

# The build-up of concentration within a single enclosed volume following a release of natural gas

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## Abstract

This paper presents results from small-scale and full-scale experiments carried out to study the mixing process and build-up of gas concentration occurring within a nominally unventilated enclosure as a result of a release of natural gas. The results are correlated in terms of dimensionless parameters and it is shown how this may be used in a simple mathematical model to predict the build-up of natural gas for a wide range of release conditions. By taking into account relative density effects, the model may also be used for predicting gas build-up following releases of other gases, such as propane.

## 1. Introduction

If a jet of natural gas is released into free air, it will mix and disperse under the influence of its own momentum and buoyancy. However, if the release takes place within a confined volume, a build-up of gas concentration may occur. This accumulation occurs because the gas-air mixture, formed during the initial stages of the release, may be re-entrained into the jet or plume rather than fresh air. As a result the concentration of gas continues to increase with time. If the volume is being ventilated mechanically or if sufficient openings are available, this concentration build-up may be limited to part of the volume and the maximum gas concentration may not be excessive. However, if the volume has no mechanical ventilation or large openings, then a hazardous accumulation of gas-air mixture may occur. The rate at which this gas build-up occurs depends both on the release rate and also the volume

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within which the accumulation takes place. The build-up will also depend on the momentum and buoyancy flux of the release and its position and orientation within the volume.

In the case of a release dominated by buoyancy, the experience gained from work on geophysical applications can be used to explain the observed behaviour. For example, the analysis of Baines and Turner [1] can be applied to estimate within which part of the volume natural gas would accumulate. Their work establishes that the depth of the gas-air mixture is dependent on the ratio of the destabilising buoyancy-induced momentum, gained as the lighter-than-air natural gas plume rises towards the ceiling under the influence of gravitational forces, to the stabilising buoyancy forces associated with an increase of gas concentration with height. In circumstances when the stabilising forces dominate, the gas accumulates in a stratified layer that grows down from the ceiling. Subsequent work by Germeles [2] and Worster and Huppert [3] has shown how models can be produced to predict the build-up in concentration within the stratified layer. However, if the destabilising forces dominate, a well-mixed layer of a certain depth is produced. This latter case has received less attention from the mathematical modelling viewpoint. Nevertheless, previous experimental work has been used by Marshall [4] for example, to produce 'rules of thumb' from which the behaviour can be estimated.

This paper presents experimental results, both at small-scale and full-scale, on the accumulation of natural gas in nominally unventilated enclosures. It is shown that there is a consistent pattern of behaviour across the full spectrum of possible releases and that the results can be correlated in terms of dimensionless parameters. Further, it is shown how this correlation may be included in a simple mathematical model to predict the build-up of gas for the same wide range of releases.

A comparison of the resulting model with the original data is then given and discussed.

Although the correlations have been deduced from observations of the behaviour of natural gas, it is shown that, as the model is based on the values of relevant dimensionless parameters, it has more general applicability. In particular, the model may be used to predict the build-up of denser-than-air gases such as propane, provided that allowance is made for the fact that the gravitational forces act in the opposite direction to those on natural gas releases into air. Such a model has a use in the assessment of the possible hazards posed by flammable gas releases in enclosures.

## **2. Observations on the accumulation of natural gas in enclosed volumes**

Experiments have been conducted by British Gas in which natural gas has been released through an open ended pipe or nozzle into a nominally unventilated, cuboidal enclosure. Figure 1 illustrates the situation being considered. Table 1 indicates the range of parameters that have been studied. In all cases

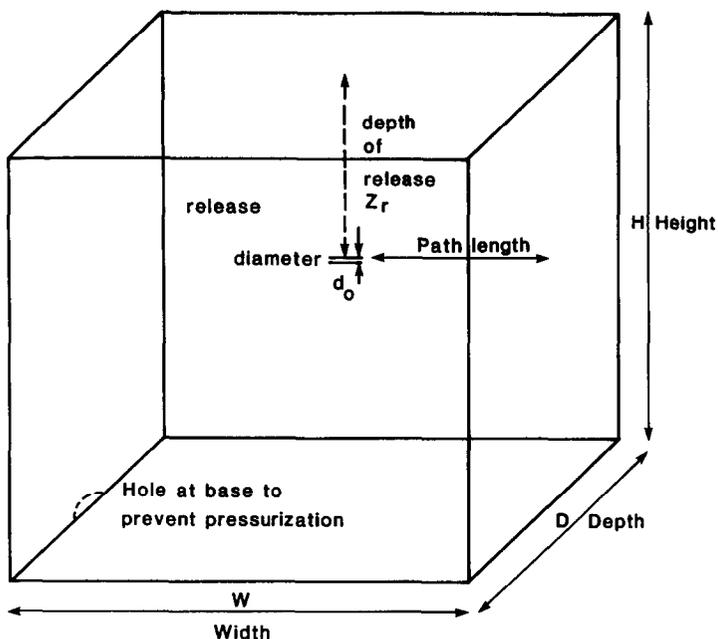


Fig. 1. Sketch of the geometrical arrangement of the enclosure and the release, showing the geometric parameters, as defined in the text.

TABLE 1

Range of conditions used in the full-scale gas experiments

Dimensions of Enclosures <sup>a</sup>	
Enclosure 1	3 m × 3 m × 3 m
Enclosure 2	3 m × 6 m × 3 m
Enclosure 3	5.4 m × 5.4 m × 2.4 m
Gases used	Natural gas, propane
Release Parameters	
Height	At intervals of 0.3 m between base and ceiling
Horizontal location	Central, near to a side wall or in a corner
Direction	Vertically up or down horizontal parallel to a side wall
Pressure	0.1 barg to 70 barg
Nozzle diameter	0.6 mm to 30 mm
Release velocity	4 m/s to sonic underexpanded jets
Inlet Richardson number	$10^{-1}$ to $10^{-8}$
Jetting lengths	0.3 m to 200 m

<sup>a</sup> With 12 mm diameter hole at the base (top) of the enclosure to prevent pressurization for the natural gas (propane) experiments

the Reynolds number of the flow in the pipe supplying the gas to the enclosure was large enough to ensure a fully turbulent exit flow.

The build-up of concentration was monitored within the volume and it was established that, in the range of geometrical configurations considered, to a first approximation the gas concentration in the bulk atmosphere of the enclosure was uniform across any given horizontal section. However, variations of the concentration with height can occur. Typically, an upper well-mixed layer of constant depth was produced with a lower stratified layer growing beneath it. As Marshall [4] noted, for any given release from a fixed position in the enclosure, a release that is aimed vertically upwards produces a smaller well-mixed layer than the same release aimed horizontally. The largest well-mixed layer is produced if the release is aimed downwards to oppose the direction of gravity. It was also noted by Marshall [4] that whilst changes in the horizontal position of the leak within the room produced minor differences in mixing behaviour, the most significant changes arose when the height of the release above the base of the enclosure was varied.

In order to shed further light on this behaviour, a series of small-scale flow visualisation experiments was carried out involving the injection of a dyed saline solution into fresh water. In these experiments, the release conditions were chosen in such a way as to duplicate the mixing behaviour observed when natural gas was released into air. Evidence was obtained to demonstrate the validity of the scaling approach. Further, as the incoming saline solution was dyed, the regions over which the mixture accumulated could be readily observed. These tests provided visual confirmation for the deductions made by Marshall [4] on the basis of the concentration records taken during the full-scale natural gas experiments.

### 3. Dimensional analysis

#### 3.1 *The governing parameters*

Dimensional analysis can be used to investigate the differences in behaviour between releases. There are two interrelated aspects to be considered. Firstly, there is the behaviour of the jet or plume emerging from the nozzle. For a given momentum and buoyancy flux, a release through a nozzle into an otherwise unconfined space has its own natural length scale influencing its behaviour. Consideration of where such a release would first impact or interact with the surrounding walls introduces the second aspect of the problem — namely, the influence on the release of constraining it within a given enclosure having its own length scale. In this Section, the interaction between these two different scales are considered.

The following nine parameters may be considered to influence the behaviour of the build-up of concentration

- (a) The density of the material being released,  $\rho_g$ .
- (b) The density of the material initially in the enclosure,  $\rho_a$ .

- (c) The initial radius of the nozzle through which the material is introduced,  $r_0$ .
- (d) The volume flux of material entering the enclosure,  $Q_0 = \pi r_0^2 u_0$ .
- (e) The specific momentum flux of the material entering the enclosure,  $M = Q_0 u_0$ .
- (f) The buoyancy flux of the material entering the enclosure,  $B = g'_0 Q_0$ .
- (g) The volume of the enclosure,  $V$ .
- (h) The horizontal cross sectional area of the enclosure,  $A$ .
- (i) The distance measured in the direction of the initial release before impacting on one of the surrounding walls,  $p$ .

In the above list of parameters  $u_0$  is the average velocity of the material entering the enclosure and  $g'_0$  is the value of the reduced gravity. In order to compare the ratio of the gravitational potential energy to the kinetic energy of the release, this is defined with respect to the density of the natural gas so that

$$g'_0 = g |\rho_a - \rho_g| / \rho_g,$$

where  $g$  is the value of the gravitational constant.

Since the Reynolds number and the Péclet number of the jet are high, the role of molecular properties such as the kinematic viscosity,  $\nu$ , and the diffusivity,  $\sigma$ , of the gas in air have been ignored.

The analysis of List in Chapter 9 of Fischer et al. [5] or Chen and Rodi [6] can be used to characterize the behaviour of the initial jet or plume emerging from the nozzle. This establishes that the length scale,  $L$ , over which the flow behaves as a jet in an otherwise unconfined environment, is given by

$$L = k r_0 / \sqrt{Ri_0}, \quad (1)$$

where  $Ri_0$ , the Richardson number of the inlet flow, is given by

$$Ri_0 = r_0 g'_0 / u_0^2, \quad (2)$$

and  $k$  is a numerical constant whose value is approximately 3. After a distance of order  $L$ , buoyancy forces become dominant. For a horizontal release, the jet will turn upwards at a distance  $O(L)$  from the nozzle. For a vertically downwards release, the jet penetrates a distance  $L$  before turning upwards and reversing, while for a vertically upwards jet,  $L$  is the distance at which the momentum flux produced by buoyancy is comparable with the initial momentum flux.

For flow into an enclosed volume, the ratio of  $L$  to  $p$  will determine by how much the trajectory of the jet is influenced in the initial stages of the build-up by the action of the buoyancy forces. However, in determining how the gas will accumulate ultimately, it is important to consider the size of the enclosure into which the leak is taking place. The jet acts as a source of kinetic energy, part of which is used to mix the gas within the enclosure. A parameter which provides some measure of the ability of the jet to promote mixing within the volume is given by  $Ri_v$

$$Ri_v = V^{1/3} g'_0 / u_0^2, \quad (3)$$

a Richardson number based on a length scale given by the characteristic dimension,  $V^{1/3}$ , of the enclosure. This parameter represents the ratio of the potential energy necessary to mix the gas uniformly throughout the enclosure compared with the kinetic energy of the gas jet.

Finally, the ratio of the time scale of the jet motion,  $T_j$ , to the time scale for filling the enclosure,  $T_v$ , will determine the influence of any build-up on the motion of the jet itself. These timescales are defined by

$$T_v = V/Q_0, \quad (4)$$

and

$$T_j = L/u_0. \quad (5)$$

### 3.2 Behaviour of releases with negligible initial momentum

Baines and Turner [1] have studied the case of a buoyant release with negligible initial momentum inside a closed volume. They showed that the behaviour was governed by the destabilising momentum flux,  $M_c$ , gained by the plume as it rose to the ceiling and the stabilising buoyancy force,  $B_c$ , in a layer that attempts to form at the ceiling. If the release is at a distance  $z$ , below the ceiling inside a closed volume with a horizontal cross-sectional area  $A$ , then  $M_c$  and  $B_c$  are given by

$$M_c = \rho \pi r^2 u^2$$

and

$$B_c = Ar\Delta\rho g, \quad (6)$$

where  $\rho$ ,  $r$ ,  $u$  and  $\Delta\rho$  denote the local density, radius, upwards velocity and density deficit from the ambient air, respectively, of the plume that is formed when it reaches the ceiling.

Baines and Turner defined the ratio of  $M_c$  to  $B_c$  as the overturning number,  $\Omega$ . They observed that, for those releases in which

$$\Omega = M_c/B_c > 0.1, \quad (7)$$

'overturning' took place. A well-mixed layer whose size was somewhere between about 1/3 and 2/3 of the depth of the release was formed in the enclosure. For smaller values of  $\Omega$ , a stratified layer is produced in the container that grows downwards with time from the ceiling. The upper layer represents that portion of the enclosure that the release is able to maintain in a well-mixed state. In an unventilated enclosure, ultimately, the environment would become filled with mixture. The density difference between the release and its surrounding environment would then decrease and this would cause the upper layer to grow. For gas releases, however, over the time taken for flammable concentrations to be produced, it can be taken as constant.

For a buoyant plume, the dependence of  $r$ ,  $u$  and  $\Delta\rho/\rho$  on the travel distance  $z_r$  is given by

$$r = d_1 z_r, \quad u = d_2 (B_0/z_r)^{1/3}, \quad \text{and} \quad g\Delta\rho/\rho = d_3 (B_0^2/z_r^5)^{1/3}, \quad (8)$$

where  $d_1$ ,  $d_2$  and  $d_3$  are numerical constants.

Substituting eqs. (8) into the expressions (6) for  $M_c$  and  $B_c$  and using values of 0.11, 2.1 and 7.1 for the constants  $d_1$ ,  $d_2$  and  $d_3$  inferred from the results presented in Papanicolaou and List [7], it follows that the criterion (7) for overturning to occur is equivalent to the condition that

$$z_r > 0.38\sqrt{A}. \quad (9)$$

Observations of the experiments referred to in Section 2 above, conducted at the full-scale using natural gas, support relationship (9).

### 3.3 Behaviour of forced plumes or buoyant jets

For those experiments likely to show the influence of the source momentum, the vertical concentration profiles were examined. In the majority of cases for which  $L \gg r_0$  a distinct well-mixed upper layer of depth  $h$  could be identified. However, the accuracy with which  $h$  could be determined is not only subject to the limitations imposed by the spacing between the probes (0.15 m or less), but also the somewhat subjective difficulty in defining the extent of a layer. For this reason, the values chosen for  $h$  are considered to be subject to an uncertainty of 0.3 m.

In order to examine the influence of the parameters introduced in Section 3.1 on the build-up of gas in an enclosure, for those experiments in which an upper well-mixed layer of depth  $h$  could be identified, an 'additional mixing depth',  $\delta$ , was defined by

$$\delta = h - \lambda z_r, \quad (10)$$

for some constant  $\lambda$ . This relationship assumes that a purely buoyant source would produce a well-mixed layer extending to some fraction of the distance between the release and the ceiling in those cases where overturning is observed to occur. The additional depth,  $\delta$ , of the well-mixed layer is attributed to the initial momentum of the release.

A table of values of  $\delta$ ,  $r_0$ ,  $L$ ,  $V^{1/3}$ ,  $Ri_0$  and  $Ri_v$  was prepared assuming different values of the parameter  $\lambda$  in the range between 0.3 and 0.7. It should be noted that cases where the mixed layer extended throughout the domain were excluded from the analysis, as in these cases there is no way of knowing whether a larger value of  $\delta$  would have resulted had the enclosure been any taller. For high pressure releases, an underexpanded sonic jet is produced at the nozzle. In these cases, the pseudo-source approach of Birch et al. [8] was used to define the Richardson numbers from the respective pseudo-velocity and radius. Graphs were prepared examining relationships between the parameters. From these plots, it was found that the best collapse of the experimental data was obtained by plotting  $\delta/r_0$  against  $Ri_v$  with  $\lambda = 0.5$ .

Figure 2 presents the data with this choice of  $\lambda$ . The vertically upwards, horizontal and vertically downwards releases are denoted by different symbols, as are the full-scale natural gas-air experiments and the small-scale brine-water simulations. The size of the error bars to be applied to the measurements made in the full-scale natural gas-air experiments are shown in

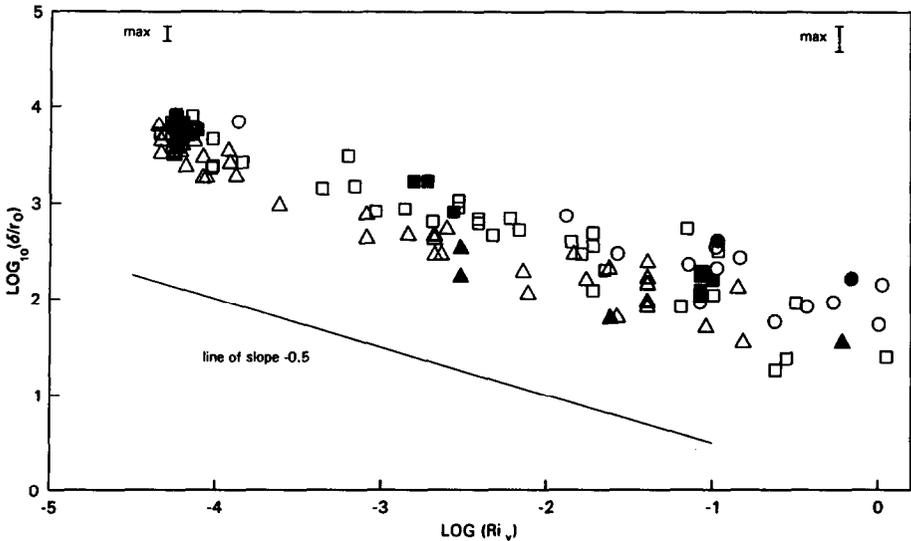


Fig. 2. Dimensionless plot to show the dependence of the additional mixing depth as a function of the release conditions. The different release orientations are shown by the different symbols as follows: (○) Vertically upwards, (□) horizontal, (△) vertically downwards. The open symbols represent full-scale gas-air experiments, the filled ones small-scale brine-water experiments. The error bars refer to the maximum uncertainty in the gas-air experiments.

the upper left hand and right hand corners of Fig. 2. These reflect the uncertainty in defining a precise value for the well-mixed layer depth,  $h$ . When plotted in dimensionless form with logarithmic scales, the size of the error bar appears proportionately greater for the experiments with the larger values of  $Ri_v$ .

It can be seen that there are no significant differences between equivalent small-scale and full-scale experiments. In all cases, an increase in the momentum flux for a given buoyancy flux, corresponding to a decrease in the Richardson number, produces relatively more 'additional mixing'. This is reflected by the observation that the experimental data shown on Fig. 2 follows a line with a slope of approximately  $-0.5$ . In dimensional terms, such a line would represent a relationship between  $\delta$  and  $Ri_v$  in the form

$$\delta = C_1 r_0 / \sqrt{Ri_v}, \quad (11)$$

for some constant  $C_1$ . A least squares best fit applied to the data in Fig. 2 produces values for the constant  $C_1$  of 25, 40 and 63 for vertically upwards, horizontal and vertically downwards releases, respectively.

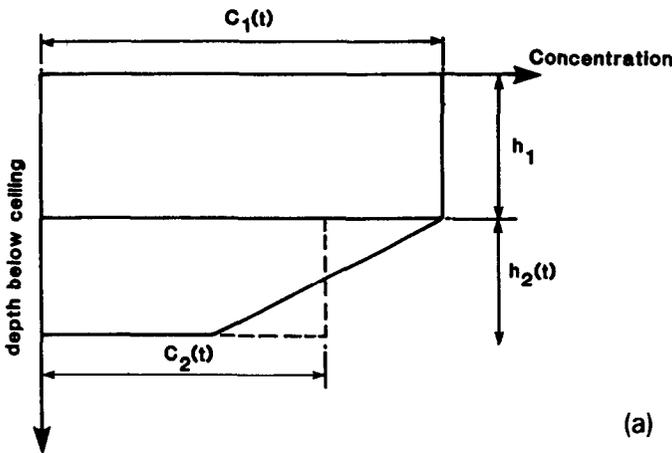
Further examination of similar graphs showed that there were no systematic differences between the releases in the different volumes, indicating an insensitivity to variations in the width-to-height (aspect) ratio of the volume for the limited range of between 1 and 2.6 over which the experiments took place. The scatter apparent in Fig. 2 may be an indication of the importance of other parameters,

such as variations in horizontal position of the release, that have been neglected in this analysis. A more detailed model of the motion of the jet and its interaction with the solid surfaces would be required to address this question further.

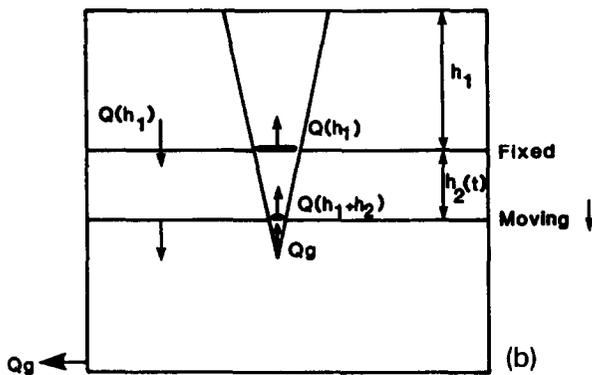
Nevertheless, eqs. (10) and (11) can be used as a means of estimating the size of the well-mixed layer applicable to the different release directions. This has been incorporated in a simple mathematical model described in the Section 4. Such a model may be applied to assess the likely build up of concentration following a natural gas release in approximately cuboidal enclosures.

#### 4. A mathematical model for the build-up of gas

A model is proposed to give an approximate description of the build-up in concentration within a volume as a function of time. As sketched in Fig. 3a, it



(a)



(b)

Fig. 3. (a) The definition of the two layers assumed in the mathematical model. (b) A sketch of the flows between the control volumes used in the mathematical model.

is assumed that initially an upper well-mixed layer of depth  $h_1$  is formed. Since this layer is produced by the (constant) inflow of momentum from the jet, it is assumed that  $h_1$  does not vary with time. Considering a control surface formed by a horizontal plane at this level, the volume flux into this layer is balanced by an equal and opposite volume flux at the walls of the enclosure. A lower layer of thickness  $h_2$  is predicted to grow beneath this ceiling layer. Its rate of growth is determined by considering the volume fluxes across the notional horizontal 'control' surfaces formed by the two layers in the box as sketched in Fig. 3b.

The equations for conservation of gas in the two layers are

$$\frac{dV_{g1}}{dt} = Q_0 + c_2 [Q(h_1) - Q(h_1 + h_2)] - c_1 Q(h_1), \quad (12)$$

and

$$\frac{dV_{g2}}{dt} = c_1 Q(h_1) - c_2 [Q(h_1) - Q(h_1 + h_2)], \quad (13)$$

where  $V_{g1}$  is the volume of gas in the upper layer,  $V_{g2}$  is the volume of gas in the lower layer,  $c_1$  is the gas concentration in the upper layer, defined by

$$c_1 = V_{g1} / Ah_1,$$

$c_2$  is the gas concentration in the lower layer, defined by

$$c_2 = V_{g2} / Ah_2,$$

$t$  is the time after initiation of the leak, and  $Q(h_1)$  and  $Q(h_1 + h_2)$  represent the volume fluxes transported by the jet into the upper and lower layers, respectively.

The values of  $c_1$  and  $c_2$  represent 'bulk-averaged' values. From the observations of the experiments, a better estimate for the actual profile in the lower layer is obtained by imposing a similarity-type of profile in the form of a linear gradient of concentration. The gradient of the line is determined by the requirement that the mass of gas in the volume is conserved, as indicated in Fig. 3a.

Information deduced from the analysis of the experiments referred to in Section 3 is used to define the upper layer depth as follows. A value of the local overturning number,  $\Omega$ , on arrival of the plume or jet at the upper surface, is estimated from a calculation of the initial trajectory and dilution of the release within the enclosure. The value of  $h_1$  is then given by

$$h_1 = \begin{cases} \text{Min} [0.5z_r + \delta, H] & \text{for } \Omega > 0.3, \\ ((0.3 - \Omega) \text{Min} [0.5z_r + \delta, H] + (\Omega - 0.1)0.5z_r) / 0.2 & \text{for } 0.1 < \Omega < 0.3, \\ (\Omega / 0.1)0.5z_r & \text{for } \Omega < 0.1, \end{cases} \quad (14)$$

where  $\delta$  is given by eqn. (11).

It should be noted that for those releases for which

$$\Omega < 0.1$$

the model is not strictly valid. In these circumstances, a model such as that developed by Barnett [9] should be used. However, eqn. (14) has been found to give a useful approximation for these cases and is included here for completeness. The interpolation used in eqn. (14) for  $0.3 > \Omega > 0.1$  is included to ensure a smooth transition between the two limiting cases.

The growth of the lower layer is determined from the rate at which material is entering into it,

$$\frac{dh_2}{dt} = Q(h_1 + h_2)/A.$$

Once the lower layer has passed below the lowest level reached by the plume or jet flow, its growth is determined by the rate at which material is added to the enclosure,  $Q_0$ .

The above series of equations can be integrated until such a time as the lower layer reaches the base of the enclosure. Thereafter, allowance must be made for the gas leaving the base of the enclosure to prevent the pressurization of the enclosure. After this time, eq. (13) is modified to become

$$\frac{dV_{g2}}{dt} = c_1 Q(h_1) - c_2 [Q(h_1) - Q_0], \quad (15)$$

and  $h_2$  is fixed so that

$$h_2 = H - h_1. \quad (16)$$

These equations allow the build-up of concentration to be estimated over the course of time.

Figures 4 to 6 compare the predictions obtained using these model equations, with observations made in the course of six of the experiments referred to in Section 2. The symbols refer to concentration measurements made in the experiments. In the cases illustrated, measurements were made with instrumentation mounted on either four or two different vertical arrays. The differences between the values from each array give an indication of the horizontal inhomogeneity in the concentration distribution. Expressed as a percentage of the average concentration value at any elevation, differences of up to 15% were observed throughout the test programme. Such differences are small compared to those that may be present in the vertical.

The figures are selected to demonstrate the model performance for representative cases of vertically downwards, horizontal and vertically upwards releases of natural gas. For each release orientation, an example of a sonic, underexpanded jet release and a subsonic release driven by a pressure of 25 mbar pressure are shown. The comparison is illustrated at the final time at which measurements were made in the individual experiments. Similar behaviour is observed at earlier times. Whilst it is not possible to generalise, and this was one

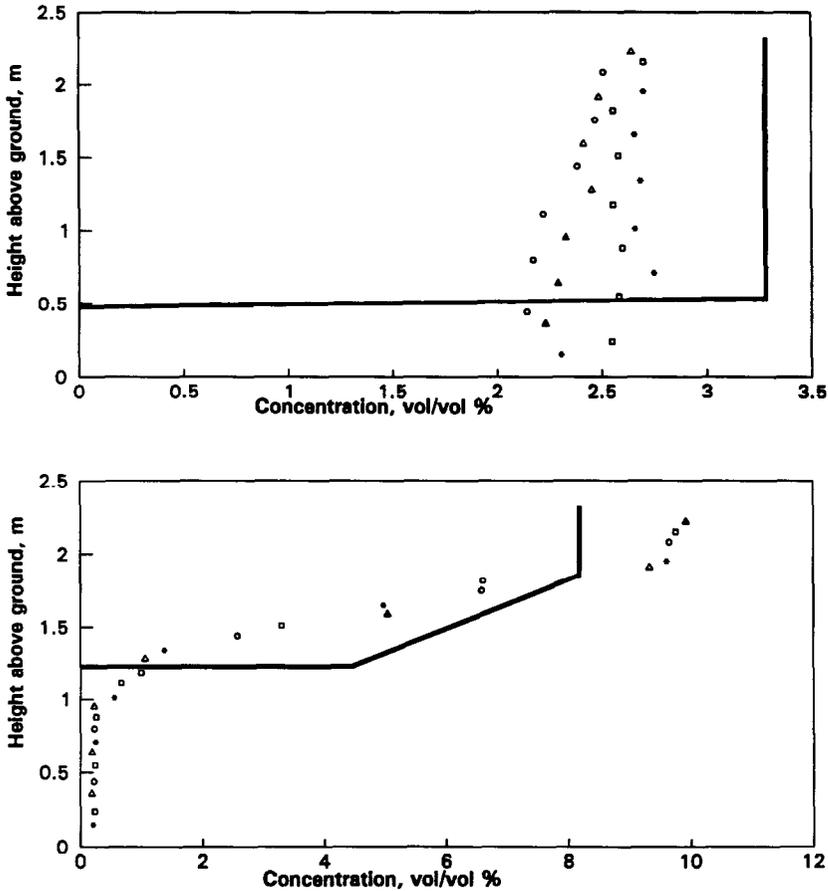


Fig. 4. A comparison of the predictions of the model with experimental data. The releases were in the 5:5:2 ratio enclosure and directed vertically upwards at (a) sonic, and (b) subsonic pressure. The solid lines denote the model predictions, the symbols the measurements made with the vertical arrays of probes centred on the four quadrants of the enclosure.

of the reasons that led to the production of the mathematical model, the sonic releases tend to produce more well-mixed enclosures, whilst the subsonic releases tend to stratify. Within the limitations of the simple model, such gross features of the concentration distribution and mixture accumulation are captured.

Figure 7 gives an overall picture of the model performance. It compares the maximum of the observed concentrations measured at the termination of each experiment with the concentration predicted in the upper layer at that time for more than 100 experiments. In 95% of the cases, the concentration of the upper layer is predicted to within a factor of 2. The depth of the upper layer is predicted to a similar accuracy. In many cases the model correctly predicts the growth of the underlying lower layer. However, there is evidence that stratification occurs within this layer in some of the experiments. It would

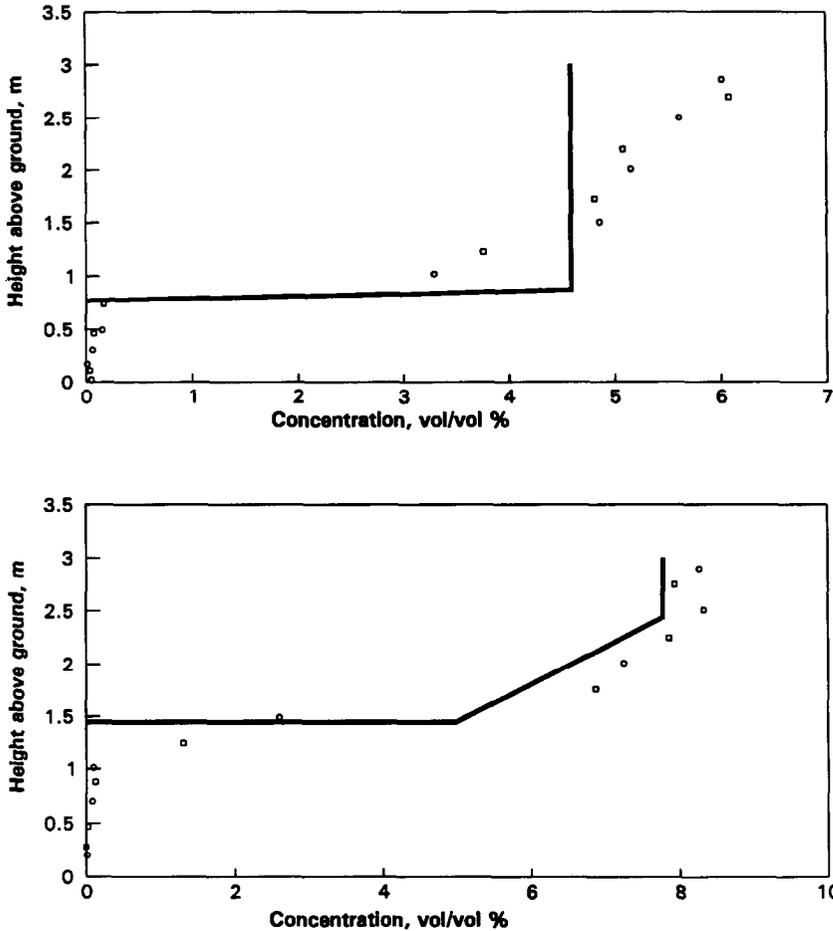


Fig. 5. A comparison of the predictions of the model with experimental data. The releases were in the 1:1:1 ratio enclosure and directed horizontally at (a) sonic, and (b) subsonic pressure. The solid lines denote the model predictions, the symbols the measurements made with the vertical arrays of probes centred on the front two quadrants of the enclosure.

require a more sophisticated modelling approach, such as that used by Barnett [9] for example, to account for such features correctly. Nevertheless, it is found that the predictions of the model with the similarity profile, give a good indication of the concentration distribution within this lower layer.

## 5. Discussion

The work in Sections 3 and 4 indicates that for the given range of geometric configurations, it is possible to describe the build-up of concentration in

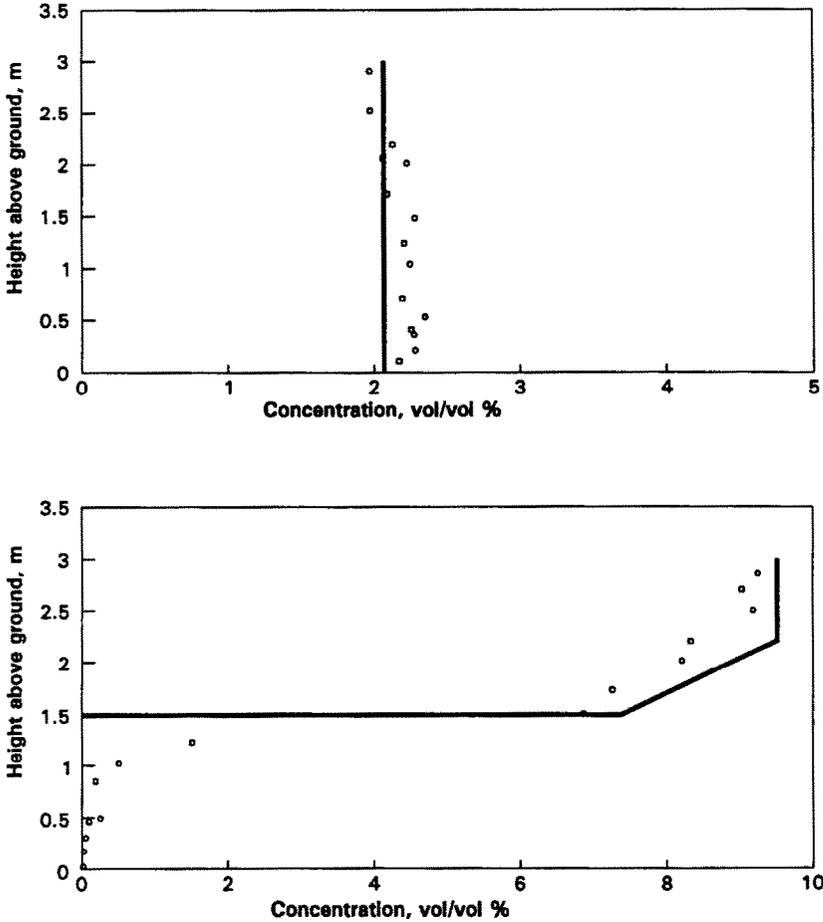


Fig. 6. A comparison of the predictions of the model with experimental data. The releases were in the 2:1:1 ratio enclosure and directed vertically downwards at (a) sonic, and (b) subsonic pressure. The solid lines denote the model predictions, the symbols the measurements made with the vertical arrays of probes centred on the front two quadrants of the enclosure.

a nominally unventilated enclosure using a simple approach. Further, the use of dimensionless parameters enables the model to be applied to different scales of problem, provided extrapolation outside the dimensionless parameter range over which the model was developed is avoided.

To demonstrate its applicability, the model has been used to obtain predictions for a number of experiments carried out by British Gas in which propane was released into an enclosure. In order to do this, allowance has to be made for the fact that the action of gravity forces will cause a well-mixed lower layer to be formed initially at ground level, with a second layer growing above it towards the ceiling. The equations for the accumulation of propane in these

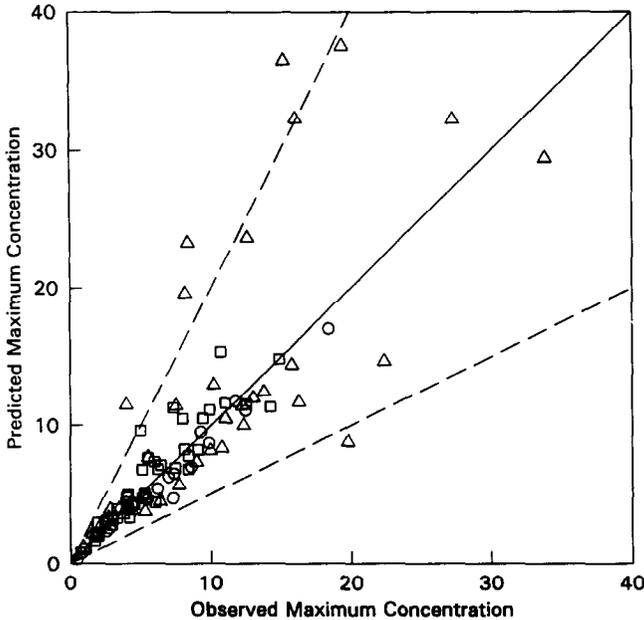


Fig. 7. A comparison of the predicted natural gas concentration in the upper layer with the observed maximum concentration during 103 different gas-air experiments. The different release orientations are shown by the different symbols as follows: (○) Vertically upwards, (□) horizontal and (△) vertically downwards. The solid line corresponds to perfect agreement between prediction and observation, the broken lines a factor of two difference between the predictions and observations.

layers are of the same form as those given in Section 4. Figure 8 compares the predictions for the concentration profiles for one set of conditions, with the measurements made during the test. The good agreement is an indication of the validity of basing the model on the dimensionless parameters defined in Section 3. This suggests that the model can be used to predict the rise in concentration that would follow a leak of any gas in a nominally unventilated enclosure, provided that the enclosure is approximately cubical in shape. Such predictions could be used to assess the benefits of placing gas detectors at a given location within an enclosure. In particular, the implications of any delay in responding to an alarm triggered at a certain concentration level can be addressed by examining the rate of change of concentration predicted by the model.

Development work could be undertaken to improve the modelling of those buoyancy-dominated releases in which overturning does not occur. From a practical viewpoint this situation is less likely to occur, especially in the commercial or industrial environment. Nevertheless, such a situation could be produced by a diffuse area source of natural gas entering at low velocity at a high elevation in an enclosure, for example.

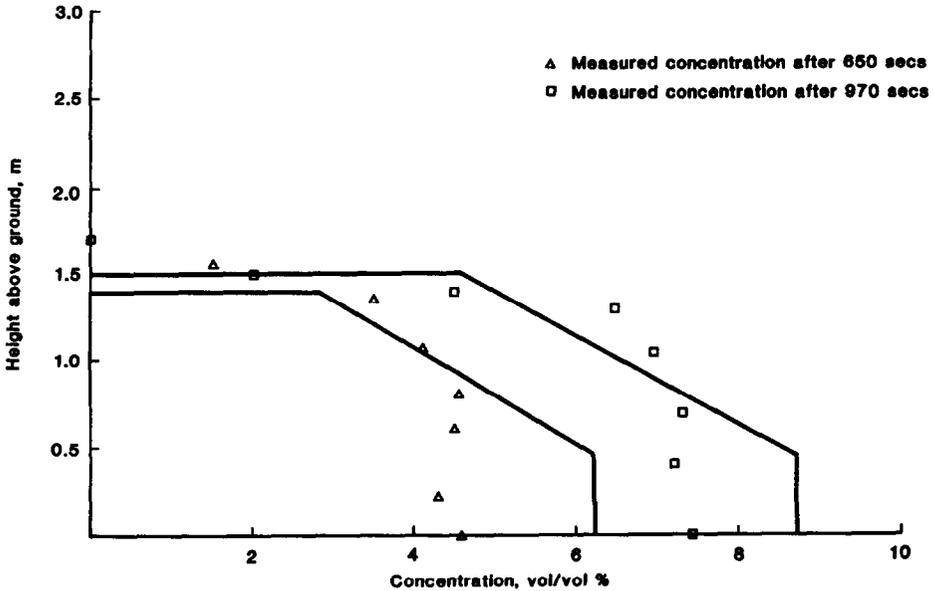


Fig. 8. A comparison of the predictions of the mathematical model with experimental data at two different times taken during a propane release into an enclosure. The solid lines denote the model predictions, the symbols the measurements made with a vertical array of probes centred on one quadrant in the enclosure.

Another area where progress could be made is in the definition of the concentration in the lower layer. As Figs. 4 to 6 indicate, in practice, stratification may occur in the lower layer. A more realistic description of the build-up here could be of use. For example, it may be necessary to obtain a more accurate estimate of the time required before a given concentration is reached at the lower elevations in the enclosure. It may also be necessary to consider the build-up of gas in a more general geometry than has been considered here. In particular, the aspect ratio of the enclosure may be an important parameter. Information on this should indicate whether or not the correlations based on Fig. 2 are of more general applicability or whether a more fundamental approach is required to predict the extent of the well-mixed layer,  $h$ .

In practice, even an enclosure with no intentional outlets has some small openings providing adventitious ventilation (for example, small cracks around door frames or slight porosity of the building material). Furthermore, in the domestic environment, airbricks and open windows or doors provide opportunities for deliberate ventilation. Work is underway to generalise the model in Section 4 to allow for such ventilation flows. This can be done either on a case-by-case basis for a specific geometrical layout, or in generic terms by the specification of the distribution of free area on each wall as a function of elevation. Preliminary work suggests that the results presented here are not

sensitive to the exact location of the small outlets that prevent the pressurization of the enclosure. Further, in terms of hazard assessment, the worst case in terms of mixture accumulation and the time taken to reach a given concentration level is obtained if the enclosure is considered to be nominally unventilated. Hence, the existing model has a role to play in assessing the behaviour of releases in minimally ventilated enclosures.

## 6. Conclusions

Results have been examined from a wide range of experiments, carried out to study the build-up of concentration in nominally unventilated enclosures, following a release of natural gas. It has been shown that a consistent pattern of behaviour emerges, with variations in the release and geometry being accounted for by relevant dimensionless parameters. In particular, it is concluded that, for the ranges of parameters in Table 1, the mixing due to the momentum flux of the release can be correlated with a single parameter, in the form of a Richardson number.

The above conclusions have allowed the development of a simple mathematical model to predict the build-up of gas in such an enclosure. The predictions of this model are in reasonable agreement with the experimental observations. For more than 95% of the cases, the maximum concentration in the enclosure is predicted to within a factor of 2.

By comparing the model predictions with a limited number of experimental results available for the build-up of propane in unventilated enclosures, it is concluded that the relevant dimensionless groups have been identified over the range of parameters in Table 1. Hence the model can be used with some confidence for more general problems involving the build-up of other gases released into enclosures.

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