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Modelling and simulation of heavy gas dispersion on the basis of modifications in plume path theory

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Abstract

An analytical model for heavy gas dispersion based on the modifications in plume path theory has been developed. The model takes into account the variations in temperature, density, and specific heat during the movement of heavy gas plume.

The model has been tested for three hazardous gases — chlorine, natural gas and liquefied petroleum gas. The results have been compared with the recently generated experimental data as also with the outputs of other models. A good agreement is observed qualitatively as well as quantitatively.

A study has also been carried out to simulate the effect of the wind speed, density of the gas, and venting speed on dispersion. Based on the simulation study a set of empirical equations has been developed. The equations are validated by theoretical as well as experimental studies.

Keywords: Plume path theory; Dispersion; Air quality modelling; Heavy gas dispersion

1. Introduction

Modelling of the dispersion of the 'dense' gases — gases with density higher than air — has been assuming ever greater importance as many of the hazardous gases (chlorine, hydrogen fluoride, liquefied petroleum gas) are denser than air. Numerous air pollution models, which were developed for lighter-than-air or light-as-air gases, have not been successful with dense gases; accentuating the need for mathematical models appropriate for dense gas dispersion. In recent years, a few mathematical models have been proposed for the study of

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heavy gas dispersion — notably by Ooms et al. [21], Ooms and Duijm [24], Colenbrander [6], Eidsvik [9], Ermak and Chan [11], Van Ulden [30,31], Langlo and Schatzmann [16] and Deaves [7,8].

One of the first attempts to model the heavy gas dispersion was made by Ooms et al. [23]. They proposed an analytical model based on using the conventional transport phenomena and the plume path theory (Ooms [21]). Later Colenbrander [6] proposed slab (continuous release box) model which assumes normal distribution of concentration within the slab. Around the same time Eidsvik [9] proposed a refined box model with equations modified to estimate vertical entrainment of air. Van Ulden [30], Van Ulden and Holtslag [32], and Van Ulden [31] used K-theory with atmospheric scaling parameters to model heavy gas dispersion. Ermak and Chan [11] proposed a model based on the turbulence dissipation and boundary layer parameters. In subsequent years, Langlo and Schatzmann [16] modelled the heavy gas dispersion using Langrangian approach based on similarity theory. Deaves [8] modelled the atmospheric turbulence and analysed the way it affects dense gas dispersion. He also used K-theory and employed more extensive meteorological data than the other models did: wind profile, turbulence and boundary layer profiles.

Surprisingly in the present age of computer-based application software, very few such models have been proposed. They include finite difference models which use K-theory: MARIAH (Taft et al. [28]), SMART (Tran and Liu [29]), SIGMET (England et al. [10]; Havens [14]) and MERCUR-GL (Riou [26]), or box model such as HEGADAS (Colenbrander [6]; Puttock [25]). Of these the last named is the most often cited one. The outputs of these models are well tested with experimental values and are found to be in fairly good agreement.

Although the above mentioned models have been reasonably successful in some cases, they are limited in scope and have found applicability in only certain specific conditions. In this paper, we present a model based on plume path theory (PPT) which, we hope, may enrich the repertoire of the heavy gas dispersion models presently available.

Plume path theory (PPT) was proposed by Ooms [21] and has been used mainly to calculate the plume path of the lighter-than-air and light-as-air gases escaping from the stacks into the atmosphere at atmospheric temperature and pressure. Later this theory was extended to ‘heavy’ gases (of density higher than air; Ooms et al. [23]) with a number of assumptions. Numerous applications of the PPT have been reported, e.g. Rottman et al. [27] and McQuaid [17] have used the theory for analysing toxic gas dispersion; Niewstadt [19,20], Blewitt et al. [2] and Weil [33] have used the same for vapour cloud modelling; and Ooms and Duijm [24] have used the theory to estimate the dispersion of heavy gases coming out of the stacks with high momentum. The theory has also been the basis of the commercial packages PLUME and HFPLUME. In spite of the obvious potential of Ooms’ theory, it has not enjoyed wider applicability because the main assumptions have not yet been overcome. The authors of this paper have recently modified Ooms’s theory to significantly enhance its range, accuracy, and precision. Most importantly we have enabled application of the theory to ‘heavy gases’ which is a much less explored domain of air quality modelling than the dispersion of the lighter-than-air or light-as-air gases. PPT (Ooms [21]; Ooms et al. [23]; Ooms and Mahiue [22]) is a simple approach based on the fundamental principles of fluid dynamics such as Fick’s law of diffusion, turbulent kinetic energy and fluid flow. It is based on the assumption that the density and the specific heat of a gas do not differ significantly

Table 1
Redefinition and advancement in the assumption made in Oom's PPT model

Assumptions made in PPT (Ooms and cowrokers, 1972 1974, 1983)	Modifications proposed by the authors
The mean flow velocity perpendicular to the main flow in the direction of the plume is negligible till a late stage of the plume movement	Secondary flow perpendicular to the plume axis is significant at much earlier stage as well
The velocity profile, density, and pollutant concentration are similar in all sections normal to the plume axis	None
Molecular transports is considered negligible in comparison with turbulent transports	Molecular transport has been treated as significant and taken into account in parameter estimation
Longitudinal turbulent transport is considered negligible compared with longitudinal convective transport	Both longitudinal as well as convective transports have been taken into account
–	Physical properties of venting gas have been considered as a function of downwind distance as well as atmospheric parameters

from that of air. In dispersion calculations, it neglects density spread as well as buoyancy effect. However, these assumptions do not hold true for heavy gas dispersion. In the present paper, we have modified PPT in an attempt to make it suitable to model heavy gas dispersion. Some empirical correlations have also been developed to show the dependency of plume variables (concentration, density, plume width, plume velocity) on atmospheric operating variables such as wind velocity, venting velocity and density difference. The applicability of the model developed by us has been demonstrated.

2. Mathematical representation

In its original form (Ooms [21]) plume path theory takes into account only plume — dimensions namely velocity and concentration. Later it was modified to take into account density and specific heat variations (Ooms and Mahiue [22]). Ooms et al. [23] demonstrated its application to the modelling of venting gases heavier than air at high temperature. However, the modified PPT was based on a number of assumptions (Table 1). The present work is an attempt to make the existing theory more reliable by redefining the assumptions (Table 1) and developing empirical relations to estimate the effect of release and atmospheric parameters on dispersion.

2.1. Profiles

Let s, r, and ϕ be the plume co-ordinates at the plume axis as shown in Fig. 1. These co-ordinates are related to the horizontal and vertical axis as:

$$\frac{\mathrm{d}x}{\mathrm{d}s} = \cos\phi$$

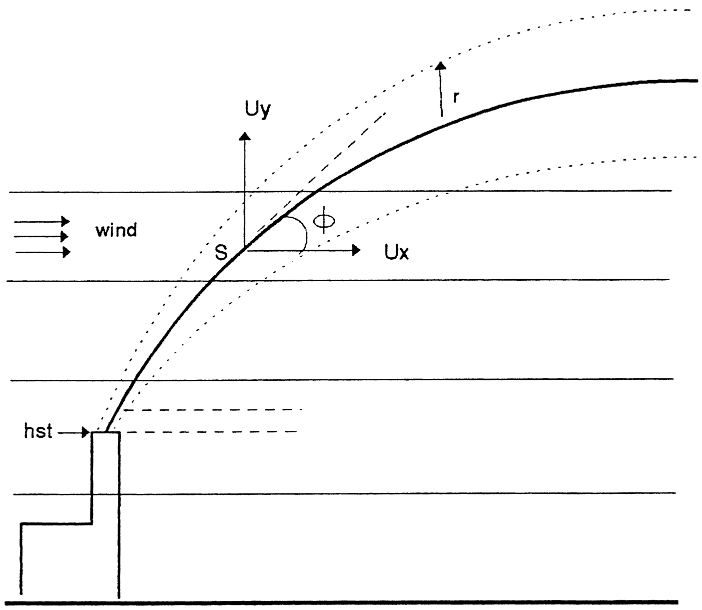

Fig. 1. The plume coordinates as used in the present study.

$$\frac{dz}{ds} = \sin\phi \tag{1}$$

In the earlier form of PPT (Ooms and co-workers [21–23]) only three parameters (u,ρ,c) have been considered as significant. In the present work, temperature also has been taken as one of the dominant parameters. Incorporating the aspects of plume density, temperature and specific heat, the plume characteristics can be written as:

$$u(s,r,\varphi) = u_a\cos\varphi + u^*\exp\left(\frac{-r^2}{b_s^2}\right) \tag{2}$$

$$\rho(s,r,\varphi) = \rho_a + \rho^*\exp\left(\frac{-r^2}{\lambda^2 b_s^2}\right) \tag{3}$$

$$c(s,r,\varphi) = c^*\exp\left(\frac{-r^2}{\lambda^2 b_s^2}\right) \tag{4}$$

$$T(s,r,\varphi) = T_a + \exp\left(\frac{-r^2}{Pr^2 b_s^2}\right) \tag{5}$$

where $u(s,r,\phi)$, $\rho(s,r,\phi)$, $c(s,r,\phi)$ represent the values of the variables at an arbitrary point in the plume; u^*, r^*, c^* denote the values of variables relative to the surroundings on the plume axis in the direction at a tangent to the plume axis; and b represents the local characteristic width of the plume. In the present study it is equal to the radius of plume (b/2).

2.2. Plume path

As the plume moves through the atmosphere, air is entrained. Getting a precise mathematical description of this entrainment is one of the most difficult problems in the air pollution modelling (Hawthrone [15], Abraham [1], Briggs [4], McQuaid [17]). Here we have tried to represent the entrainment in terms of mass flow equations keeping the following facts in mind:

(a) in the vicinity of vent or release point venting velocity is higher than wind velocity;
(b) at a sufficiently long distance downwind, the velocity of the plume may equal the wind velocity; and
(c) atmospheric turbulence is one of the most effective factors causing entrainment.

These three facts have been taken into account independently by Abraham [1], and recently by Briggs [4] and Fay and Zemba [12,13] who have proposed different flow equations for each type of entrainment. The final mass flow equation will be a combination of these three entrainment modes with modified profiles of plume characteristic parameters. The mass flow equation can be written as;

$$\frac{\mathrm{d}(\int \rho u 2\pi r\,\mathrm{d}r)}{\mathrm{d}s} = 2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}\{\alpha_1|u^*| + \alpha_2 u_{\mathrm{a}}|\sin\varphi|\cos\varphi + \alpha_3 u\} \tag{6}$$

where $2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}\alpha_1|u^*|$ represents the entrainment due to the jet release of gas, $2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}\alpha_2 u_{\mathrm{a}}|\sin\varphi|\cos\varphi$ the entrainment in a thermal stagnant atmosphere and $2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}\alpha_3 u$ the entrainment due to atmospheric turbulence.

The values of entrainment coefficient α_1=0.0762, α_2=0.61, and α_3=1.0 have been taken from Fay and Zemba [12,13].

2.2.1. Component mass balance

The component mass balance over a cross-section of plume is worked out as:

$$\frac{\mathrm{d}(\int c u 2\pi r\,\mathrm{d}r)}{\mathrm{d}s} = 0 \tag{7}$$

This implies that no gas is assumed to be present in the atmosphere outside the plume.

2.2.2. Momentum balance

In plume, the momentum occurs mainly due to

(a) entrainment of air, and
(b) force exerted by wind.

Keeping these in view the momentum balance equation in the downwind direction can be written as:

$$\frac{\mathrm{d}(\int(\rho u^2\cos\varphi 2\pi r\,\mathrm{d}r))}{\mathrm{d}s} = 2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}u_{\mathrm{a}}\{\alpha_1|u^*| + \alpha_2 u_{\mathrm{a}}|\sin\varphi|\cos\varphi + \alpha_3 u\}c_{\mathrm{d}}\pi b_{\mathrm{s}}{u_{\mathrm{a}}}^2|\sin^3\varphi| \tag{8}$$

where $2\pi b_{\mathrm{s}}\rho_{\mathrm{a}}u_{\mathrm{a}}\{\alpha_1|u^*|+\alpha_2 u_{\mathrm{a}}|\sin\varphi|\cos\varphi+\alpha_3 u\}$ represents the increase in momentum due to inflow of air from the surrounding atmosphere.

$c_d \pi b_s \rho_a u_a^2 |\sin^3 \varphi$ represents the increase in impulse due to the drag force exerted by the wind on the plume.

The momentum balance in the cross-wind direction is a combination of

- density spread
- drag force exerted by wind

The final balance equation can be written as:

$$\frac{\mathrm{d}(\int(\rho u^2|\sin\varphi|2\pi r\,\mathrm{d}r))}{\mathrm{d}s} = \int g(\rho-\rho_a)2\pi r\,\mathrm{d}r - c_d \pi b_s \rho_a u_a^2 \sin^2\varphi \cos\varphi \tag{9}$$

The first term $\int(\rho u^2|\sin\varphi|2\pi r\,\mathrm{d}r)$ represents density spread while second term $c_d \pi b_s \rho_a u_a^2 \sin^2\varphi\cos\varphi$ represents the impulse due to drag force exerted by wind.

2.2.3. Energy balance

The energy balance for the plume implies that the amount of heat emitted by the gas per unit time is conserved with respect to a chosen reference. So, for a reference temperature T the energy balance equation can be written as:

$$\frac{\mathrm{d}(\int \rho u c_p (T-T_{a_0})2\pi r\,\mathrm{d}r)}{\mathrm{d}s} = 2\pi b_s \rho_a c_{p_a}(T_a - T_{a_0})\{\alpha_1|u^*| + \alpha_2 u_a|\sin\varphi|\cos\varphi + \alpha_3 u\} \tag{10}$$

If it is assumed that air and vent gas obey ideal gas law, then the temperatures (plume and air temperature) can be expressed as

$$T = \frac{M_w P}{(R\rho)} \quad \text{and} \quad T_a = \frac{M_{w_a} P}{(R\rho_a)} \tag{11}$$

where M_w and M_{w_a} represent molecular weight of plume and air respectively at any point in the plume. As molecular weight and specific heat differ, unlike what was assumed in the original PPT (Ooms [21]), these variables can be expressed as:

$$M_w = \frac{M_{w_0} cT}{c_o T_0} + M_{w_0}\left(\frac{1-cT}{c_o T_0}\right) \tag{12}$$

$$c_p = \frac{\{M_{w_0} c_{p_0} cT/(c_o T_0) + M_{w_a} c_{p_a}(1-cT/(c_0 T_0))\}}{M_w} \tag{13}$$

Combining the above energy balance equations with molecular weight variation and specific heat variation, the final equation can be written as:

$$\frac{\mathrm{d}(\int M_w c_p/(M_{w_a} c_{p_a}) u[1-\rho/\rho_{a0}\{1+c^*\rho_0/(c_0\rho)(M_{w_a}/M_{w_0}-1)\}]2\pi r\,\mathrm{d}r)}{\mathrm{d}s} = 2\pi^* b_s\left(\frac{1-\rho_a}{\rho_{a_0}}\right)\{\alpha_1|u^*| + \alpha_2 u_a|\sin\varphi|\cos\varphi + \alpha_3 u\} \tag{14}$$

Table 2
Ambient operating variables used in the study

Gas	Vent characteristics		Ambient characteristics		
	Vent diameter (m)	Venting speed (m/s)	Temperature (°C)	Wind speed (m/s)	Atmospheric stability
Natural gas	0.37	95	50	5	Slightly stable
	0.37	95	50	7	Slightly stable
	0.37	125	50	5	Slightly stable
	0.37	125	50	7	Slightly stable
LPG	0.25	45	40	5	Slightly stable
	0.25	45	40	7	Slightly stable
	0.25	63	40	5	Slightly stable
	0.25	63	40	7	Slightly stable
Chlorine	0.20	25	35	5	Slightly stable
	0.20	25	35	7	Slightly stable
	0.20	35	35	5	Slightly stable
	0.20	35	35	7	Slightly stable

3. Solution of the model

By substituting the similarity profile to these conservation equations, integrals can be calculated by using a suitable numerical integration technique — here we have used Simphson-1/3 technique. Using Newton–Raphson method (Carnahan [5]) coupled with L–U decomposition (Carnahan [5]) technique, we have solved sets of non-linear simultaneous equations. The model has been solved for three different gases and for different atmospheric operating conditions as presented in Table 2.

3.1. Experimental studies

An extensive study to measure the quality of stack emissions and the behaviour of the plume formed when ammonia is released from a pressurised storage vessel was conducted at Manali (near Madras, southern peninsula of India). The initial and boundary conditions of the release are given in Table 3. The study area has flat terrain and is made up of rural habitat. The study included meteorological parameters (vertical temperature profile, vertical as well as horizontal wind velocity profile), air quality (concentration profiles), and behaviour of the plumes (of heavier-than-air as well as heavy-as-air gases) under different sets of conditions influencing dispersion for a continuous as well as an instantaneous release. The following characteristics of the plume were studied measuring various parameters such as; temperature variation within the plume, concentration profiles in the cross wind and downwind directions, plume width, plume height, and the effect of the meteorological parameters on the plume behaviour. A gist of the experimental results obtained in the present study is presented in Table 4.

Table 3
The initial and boundary conditions for release of ammonia from pressurized vessel through vent valve

Parameters	Values
Storage capacity	200 t
Storage temperature	45°C
Storage pressure	1625 kPa
Height of the vessel	10.5 m
Height of vent pipe	2.5 m
Vent diameter	0.2 m
Ambient temperature	27°C
Ambient pressure	107.3 kPa
Wind speed (at 10 m)	5.5 m/s
Wind direction	North–West
Terrain of the area	Flat rural area with a roughness height of 1.2 m

4. Results and discussion

The comparison of the plume path (height of plume rise) obtained by our model with the results reported by Bodurtha [3], Moore et al. [18] and our own recent experimental studies are presented in Fig. 2. Good, qualitative as well as quantitative, agreements have been observed.

The temperature and the plume velocity variations have also been compared with the experimental data (Table 4), and a fairly good agreement has been observed (Figs. 3 and 4). When the concentration profile obtained by the present model (for release of ammonia) is compared with our experimental results (Fig. 5) the predicted results are seen to lie within the confidence interval of 40–50%, a match acceptable for air pollution models.

The simulation study reveals that the plume width and the plume velocity both increase in the downwind direction, while density of the plume, temperature of the gas (above

Table 4
Experimental results obtained in the present study

Downwind distance (m)	Plume velocity (m)	Ground level concentration (wt.%)	Plume width (m)	Plume temperature (°C)
10	0.85	0.001	0.027	42.66
50	1.55	0.002	0.065	39.69
100	2.15	0.038	0.097	35.40
200	2.75	0.045	0.137	33.48
300	3.25	0.087	0.174	30.78
400	3.65	0.098	0.202	29.43
500	4.00	0.129	0.245	28.35
600	4.35	0.157	0.312	27.81
700	4.50	0.175	0.357	27.54
1000	4.75	0.224	0.415	27.46
1300	4.85	0.254	0.447	27.41
1750	4.90	0.354	0.521	27.39

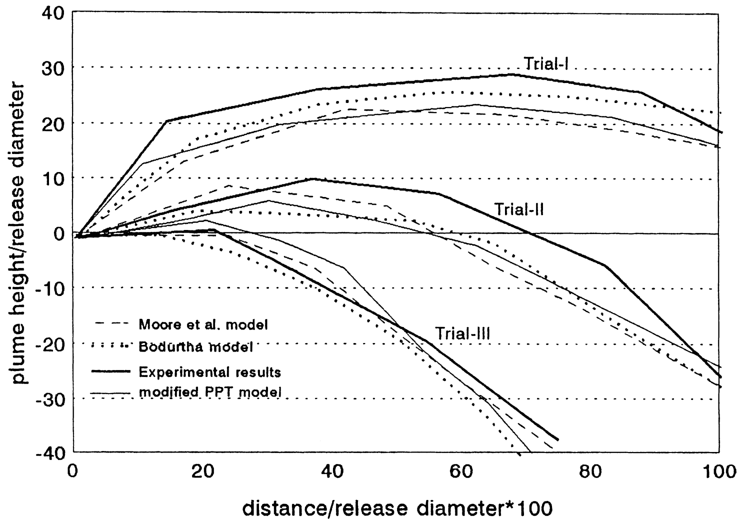

Fig. 2. Comparison of plume path estimated by PPT with other models and experimental results.

atmospheric temperature) and gas concentration all decrease downwind. We see that the trend diminishes as the distance of travel of the plume increases. This has been observed for all the three gases studied (natural gas, LPG, chlorine). The observations on the individual gases are summarised below.

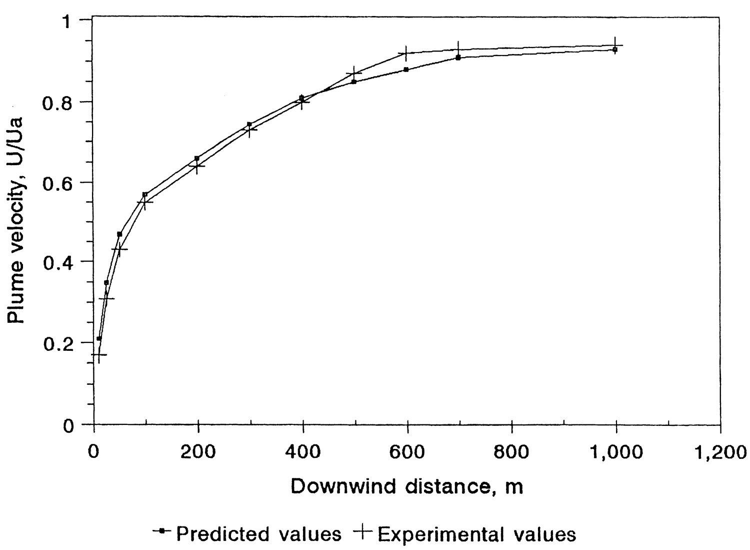

Fig. 3. Comparison of observed values of plume velocity with experimental values.

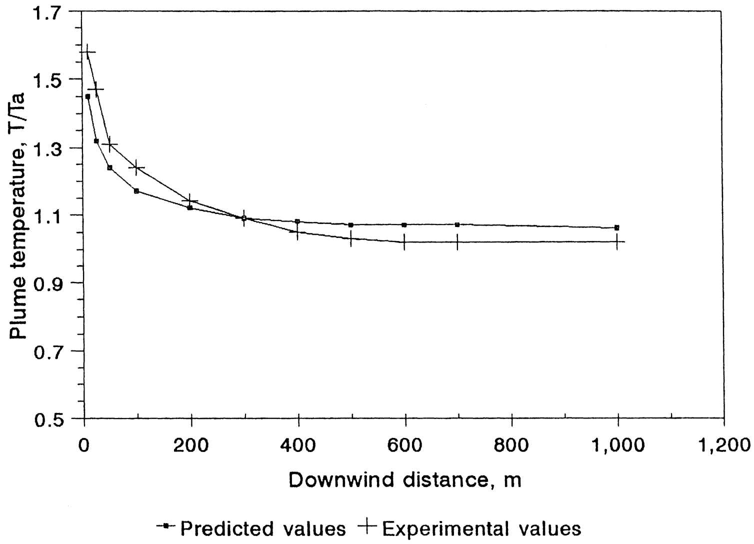

Fig. 4. Comparison of observed values of plume temperature with experimental values.

4.1. Natural gas

Fig. 6 shows the behaviour of plume variables (dimensionless form) in downwind direction due to the change (step increase) in wind and venting speeds. An increase in the wind speed causes an increase in the plume velocity and the plume width. A similar trend is also

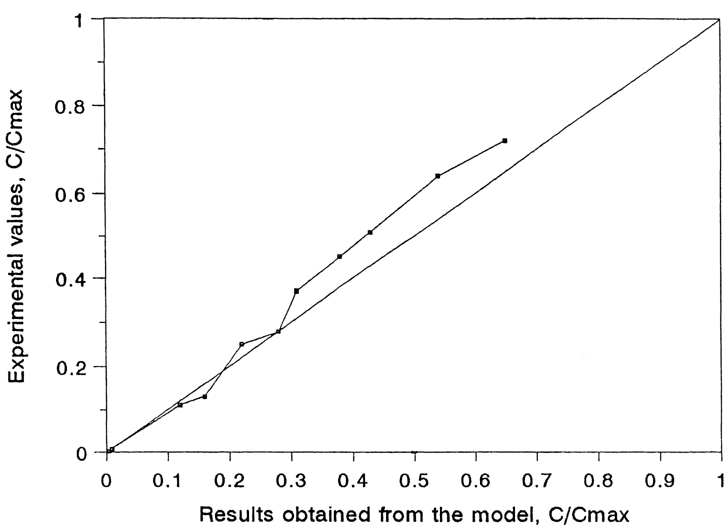

Fig. 5. Comparison of concentration of gas in the plume with experimental values (venting of ammonia).

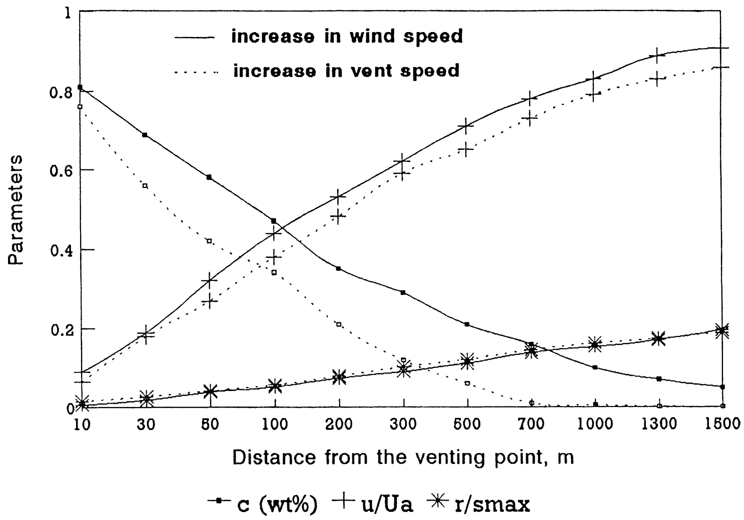

Fig. 6. Impact of 40% change in wind speed (from 5 to 7 m/s) as compared to the impact of 40% change in venting speed (from 95 to 125 m/s) on three plume variables (natural gas).

observed for an increase in the venting speed. However, the trend is more significant in the case of increase in the venting velocity compared to the increase in wind speed. Perhaps high venting speed creates high turbulence and wake formations in the atmosphere which consequently lead to the rapid entrainment of air and swift dispersion too. Wind speed effects the downwind transportation of the plume more strongly than it does the entrainment of air and its dispersion. As the density of the gas (vapour density=1.34) is not much higher than air a fast response due to a change in the controlling parameters, namely wind velocity and venting velocity, has been observed. For example, a venting velocity of 125 m/s (mass release rate 10 kg/s for 5 min) covers a smaller area under flammability limits compared to a venting velocity of 95 m/s (mass release rate 5 kg/s for 10 min) under high wind (15 m/s). This reveals that a high release (venting) velocity of this gas for shorter periods is safer than a slow release under unstable conditions for longer duration.

4.2. Liquefied petroleum gas (LPG)

The pattern of dispersion of LPG is by and large similar to the pattern of dispersion of natural gas discussed above. However, a low venting speed (45 m/s) and a higher density causes slower dispersion. It is evident from Fig. 7 that at any distance along the downwind direction, plume velocity and the concentration of gas in the plume are higher while plume width is less due to an increase in the wind speed when compared with the increase in venting speed. Thus, high venting speed has stronger influence on the entrainment of air and the plume width leading to faster dispersion. But high wind speed also transports the plume to a larger distance with higher velocity.

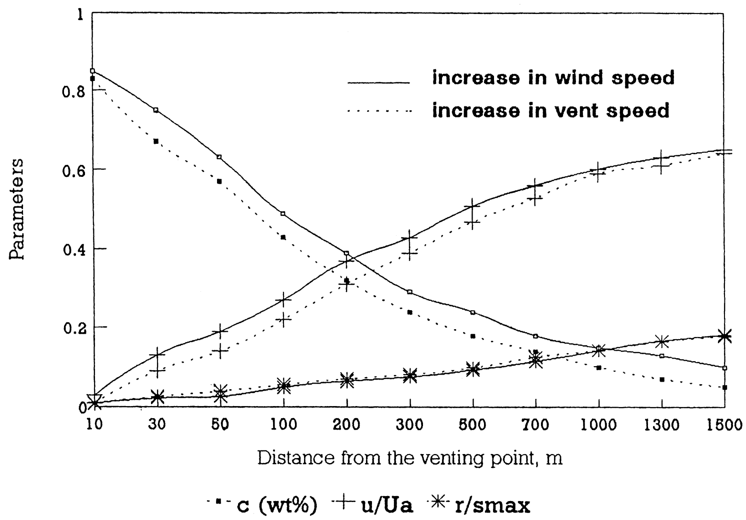

Fig. 7. Impact of 40% change in wind speed (from 5 to 7 m/s) as compared to the impact of 40% change in venting speed (from 45 to 63 m/s) on three plume variables (LPG).

4.3. Chlorine

Of the three hazardous gases discussed in this work, chlorine has by far the slowest rate of dispersion. Otherwise, the trend observed with chlorine is broadly similar to the trends seen with the other two gases. As is evident from Fig. 8 the dispersion increases with an increase in the wind speed and is faster with the higher venting speeds. For any given distance, the concentration of chlorine is higher and the plume velocity is lower compared to the other two gases. As chlorine gas is the most toxic of the three gases studied and is also the most sluggish to disperse, lethal concentration of this gas can easily build up over large areas and persist for long durations.

4.4. Parametric effect

To generalise the effect of wind speed, density and venting speed on the plume path, we have developed some empirical equations. These equations directly predict the behaviour of plume variables (gas concentration in plume, plume density, local plume width, plume velocity) with other operating variables, namely density of gas, venting speed, etc.

For this purpose a dimensionless number Q_f has been defined as:

$$Q_\mathrm{f} = \left(\frac{u_\mathrm{a}}{u_\mathrm{v}}\right)\left(\frac{\rho_\mathrm{a}}{\rho}\right) \tag{15}$$

$$p^{*} = A_1 \ln(s) + B_1$$

$$A_1 = -0.00395848 \log(Q_\mathrm{f}) - 0.01925951$$

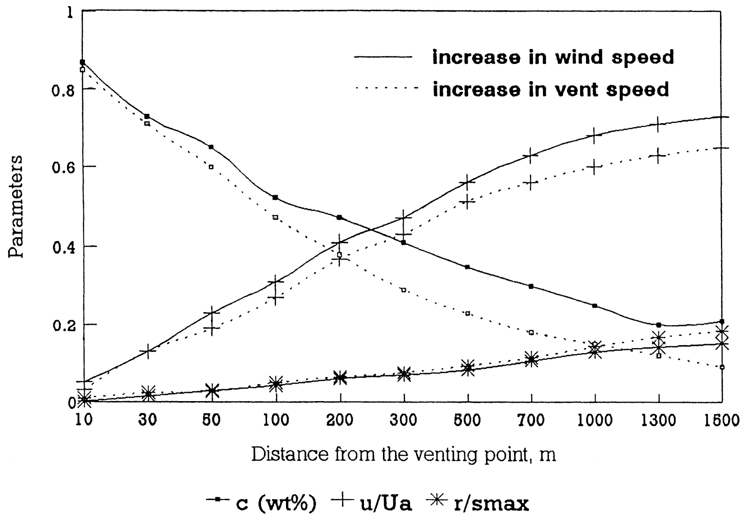

Fig. 8. Impact of 40% change in wind speed (from 5 to 7 m/s) as compared to the impact of 40% change in venting speed (from 25 to 35 m/s) on three plume variables (Chlorine gas).

$$
\begin{aligned}
&B_1 = -0.16083 \log(Q_\mathrm{f}) + 0.091579 \\
&u^* = A_2 \ln(s) + B_2 \\
&A_2 = 0.159874 + 0.960923 Q_\mathrm{f} - 1.24869 Q_\mathrm{f}^2 + 0.3728 Q_\mathrm{f}^3 \\
&B_2 = -0.47832 + 0.0418951 Q_\mathrm{f} + 0.153298 Q_\mathrm{f}^2 \\
&c^* A_3 \ln(s) + B_3 \\
&A_3 = -0.0161965 + 0.00543481 Q_\mathrm{f} - 0.00128631 Q_\mathrm{f}^2 \qquad (16) \\
&B_3 = 0.183894 \exp(-0.382484 Q_\mathrm{f}) \\
&b_\mathrm{s} = A_4 \ln(s) + B_4 \\
&A_4 = 0.0157719 + 0.104969 Q_\mathrm{f} - 0.0347085 Q_\mathrm{f}^2 \\
&B_4 = 0.953469 Q_\mathrm{f}^{0.22422} \\
&T = A_5 \ln(s) + B_5 \\
&A_5 = 3.67477 + 7.61097 Q_\mathrm{f} - 2.42655 Q_\mathrm{f}^2 \\
&B_5 = -8.5476 - 58.7278 Q_\mathrm{f} + 26.7875 Q_\mathrm{f}^2
\end{aligned}
$$

The equations have been validated with experimental values. A plot representing different plume variables at Y-axis with dimensionless number Q_f is shown in Fig. 9. It can be seen that with an increase in Q_f, variables like plume width and plume velocity (shown on Y-axis) increase while gas concentration and density difference both decrease.

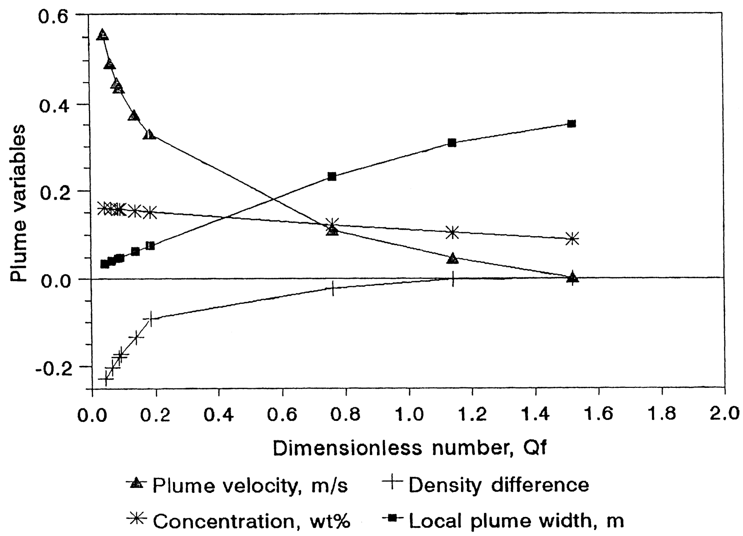

Fig. 9. Relationship of the dimensionless number Q_f (c.f. Eq. (16)) with different plume characteristics.

5. Conclusion

The plume path theory as modified by us gives satisfactory results for the dispersion of heavy gases. It also enables simulation of plume profiles along the cross-section of plume as well as in the downwind directions. The empirical equations developed by us on the basis of the present model, we hope, would prove to be helpful in air-pollution studies, as they can predict responses to the different ambient operating conditions over the plume variables (concentration, density, local width, temperature, etc.) with relative ease and fair accuracy.

List of symbols

b_s	local characteristics width (m)
c	concentration of gas at any point inside the plume (kg/m^3)
c_d	drag coefficient
c_o	concentration at outlet (kg/m^3)
c_p	specific heat of the gas at any arbitrary point (J/kg/K)
c_{p_a}	specific heat of air (J/kg/K)
c_{p_0}	specific heat at outlet (J/kg/K)
c^*	concentration of gas on the plume axis (kg/m^3)
g	acceleration due to gravity (m/s^2)
M_{w_0}	molecular weight of plume at the exit of the gas (gas and air)
P	absolute pressure (kPa)
Pr	Prandtal number
Q_f	dimensional number
r	radial distance to plume axis in a normal section of plume (m)

s	distance along the plume axis from the release point to a certain point (m)
T	temperature of the plume at any point inside the plume (K)
T_a	temperature of the atmosphere (K)
T_0	temperature of the plume at the release point (K)
T_{a_0}	temperature of the atmosphere at release point (K)
u	plume velocity at any point in the plume in the direction of the tangent to the plume axis (m/s)
u_a	wind velocity (m/s)
u_v	venting speed (m/s)
u'	entrainment velocity due to atmospheric turbulence (m/s)
u^*	plume velocity on the plume axis in the direction of the tangent to the plume axis (m/s)
x	cartesian coordinate (Figure 1)
z	cartesian coordinate (Figure 1)

Greek letters

α_1	entrainment coefficient of a free jet
α_2	entrainment coefficient due to thermal stratification
α_3	entrainment coefficient due to atmospheric turbulence
δ	length of transition zone (m)
λ	turbulent Schemedit number
ϕ	angle between plume axis to horizontal component
ρ	plume density at any point in the plume (kg/m^3)
ρ_a	density of air (kg/m^3)
ρ_{a_0}	density of air at release point (kg/m^3)
ρ_g	density of gas (kg/m^3)
ρ^*	density difference between plume and atmosphere (kg/m^3)

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