ESTIMATING THE HAZARD ROUND A VENT: A CASE STUDY

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Methods for estimating the extent of a flammable hazard and a vent orifice are described for a situation in which vapour/air mixtures are discharged with momentum from fuel tanks, taking small aircraft as the example. The results of laboratory measurements and field trials are used to validate desk estimates.

INTRODUCTION

Discharge of flammable or toxic gases or vapours from vents fitted to storage tanks usually occur when the tanks are being filled. The behaviour of the efflux depends upon its rate of discharge and its buoyancy and also on the manner in which the tank is being filled.

When filling occurs via the discharge vent itself through a hose nozzle inserted in it then the rate of filling is usually low and the discharge has little momentum; its buoyancy is relatively important. Examples of this are the fuelling of motor vehicles and, in previous years, of piston engined aircraft burning aviation gasoline by the method known as 'overwing' fuelling. Pumping of liquids directly into tanks via a separate inlet allows high rates of filling and the discharge from the vent pipe can have sufficient velocity to form a momentum jet in which the effect of the buoyancy of the material may be comparatively negligible in the early stages. Modern aircraft are fuelled by this method, known as 'pressure' fuelling or 'underwing' fuelling.

For outdoor 'overwing' fuelling, using Aviation Gasoline (AVGAS) the extent of the hazard from the vent was examined at the Fire Research Station on behalf of the Ministry of Aviation (1). A safety distance of 50 ft (~ 15 m) was set up (2) and this was subsequently reduced to 20 ft (~ 6 m) (3).

Modern aircraft serviced by 'pressure' fuelling and burning less volatile fuels such as 'Wide Cut' gasoline (AVTAG) and kerosine (AVTUR) present a different physical situation which has recently been examined by the Fire Research Station on behalf of the MOD (Air) (RAF) as part of a NATO-wide assessment of the risks associated with fuelling combat aircraft in the Hardened Aircraft Shelters (HAS) which are being increasingly deployed (Fig 1).

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METHODS FOR PREDICTING HAZARD DISTANCES

Equations have been published (4),(5) for the prediction of axial and radial concentrations in momentum plumes discharged from circular orifices and diluted with the surrounding air by turbulent entrainment. They are of the general form

$$\frac{\bar{C}_{x,r}}{C_0} = \left[k_1 \frac{d_0}{(x+k_2 d_0)} \quad \frac{\bar{\rho}_x}{\rho_0}^{1/2} \right] \left[\exp\left(-\, k_3 r/x\right) \right] \qquad (1)$$

The symbols have the meaning given in the of nomenclature. The first bracket represents the axial decay of concentration and the second the radial decay at a given axial distance.

Simplification to this equation can be usefully made, particularly when a hazard distance is being sought round a vent. The radial decay in the plane, the exponential term in equation (1), can be ignored and the axial decay distance taken and resolved to form a spherical hazard surface centred on the vent. This allows for the displacement of the momentum jet as a whole by ambient air movements.

The general equation applies to circular orifices. In practice, on combat aircraft, vent shapes are often non-circular and can be complex. A slot orifice is often seen. Equations dealing with non-circular orifices and the simplification of the equations for practical application are given in the Appendix.

Use of the equations requires a number of factors to be known, eg

1) the likely vent orifice concentration

2) the concentration to which the plume should be diluted to avoid a hazard

3) the decay constants.

PRACTICAL ASSESSMENTS

Determination of the above factors for aircraft fuelling required practical work both on a small scale in the laboratory and at full scale on airfields in HAS. The various factors were determined as follows.

Vent Orifice Concentrations

Modern aircraft fuels, although conforming closely to specifications can vary sufficiently in composition to render published values of properties unusable. Practical determinations were made as far as possible with samples of the actual fuels batch used in trials.

Measurements were made of fuel vapour concentrations in equilibrium with liquid fuel over a range of temperature so that in field trials concentrations likely to be encountered were known in advance. This data was obtained in a small (1.5 l) closed metal vessel held at a steady temperature and from which samples of vapour-laden air could be withdrawn for gas chromatographic analysis. Values were obtained for quiescent and 'shaken' conditions. The data obtained are shown in Fig 2 together with typical expected values as taken from the literature, which revealed that variations in vapour pressure of up to more *than a factor of 1.5 were possible. (The effect of icing inhibitors in AVTUR* were particularly marked). Also shown are the range of vent orifice concentrations measured during fuelling trials. Opportunity was also taken to sample from the ullage space of a fuel tanker (bowser). Vent samples were taken using an evacuated 'aerosol' can specially manufactured for the purpose and fitted with a means of taking samples from the can for gas chromatographic analysis. Fig 1(a) shows results for AVTAG over a range of ambient temperatures. Fig 1(b) shows results for AVTUR at elevated temperatures as encountered in one particular type of aircraft which deploys the fuel as a system coolant which can result in residual hot fuel being present in the tanks on fuelling.

Safe Dilution Level

Mixtures below the conventional Lower Explosible Limit (LEL) are generally considered to be non-ignitable. This is especially true for ignition by hot surfaces such as the exhaust systems of IC engines and certain light fittings, where ignition occurs only after a minimum exposure (induction) time to a given surface area at a particular temperature. Induction times for LEL mixtures are particularly long. Conventionally, safe levels in chemical plant practice are *often taken to be LEL/4 but the philosophy here is not entirely clear;* certainly conventional 'gas analysers' present an element of uncertainty in their readings which leads to caution.

Values of LEL vary markedly with chemical composition when expressed on a volume per cent basis but on a mass per unit volume basis are fairly consistent. Table 1 shows LEL measured in the FRS laboratories for the fuels encountered in this work together with published values for some of the components. In this work the LEL has been taken to be 40 g m^{-3}. In consideration of safety distances, as will be seen below, a safety margin of 25 per cent has been considered, ie an LEL of 30 g m^{-3} has been taken.

The Decay Constants

The Appendix derives simplified decay equations and gives values of the decay constants obtained from various sources. The simplified equations are

1) For the circular orifice

$$\frac{\bar{C}_x}{C_0} = 5\ d_0/x \qquad (2)$$

2) For a 'slot' orifice

$$\frac{\bar{C}_x}{C_0} = 2\ \sqrt{b_0/x} \qquad (3)$$

3) For an elliptical vent

$$\frac{\bar{C}_x}{C_0} = 6.7\ d_m/x \qquad (4)$$

In order to assess how valid these simplified equations were for predicting safety distances, field fuelling trials were carried out in which vent orifice concentrations and jet axial concentrations were monitored during the fuelling of five aircraft types at four airfield locations in the UK and Europe.

Preliminary examination of the aircraft showed a wide variety of vent orifice geometries ranging from a simple circular orifice via elliptical and 'slot' orifices to complex shapes. In order to check the jet pattern which would be encountered, mock vents were fabricated and smoke visualisation studies made. Thus the required location of gas sensor elements relative to the vents was known in advance of the field trials.

During the fuelling trials the fuelling rates were measured so as to check that the vent efflux velocities and hence the Reynolds numbers (based on air) were sufficiently high for a momentum jet to be established. Reynolds numbers ranged from 3×10^3 to 5×10^4.

Vent orifice concentrations were monitored at known and frequent intervals during a fuelling run by sampling with the evacuated 'aerosol' cans, gas chromatographic analysis being carried out on site immediately after the fuelling run.

Concentrations on the plume axis were continuously measured by specially selected gas analysis equipment placed at 0.25 m intervals from the orifice. The equipment chosen reflected the need for it to be able to indicate concentrations that might rise above the LEL (conventional hot wire element analysers are not suitable for this), concentrations that might be too low to give a reading on a hot wire analyser and to perform in a moving airstream which would introduce inaccuracies into the reading from a hot wire analyser. The particular solid state electrolytic cell gas sensor system was chosen as being the most suitable of that type available at the time of the work. It had the following advantages.

(i) It could measure down to a few ppm

(ii) It could measure > 2 LEL without damage to the sensor

(iii) It would operate in reduced oxygen concentrations

(iv) It would operate accurately in a moving airstream since the sensor operating temperature was low

(v) It would not be affected by extreme ambient conditions

(vi) It had recorder outlets.

A typical example of a plume concentration record is shown in Fig 2. The results of fuelling trials are shown plotted in a normalised form in Figs 3 and 4. Here a decay constant for circular orifices of 4 is seen to be more appropriate than the values 5 and for the case of the aircraft containing hot AVTUR, with a slot vent, 2.5 is more appropriate than 2.0.

ASSESSMENT OF HAZARD DISTANCE

The simplified decay equations, (2), (3) and (4) are seen to conservatively correlate with measurements of mean concentration. It is seen in the Appendix that a factor in this conservatism is the setting of $(\bar{\rho}_x/\rho_0)^{1/2}$ to unity - this corresponds to a margin of ten per cent. Further margins can be set by appropriate choice of C_0 and a safe level of $\bar{C}_x$. For AVTAG fuelled aircraft, *if the former is taken at* $300\ gm^{-3}$ *as opposed to* $250\ gm^{-3}$ *and the latter at* $30\ gm^{-3}$ as opposed to $40\ gm^{-3}$ then there is a built-in safety factor of 1.6 which together with the density approximation results in a factor of 1.8 over the decay constant, 4 for the circular orifices. Long (4) recommends a factor of

1.5 to allow for intermittent fluctuations of high concentration. The recommended choice for hazard distance made for this particular application incorporated a further safety factor.

Table 2(A) shows the hazard distances calculated for the various assumptions, together with the distance over which momentum is conserved. In all important cases the momentum is conserved. There are two exceptions. Firstly vent B, where momentum is conserved only to 43 g m^{-3}, a marginal value of LEL (see Table 1). Secondly, vent F, which discharged to ground from a height of about 1 metre. Interaction with the ground therefore takes place before momentum is lost. A special exploration of these conditions was made which will not be discussed in this paper.

The assumed values for hot AVTUR in Table 2(B) result in similar safety factors.

The nett result of the above considerations, which were made in the special context of this particular application, are in line with the recommendation by Long (4) for a decay constant, allowing for intermittent high fluctuations, of 9.

EFFECT OF VENT GEOMETRY UPON AXIAL CONCENTRATION DECAY

The three geometries examined yield different axial decay characteristics, given by equations (2), (3) and (4) which reflect the elemental ratio of surface area for entrainment to volume of jet $4/d$ for orifices, $3/b_m$ for ellipses of aspect ratio greater than 2 and $2/d(n/(n + 1)$, for a slot of aspect ratio n, $\rightarrow 2/d$ for high aspect ratio. Fig 6 shows a comparison between the three geometries for a given vent orifice area of 0.002 m^2, approximately equivalent to a 50 mm diameter circular orifice. It can be seen that for a constant orifice cross-sectional area elliptical orifices produce better dilution than a circular orifice, the 'degree' of dilution increasing with the aspect ratio (n). Elliptical orifices monitor three dimensional geometry at moderate aspect ratios. Extremely high values of elliptical aspect ratio would effectively give a slot orifice. Slot orifices have two dimensional geometry which is less advantageous for dilution although the surface/volume ratio is high. Even when n becomes high, the elliptical geometry still provides advantage over the slot geometry.

The advantage of a slot geometry is that at high input ratios ($n \approx 20$) it gives a more rapid initial dilution although at some distance from the vent the advantage is lost. For low aspect ratios, a slot geometry becomes a disadvantage. To equal the performance of a circular orifice at a distance the aspect ratio needs to be not less than 20.

Overall, bearing in mind other considerations such as ease of manufacture and resistance to flow a good compromise for choice of vent orifice shape would seem to be an ellipse of modest aspect ratio, say $n \approx 5$.

CONCLUSIONS

A study of the extent of the hazard around vent orifices on combat aircraft handling the efflux from the aircraft fuel tanks was made for five different aircraft types and two fuel types with a special case of hot fuel in one of the aircraft. The outcome was the establishment of safety distances which were less than those currently in force and which were inhibiting the practice of fuelling aircraft in HAS when required in terms of procedures and the provision of specially protected equipment. These inhibitions have now been removed. Additional flexibility has also been introduced into outdoor fuelling. The results of this study have therefore resulted in significant savings and increases in flexibility and efficiency in terms of capital costs and fuelling procedures.

The study has enabled an examination to be made of the effect of vent orifice geometry on the dilution of momentum jets. With a circular vent orifice as the datum, elliptical orifices perform better than circular. Slot orifices give increased initial dilution, but unless the aspect ratio is high, dilution performance is worse at a distance.

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TABLE 1. Values for lower explosible limit (LEL) for jet fuels and hydrocarbons

Fuel	LEL (gm^{-3})
Paraffins (carbon number >4)	41-46[1]
Aromatics	44-48[1]
Alicyclics	43-45[1]
AVTAG	43[2]
AVTUR	43[2]

[1] Literature value

[2] Laboratory measurements

TABLE 2. Application of simplified predictive equations to estimate hazard distances for AVTAG and AVTUR, based on field trial results

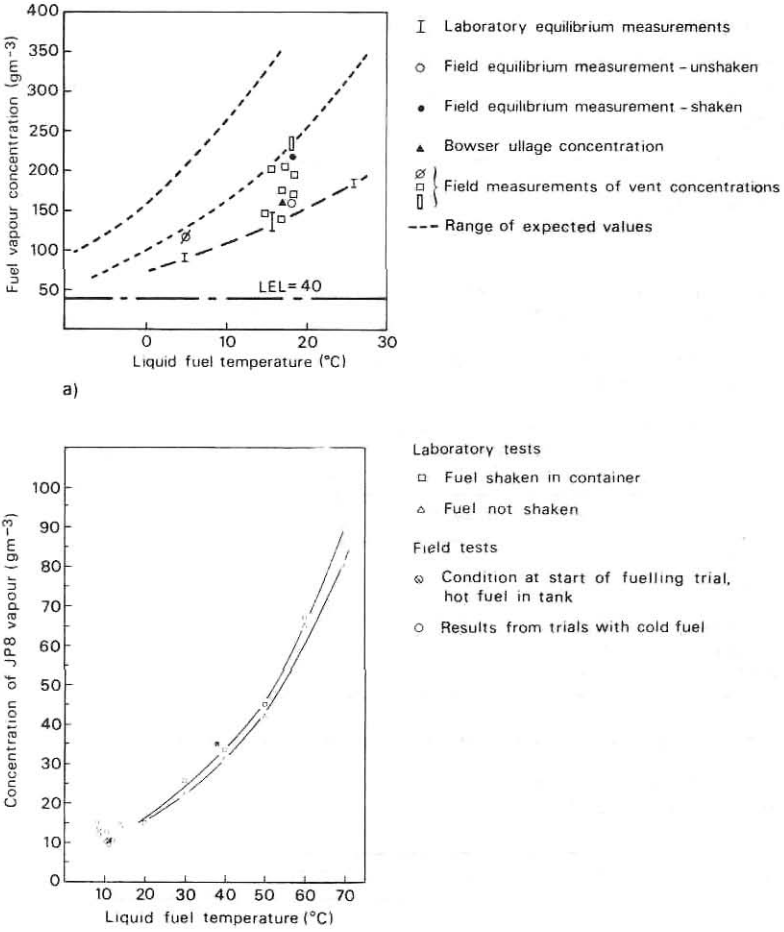
A. AVTAG (JP4, F40) at ambient temperatures
Taking $C_0 = 300\ g/m^3$

Vent	Hazard distance (m) based on LEL of		Distance for conservation of momentum (m)	Concentration at this distance (gm^{-3})
	40 gm^{-3}	30 gm^{-3}		
A, elliptical	1.5	2	3.5	17
B, circular	2.3	4	2	43
C, circular	1.5	2	4	15
D, elliptical	1.7	2.2	3	22
E, circular	1.5	2	3	20
F, slot*	2.3	4	2.8	36

*Vent orifice discharge towards ground, at height approx 1m

B. AVTUR (JP8, F34) at 60°C
Taking $C_0 = 100\ gm^{-3}$

G, slot	0.6	0.8	0.7-1.3	24-32



a)

b)

Figure 1 Fuel vapour concentrations as a function of liquid fuel temperature a) Avtag (JP4, F40), b) Avtur (JP8, F34)

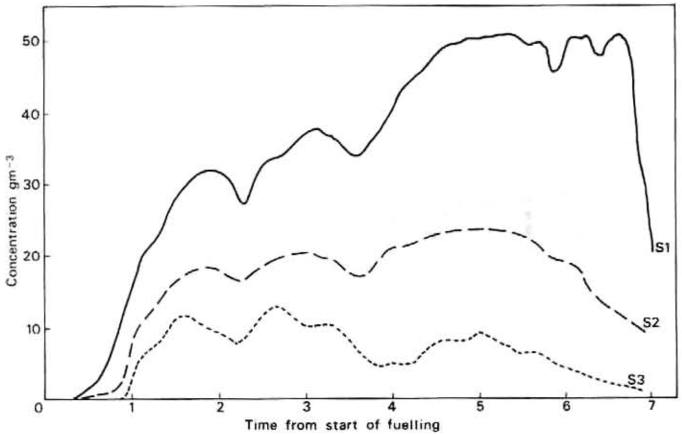


Figure 2 Typical plume vapour concentration record, sensor distance from vent S1: 0.75m
S2: 1.25m
S3: 2.0m

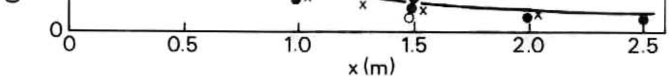


Figure 3 Decay of concentration from circular vents

—— $\frac{C_x}{C_o} = 4\,do/x$

● Results of three sets of trials on
○ two aircraft types with Avtag (●,x)
x and Avtur (o)

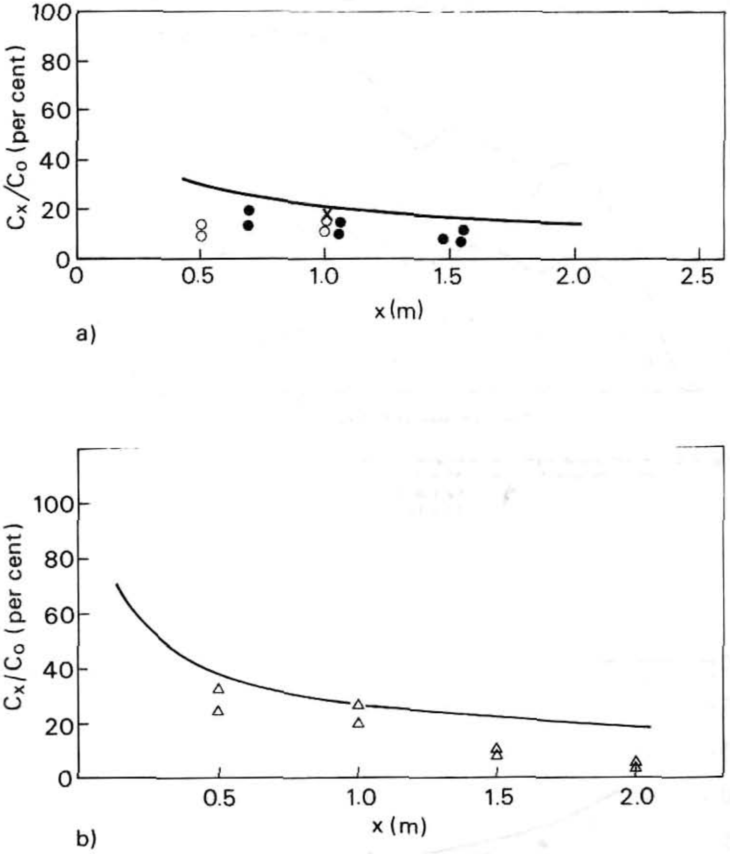


Figure 4 Decay of concentration from slot vents

a) $\frac{C_x}{C_o} = 2\sqrt{b_o/x}$ ——

● Results of three sets of trials on two
○ aircraft types with Avtag (●, x) and
△ Avtur (o)

b) $\frac{C_x}{C_o} = 2.5\sqrt{b_o/x}$ ——

△ Results of trials with hot Avtur

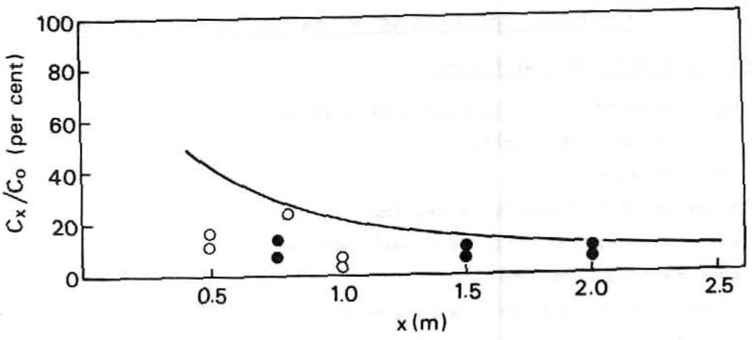


Figure 5 Decay of concentration from elliptical vents

— $\frac{C_x}{C_o} = 6.7\, d_o/x$

●} Results of two sets of trials on one aircraft type
○} with Avtag (●) and Avtur (○)

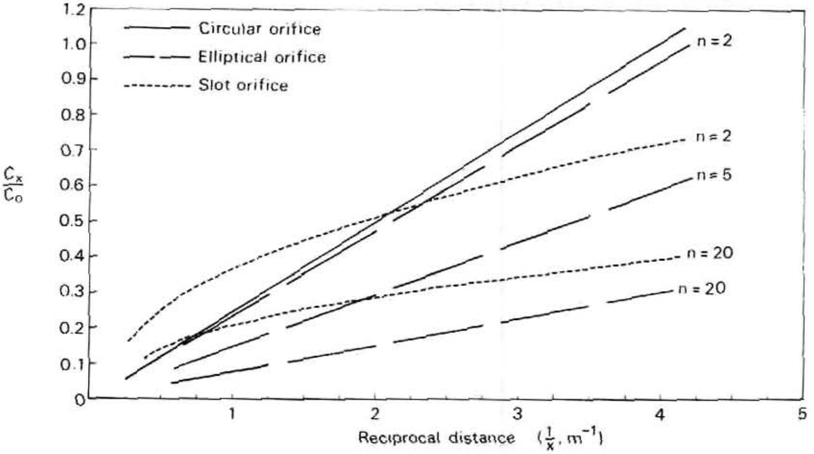


Figure 6 Comparison of circular, elliptical and slot orifices at different aspect ratios for a vent area of $0.002m^2$ (50mm dia circular orifice)

APPENDIX: THE DILUTION OF TUBULENT MOMENTUM PLUMES

Nomenclature for Momentum Plumes

a	major diameter of elliptical vent orifice
b	width of slot vent orifice
C	concentration
d_0	diameter of circular vent orifice
d	minor diameter of elliptical vent orifice
g	gravitational constant
l	distance from vent orifice to virtual origin of plume
m	mass flow rate through plume cross section
n	radius of plume
u	velocity of plume
x,z	axial distances from vent orifice, as defined locally
α	plume half angle
ρ	density
k,K	constants as defined locally

Subscripts

conditions at orifice (vent outlet)
condition at axial distance x from orifice (vent outlet)
conditions ambient to the plume

A1. The axisymmetrical (Conical) Plume

Consider an axisymmetrical plume whose momentum, by definition, is conserved

With nomenclature as defined in Figure A1.

Momentum flux $M = n.m.u = n\,d^2\bar{\rho}\,\bar{u}^2$

Where n is a numerical constant dependent upon the velocity distribution at plane distance x from the orifice.

$M_o = n_o m_o \bar{u}_o = n_o \pi/4.d_o^2 \rho_o \bar{u}_o^2$

Where n_o is a numerical constant dependent upon the velocity distribution at the orifice.

By similarity:

$$\frac{d.x}{x+\ell} = \frac{d_o}{\ell} = 2\tan\alpha \therefore 1 = d_o/2\tan\alpha$$

$$\frac{d}{d_o} = \frac{x+\ell}{\ell} = \frac{x+d_o/2\tan\alpha}{d_o/2\tan\alpha}$$

Equating $M_o = M_x$ and substituting for u_x, thus

$$u_x = \frac{n_o}{n_x}.\frac{m_o}{m_x}.\bar{u}_o$$

$$\frac{m_x}{m_o} = {\frac{n_o}{n_x}}^{1/2} \frac{d_x}{d_o} {\frac{\bar{\rho}_x}{\rho_o}}^{1/2}$$

$$= {\frac{n_o}{n_x}}^{1/2} \frac{x+d_o/2\tan\alpha}{d_o/2\tan\alpha} {\frac{\bar{\rho}_x}{\rho_o}}^{1/2}$$

or

$$\frac{m_x}{m_o} = \frac{K_1}{K_2} \frac{x+K_2}{d_o} {\frac{\bar{\rho}_x}{\rho_o}}^{1/2}$$

where

$$K_1 = \frac{n_o}{n_x}^{1/2}, \quad K_2 = \ell/2\tan\alpha$$

The property of the plume which is being diluted is conserved. In the present case it is the total amount of fuel vapour. Although the concentration (mass/volume) of the vapour is being reduced, the total quantity present in the plume at any normal plane is constant. Therefore one can write that $(m_o/\rho_o)C_o$ is the quantity of fuel vapour issuing from the vent per unit time and that $m_x/\bar{\rho}_x$). $\bar{C}_x$ is the quantity of fuel vapour crossing a plane normal to the plume distance x from the vent $\therefore (m_o/\rho_o)\, C_o = (m_x/\bar{\rho}_x).\bar{C}_x$

$$\frac{\bar{C}}{C_o} = k'_c \, \frac{d_o}{x + k''_c\, d_o} \, \frac{\rho_o}{\rho_x}^{1/2} \, \frac{\bar{\rho}_x}{\rho_o}$$

$$= k'_c \, \frac{d_o}{x + k''_c d_o} \, \frac{\bar{\rho}_x}{\rho_o}^{1/2}$$

where k'_c and k''_c are decay constants of the same type as $\mathcal{K}_1$ and $\mathcal{K}_2$ but numerically different on account of concentration profiles differing from velocity profiles.

A2. The Plane Two Dimensional (Slot) Plume

The coresponding momentum fluxes are, per unit length

$M_x = n_x m_x \bar{u}_x = n_x b_x \bar{u}_x^2 \rho_x$ at plane distance x

$M_o = n_o m_o \bar{u}_o = n_o b_o \bar{u}_o{}^2 \rho_o$ at orifice

where b_o is the width of the slot.

It follows that:

$$\frac{m_x}{m_o} = \frac{n_x}{n_o} \, \frac{b_x}{b_o} \, \frac{\bar{\rho}_x}{\rho_o}^{1/2}$$

$$= \frac{K_1}{K_2} \, \frac{x + K_2 b_o}{b_o}^{1/2} \, \frac{\bar{\rho}_x}{\rho_o}^{1/2}$$

The decay of time-mean axial concentrations can similarly be written

$$\frac{\bar{C}_x}{C_o} = k'_c \, \frac{b_o}{x + k''_c b_o}^{1/2} \, \frac{\bar{\rho}_x}{\rho_o}^{1/2}$$

A3. The Elliptical Plume

From geometric considerations noting that the area of an ellipse is ($\frac{\pi}{4}$.a.d) and the circumference is approximated by $2\pi\sqrt{(a^2 + d_m^2)/8}$ where a and b are the major and minor diameters, it can be shown that ratio of the circumference to the area which is essentially the ratio of the surface area per unit volume of a eulerian element of an elliptical plume available for dilution by entrainment is approximately $3/d_m$ for a $>2d_m$ compared with $4/d_m$ for a = d_m ie an axisymmetric plume.

The decay constant for an elliptical plume can therefore be estimated at 1.33 k_c'. In practice k_c' may well not be applicable to an elliptical plume on account of the three dimensional asymmetry of the velocity and concentration profiles.

A4. Experimental Values for k_c' and k_c''

Experimentally determined values for the velocity decay constants (K_1, K_2) are more numerous in the literature than those for concentration decay constants (k_c', k_c'').

It is possible to calculate values for velocity decay constants assuming analytical forms of the velocity profiles at the orifice and in the fully-developed plume. Concentration decay constants are not so readily calculable on account of the additional role that eddy diffusion plays in the dilution process.

It should be noted that the temperature of initially hot plumes decays in a manner identical to that of species concentration.

Long (4) and Field et al (6) have summarised values of k_c' and k_c'' and there is recent work by Sforza and Mons (7) and by Birch et al (8), for the round jet. There appears to be only one reported set of values for the plane plume, that of Zijnen (10). The elliptical plume appears not to have been investigated. Table A1 summarises the available data.

TABLE A1. Summary of experimentally determined values of k'_c and k''_c

The Round Plume

Value for k'_c	Value for k''_c	Reference
4.1-5.9	-	Review by Long (4)
6.0	-	*Working value suggested by Long (4)*
4.35-5.85	0.8	Review by Field et al (6)
5.0	0.8	Working value suggested by Field et al (6)
4.65	-0.9	Sforza and Mons (7) (temperature)
4.0 remote from orifice 4.7 near orifice	-5.8	Birch et al (8) (methane)
3.0	-	Ricou and Spalding (9). Relates to mean concentration only. *(Experiments measured air entrainment into plume)*

The Plane Plume

Value for k'_c:	2.0
Value for k''_c:	0.6
Size of slot:	0.5 cm x 10 cm
Reference:	van der Hegge Zijnen (10)

A negative value for k''_c indicates that the virtual origin of the plume is located downstream of the orifice.

A5. Simplified working equations

The foregoing equations describing the decay of concentrations with axial distance can be simplified without serious loss of accuracy for the present purposes.

Firstly the value of the term $k''_c.d_0$ is small compared with values of x of *practical interest;* typically $k''_c.d_0 \ll 0.1x$.

Secondly at distances at which concentration has decayed to the LEL, the ratio $(\bar{\rho}_x/\rho_0)^{1/2}$ approximates to unity. For example considering the LEL to be 40 mg/litre (gm^{-3}), the concentration at the orifice to be, say, 300 mg/litre (gm^{-3}) and the density of air at 20°C to be 1.2 kgm^{-3}, the ratio is $\sqrt{1.24/1.5} = 0.91$, assuming $\bar{\rho}_x = \rho_{x \cdot max}$ and $\sqrt{1.2/1.5} = 0.89$, assuming $\bar{\rho}_x = \rho_a$.

Mean values for k'_c for use in the simplified equations can be chosen to be 5, for circular vents, 2 for slot vents. The decay constant for elliptical vents is then $1.33k'_c = 6.7$.

The simplified equation can therefore be written

(a) Circular vents $\frac{C_x}{C_0} = 5\,\frac{d_0}{x}$ d_0 = vent diameter

(b) Slot vents $\frac{C_x}{C_0} = 2\,\overline{\frac{b_0}{x}}$ b_0 = slot width

(c) Elliptical vents $\frac{C}{C_0} = 6.7\,\frac{d_m}{x}$ d_m = vent minor diameter

These three equations are shown plotted in Figure A2.

A6. Persistence of Plume Momentum

Long (4) discusses the transition of a plume from momentum to buoyant in terms of the Froude number defined as

$$\text{Fr.} = \frac{\rho_0{}^{3/2}\bar{u}_0{}^2}{\rho_a{}^{1/2}\Delta\rho . g . d_0} \qquad \Delta\rho = \rho_0 - \rho_a$$

Momentum point for a distance z,

$$z = k.\text{Fr.}^{1/2}d_0.$$

Long shows that a calculated value for k of 2.4 is in good agreement with a value of 2.3 given by Ricou and Spalding (9) although the latter's results indicate that transition is gradual and can be expected to occur over the range $0.5<k<3.0$.

A value for k of 2.4 is used in this work.

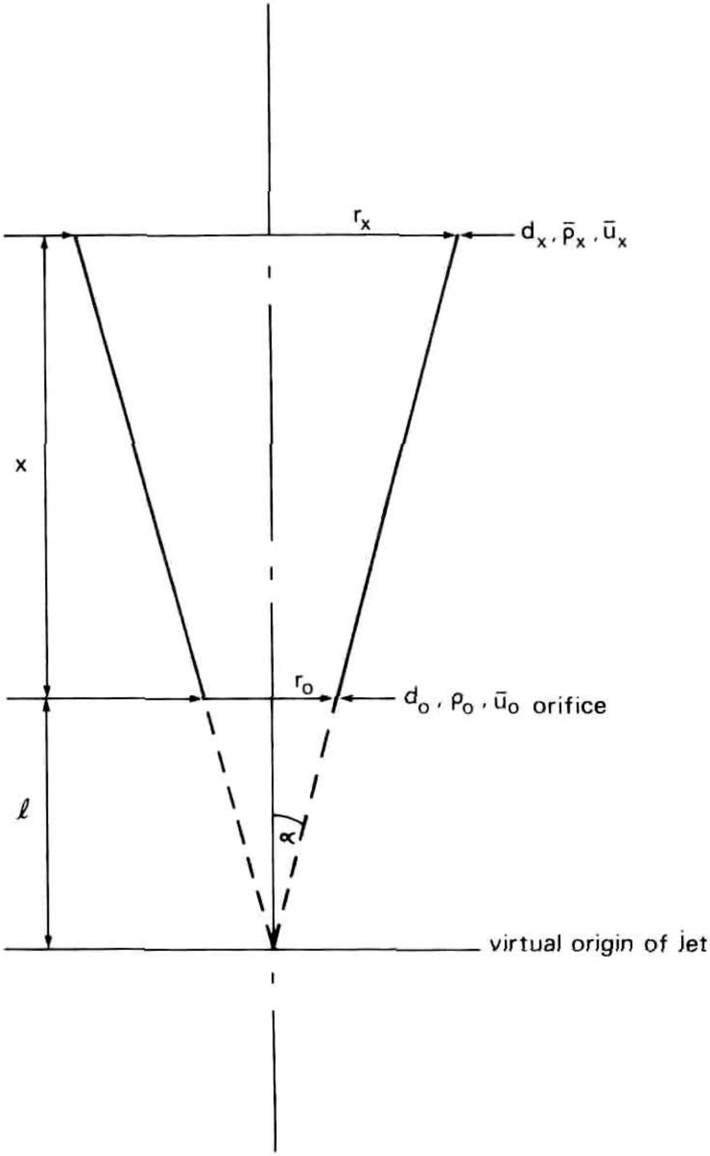


Figure A1 General nomenclature for turbulent jets