modify the critical height of stacks.

REFERENCES

Anfossi, D., Bacci, P. and Longhetto, A.	1976	*Quart. J.R. Met. Soc.*, **102**, pp. 173-180.
Briggs, G. A.	1969	*Plume rise*, AEC Critical Rev. Ser. TID-25075, 81 pp.
	1971	Proc. second Int. Clean Air Congress, Academic Press, pp. 1029-1032.
	1972	*Atmosph. Environment.*, **6**, pp. 507-510.
	1975	Plume rise predictions, Lectures on air pollution and environmental impact analyses, Am. Met. Soc., pp. 59-105.
CONCAWE	1966	The calculation of dispersion from a stack, Stitching CONCAWE, Heague, The Netherlands.
Environmental Protection Agency	1972	*Field operation guide for automatic air monitoring equipment*, US EPA, pp. 137-138.
Guldberg, P. H.	1975	*J. appl. Met.*, **14**, pp. 1402-1405.
Haltiner, C. J. and Martin, F. L.	1957	*Dynamical and Physical Meteorology*, Mc-Graw Hill, New York.
Holland, J. Z.	1953	A meteorological Survey of the Oak Ridge area, Atom. Energy Comm. Rep. ORC-99, Wash. D.C., pp. 554-559.
India met. Dep.	1960	*Climatological Tables of Observatories in India, (1931—1960)*.
List, R. J.	1951	*Smithsonian Meteorological Tables*, Wash. D.C., pp. 497-505.
Lucas, D. H., Moore D. J. and Spur, G.	1963	*Int. J. Air Water Pollut.*, **7**, pp. 473-500.
Lucas, D. H.	1967	*Atmosph. Environment*, **1**, pp. 421-424.
McElroy, J.	1969	*J. appl. Met.*, **8**, 1, 19 p.
Montgomery, T. L., Carpenter, S. B. Colbaugh, W. C. and Thomas, F. W.	1972	*J. Air Pollut. Control Ass.*, **22**, pp. 779-784.
Moore, D.J.	1974	*Atmosph. Environment*, **8**, 5, pp. 441-458.
Morton, B. R., Taylor, C. I. and Turner, J S.	1956	*Proc. R. Soc. London*, Ser. A 234 : 1-23.
Pasquill, F.	1961	*Met. Mag.*, **90**, 1063, pp. 33-49.
	1974	*Atmospheric diffusion*, John Wiley and Sons Ltd., England.

REFERENCES (contd)

Slade, D. H.   1968   *Meteorology & Atomic Energy*, U. S. Atomic Energy
                                                    Comm., Div. of Tech. Inf.

Smith, M. (Ed.)   1968   *Recommended guide for the prediction of the dis-
                                                    persion of airborne effluents*, Am. Soc. Mech.
                                                    Engy., 47 pp.

Sutton, O. G.   1953   *Micrometeorology*, Mc. Graw Hill Book Co., New
                                                    York.

Turner, D. B.   1964   *J. Appl. Met.*, **3**, p. 83.

                                          1970   *Workbook of Atmospheric Dispersion Estimates*,
                                                    Environ. Protection Agency, North Carolina.

Whaley, H.   1969   *Atmosph. Environment*, **3**, p. 177.