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Maximum ground level concentration of air pollutant

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सार — गाउसीय पुच्छ निदर्श के अनुसार उत्थित बिन्दु स्रोत से वायु-प्रदूषकों के उत्सर्जन को प्रस्तुत किया गया है। उच्चतम संभाव्य भूमितल सान्द्रता और अनुवात दूरी के लिए, जिस पर यह विभिन्न स्थायित्व वर्गों के लिए अधिकतम रूप से घटित होता है, इन दोनों के लिए प्रारम्भिक सैद्धान्तिक विवेचन का निर्माण किया गया है। प्रभावी उच्च निर्मुक्त (रिलीज) परिस्करण पर विचार किया गया। एक उधृत मामला-अध्ययन इन्काज में अनुसंधान रिएक्टर से उत्सर्जन का अध्ययन किया गया।

इस विश्लेषित विवेचन के परिणाम और व्युत्पत्ति अर्द्ध- आनुभाविक सूत्रों पर चर्चा की गई है और कुछ उधृत रेखाचित्रों को प्रस्तुत किया गया है।

ABSTRACT. The emission of an air pollutant from an elevated point source according to Gaussian plume model has been presented. An elementary theoretical treatment for both the highest possible ground-level concentration and the downwind distance at which this maximum occurs for different stability classes has been constructed. The effective height release modification was taken into consideration. An illustrative case study, namely, the emission from the research reactor in Inchas, has been studied.

The results of these analytical treatments and of the derived semi-empirical formulae are discussed and presented in few illustrative diagrams.

Key words — Air pollution, Plume rise, Standard deviation, Stability classes, Stack height.

1. Introduction

The Gaussian plume model first derived by Sutton (1953), Csanady (1973) Smith (1973), Turner (1970) provides the primary method having widespread use in air pollution calculations.

The equation for estimating the concentration of a gaseous pollutant from a continuous point source at some point above the ground is given by (IAEA Safety Guide) :

$$\chi(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left\{-\frac{1}{2}(y^2/\sigma_y^2)\right\}\times \left[\exp\left\{-(z-H)^2/2\sigma_z^2\right\} + \exp\left\{-(z+H)^2/2\sigma_z^2\right\}\right] \quad (1)$$

where,

x — Downwind distance from the source (m),
y — Cross-wind distance from the source (m),
z — Vertical distance above the ground (m),
χ — Concentration of pollutant (g/m^3),
u — Downwind velocity (m/sec),
Q — Emission rate (g/sec),
H — Effective stack height (m),

σ_y, σ_z are the standard deviations of plume concentration distribution in the horizontal and vetrical directions respectively.

The effective stack height is generally presented in the form :

$$H = h_s + \triangle h \quad (2)$$

where,

h_s is the physical stack height and $\triangle h$ is the plume rise.

The mean ground-level concentration for an elevated release, is then given by (IAEA Safety Guide) :

$$\chi(x, y, 0) = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left\{-\left(y^2/2\sigma_y^2 + H^2/2\sigma_z^2\right)\right\} \quad (3)$$

TABLE 1

Diffusion coefficients of the Pasquill-Gifford diffusion parameter for different stability classes

Stability	a_1	a_2	b_1	b_2	b_3
A (Extremely unstable)	—0.0234	0.0350	0.8800	0.1520	0.1475
B (Unstable)	—0.0147	0.2480	—0.9850	0.8200	0.0162
C (Slightly unstable)	—0.0117	0.1750	—1.1860	0.8500	0.0045
D (Neutral)	—0.0059	0.1080	—1.3500	0.7930	0.0022
E (Slightly stable)	—0.0059	0.0880	—2.8800	1.2550	—0.0420
F (Stable)	—0.0029	0.0540	—3.8000	1.4190	—0.0550

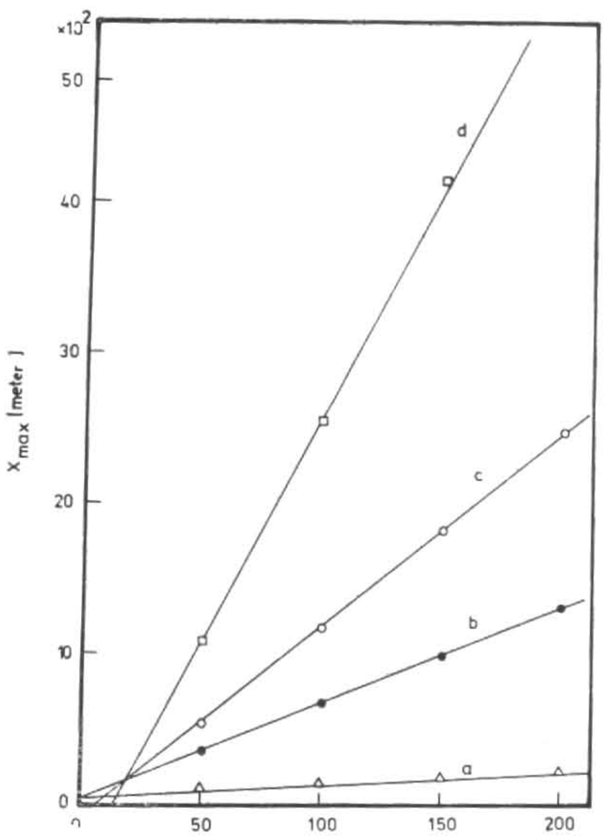

Fig. 1

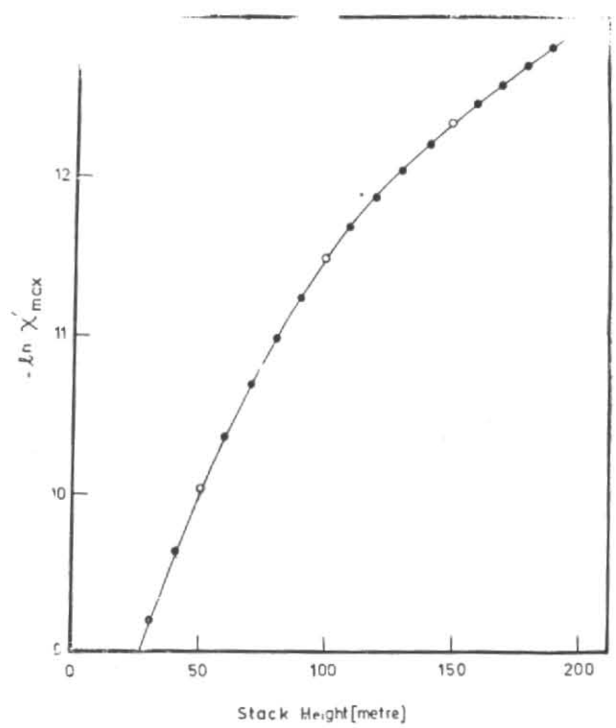

Fig. 2

For the ground-level concentration below the centre line of the plume, the formula for the concentration is obtained by setting $y=0$ in Eqn. (3), to yield :

$$\chi\,(x, 0, 0) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u}\,\exp\,(-\,H^2/2\sigma_z^2) \qquad (4)$$

Since the Gaussian plume model is expressed in terms of the diffusion parameters σ_y and σ_z, the subjective aspect of using this model is the selection of appropriate horizontal and vertical diffusion parameters. A number of field experiments have been carried out to derive these parameters used in radioactive releases from various nuclear facilities. One of the most common and important systems of diffusion parameters based chiefly on test series are those presented by Gifford (1961). Gifford developed σ_y and σ_z values representative of each stability class as a function of downwind distance x, often called Pasquill-Gifford curves. These curves could be approximated by the equations (Till John and Robert Meyer 1983).

$$\sigma_y\,(x) = (a_1 \ln x + a_2)\,x \qquad (5)$$

$$\sigma_z\,(x) = \frac{1}{2.15}\,\exp\,(b_1 + b_2 \ln x + b_3 \ln^2 x) \qquad (6)$$

The coefficients a_1, a_2, b_1, b_2 and b_3 are specified by Till John and Robert Meyer (1983) in Table 1 for different stability classes.

TABLE 2

The constants K_1 and K_2 for different stability classes

	Stability class			
	A	B	C	D
K_1	0.8049	6.4	13	31.985
K_2	44.317	24.0	1110	—583.077

TABLE 3

Wind speed and directions, the plume rise, maximum concentration of the reactor release and the distance of this maximum during the year 1987

Month	Wind speed (m/sec)	wind direction	$\triangle h$ (m)	x_m (m)	χ_m (10^{-5} m^3/sec)
Jan	4.4	SSW	1.88	852	2.70
Feb	3.6	NNE	2.28	865	3.10
Mar	6.2	WSW	1.34	835	1.94
Apr	3.6	N	2.28	865	3.20
May	4.6	NNE	1.80	850	2.56
Jun	4.4	N	1.88	852	2.70
Jul	4.1	NNW	2.02	857	2.88
Aug	4.1	NNW	2.02	857	2.88
Sep	3.6	N	2.28	865	3.20
Oct	3.6	N	2.28	865	3.20
Nov	2.6	NNE	3.18	894	4.54
Dec	4.4	SSW	1.88	852	2.70

These functions are applicable for short time releases and generally provide reasonable estimates of the magnitude of long-term concentrations from point of release at near ground level in a uniform terrain.

For very high elevated releases or release in complex terrain these functions are least appropriate.

2. Theoretical treatment

The calculations of the possible ground-level air concentration due to an elevated point source diffusing over flat surface are important in both the design of stacks and environmental impact analysis. Due to the complexity of the concentration formula depending on wind speed, atmospheric stability and distance we refer in the present work to a simple formula for the worst case conditions.

Along the axis of the plume at ground level, the concentration of pollutants given by Eqn. (4) may be written as :

$$\chi\,(x, 0, 0) = [Q/A_1\,(a_1 \ln x + a_2)\, u\, x^{(1+b_2+b_3 \ln x)}] \times [\exp - \{H^2 / A_2\, x^{2(b_2+b_3 \ln x)}\}] \qquad (7)$$

where,

$$A_1 = \pi\, e^{b_1} / 2.15$$

$$A_2 = 2\, e^{2b_1} / (2.15)^2$$

On using Eqn. (7), the maximum concentration occurs at the point where,

$$\frac{d\,\chi\,(x,0,0)}{d\,x} = 0 \qquad (8)$$

The value of x_m (the distance at which the maximum concentration occurs) is then given through the following equation :

$$\frac{2\,H^2}{A_2} = x_m^{2\,(b_2 + b_3 \ln x_m)} \left[1 + \frac{a_3 + a_1 \ln x_m}{(a_1 \ln x_m + a_2)\,(b_2 + 2b_3 \ln\, x_m)} \right] \qquad (9)$$

where, $a_3 = a_1 + a_2$

The explicit formula of x_m cannot be easily deduced analytically from Eqn. (9), hence a computer programme was performed to compute the ground level concentration for small steps of the downwind distance along the plume centre line using different values of the release height H.

The values of x_m deduced from these computations were plotted against H for the stability classes A, B, C and D as illustrated in Fig. 1.

It is to be noted that from Fig. 1 the relation between x_m and H is a linear one. A least square fitting of the results was performed, which yields the following semi-empirical formula :

$$x_m = K_1\, H + K_2 \qquad (10)$$

The values of the constants K_1 and K_2 for the different stability classes are given in Table 2.

The dispersion parmeters σ_y and σ_z at x_m can be written as:

$$\sigma_y = [\, a_1 \ln\,(K_1 H + K_2) + a_2\,]\,[\,K_1 H + K_2\,] \qquad (11)$$

$$\sigma_z = \frac{1}{2.15}\, \exp\,[\, b_1 + b_2 \ln\,(K_1 H + K_2) + b_3 \ln^2\,(K_1 H + K_2\,)] \qquad (12)$$

On substituting Eqn. (11) and Eqn. (12) into Eqn. (4) we get the following expresion for the maximum ground level concentration along the plume centre line :

$$\chi_m = R \exp - (\,S + T^2\,) \qquad (13)$$

where,

$$R = \left(\frac{2.15\, Q}{u\, \pi\, [a_1 \ln\,(K_1 H + K_2) + a_2]\ [K_1 H + K_2]} \right)$$

$$S = \{\, b_1 + b_2 \ln\,(K_1 H + K_2) + b_3 \ln^2\,(K_1 H + K_2)\}$$

$$T = \sqrt{\frac{2.15\, H}{2 \exp\,(S)}}$$

Defining the maximum ground level concentration for unit wind speed value and unit emission rate χ_m as :

$$\chi_m = \frac{\chi_m u}{Q} \qquad (14)$$

The values of χ_m were calculated for different release heights (H=50, 100, 150 and 200 m) in case of neutral stability conditions. Fig. 2 illustrates χ_m values against H. A least square fitting was performed for the data using the following relation :

$$\ln \chi_m = C_1 + C_2 H + C_3 H^2 + C_4 H^3 \qquad (15)$$

The constants C_1, C_2, C_3 and C_4 which give the best fitting of the results as shown in Fig. 2 are:

$C_1 = -7.653$, $C_2 = -0.05875$, $C_3 = 2.478\times10^{-4}$, $C_4 = -4.29\times10^{-7}$.

3. Case study

It is useful to apply the derived expression for x_m, χ_m on the research reactor in Inchas. A continuous ventillation system is provided with the reactor to the areas where radioactive gases, volatile materials and suspended particles can exist due to either leakage or airborne radioactivity. The total ventillation rate which could be emitted from the reactor stack of 43 m height and 2m internal diameter is 7850 m^3/hr. The plume rise $\triangle h$ have been calculated adopting the following equation (IAEA Safety Guide).

$$\triangle h = 3\left(\frac{w}{u}\right) D_i \qquad (16)$$

where, w is the exit velocity of the pollutants and D_i is the internal stack diameter.

The calculated values of $\triangle h$, x_m, χ_m according to Eqns. (16), (10) and (15) respectively are presented in Table 3.

The last column in this table presents the acumulated release in 48 hours which is the usual continuous operation time of the reactor.

4. Conclusion

Two simple formulae for calculating both the highest possible ground level ambient air concentration due to release from an elevated point source and the position of this maximum are derived.

The application of these formulae on the case of the research reactor in Inchas during the year 1987 showed that the maximum concentration values lies between 2×10^{-5} and 4.5×10^{-5} m^3/sec, while their downwind positions are approximately 850 m from the stack base.

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