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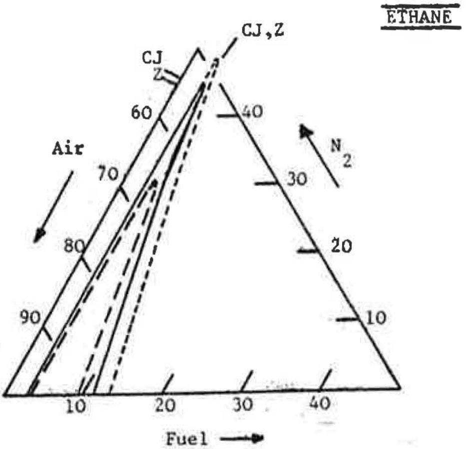

FIGURE 3

FIGURES 2-5

Flammability Limits for Fuel-Air-Nitrogen Mixtures.

KEY:
- - - - - ↑ ↑
——— ↕
— — ✥

CJ: Coward & Jones
Z: Zabetakis

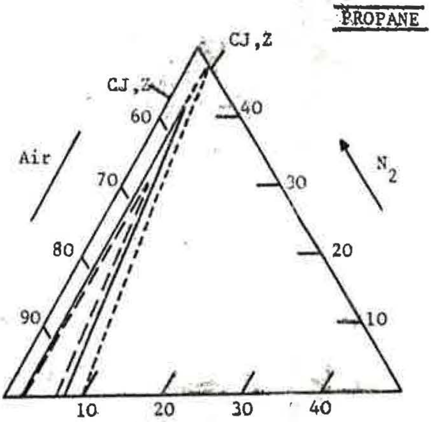

FIGURE 4

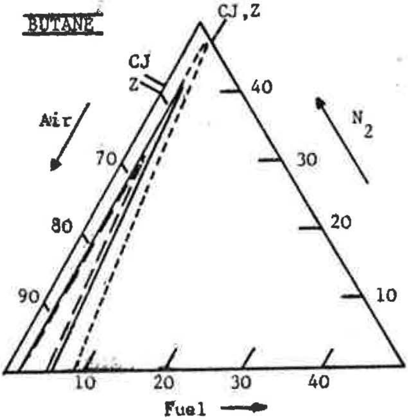

FIGURE 5

THE EFFECT OF VENTILATION ON THE ACCUMULATION AND DISPERSAL OF HAZARDOUS GASES.

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INTRODUCTION

Whenever gases and vapours are contained in pipework and process plant, the possibility exists that an accidental release of these substances can occur. In addition, if the primary containment is itself located within a confining enclosure (for example, a building) the leaking gas or vapour could accumulate and produce a potentially hazardous situation. For example, if an uncontrolled release involves a flammable gas or vapour, an explosion and/or fire hazard could exist.

Whilst good plant design and construction, complemented by planned maintenance and well-defined operating procedures, should minimise the likelihood of an accidental release this cannot be guaranteed. Means of preventing such an escape subsequently producing a hazardous situation therefore should always be considered. An effective measure is to provide sufficient ventilation so that any credible accidental leakage can be dispersed safely, i.e. the maximum concentration of gas or vapour is prevented from exceeding the safe limit.

In most cases, the ventilation air will be provided by natural ventilation (wind driven and/or buoyancy driven) and therefore the air change rate will be variable, depending on weather conditions. However, there are general design principles on which to base such ventilation systems.

Whilst there is guidance on the ventilation requirements of buildings, for example incorporated in Standards, Building Regulations, Codes of Practice, etc., this is usually concerned with air change rates to ensure comfort, adequate combustion air supplies and, in some cases, flue product dilution. Hence, it is not necessarily relevant to the dispersal of leakages of potentially hazardous gases and vapours. Similarly, few studies on the mixing behaviour of leaking gases relevant to an industrial situation have been reported in the literature[1].

This paper presents the results of a study into the way leaking gas mixes with air and the modifying role of ventilation on this process. The application of the data to the design of effective natural ventilation systems for buildings is discussed together with the limitations inherent in such systems.

EXPERIMENTAL ARRANGEMENT

The four most important factors which influence the manner of build up of gas concentration from a release into an enclosure are the density of the gas released, the nature of the gas leakage source, ventilation and the enclosure volume. The effect on the mixing process of these parameters has been investigated in an experimental study. The main series of tests was carried out in a cubical enclosure of 20.6m^3 volume. Additional tests were made in a smaller 8m^3 rectangular shaped enclosure and also in buildings (20.6-55.6m^3). Although the experimental programme was designed to determine the behaviour of leaking gas under naturally ventilated conditions, for ease of experimentation and to provide control of the variables, the main experimental study was carried out using controlled air flow conditions. However, comparisons with the behaviour under these essentially forced ventilation conditions were obtained from experiments in naturally ventilated buildings.

Unventilated Situation

For the tests carried out under zero ventilation conditions, the variables investigated were gas specific gravity, gas flowrate, gas leak velocity, leak position and orientation, duration of leakage and enclosure volume. Table 1 shows the range of these variables.

Table 1: Range of Variables in Experiments

Variable	Unventilated	Ventilated
Gas specific gravity	0.46 (town gas) 0.6 (natural gas) 1.5 (propane)	0.6 (natural gas)
Gas flow rate, Q_g	0.48 to 9.75	0.28 to 9.75
Gas velocity, v	0.3 to 122	0.7 to 61
Leak position, z	0 to 1.0	0.04 to 0.95
Leak orientation	Upwards, horizontal, downwards	Upwards, horizontal
Test Volume, V	8 (tall chamber) 20.6 (cubic chamber) 20.6 to 55.6 (test buildings)	20.6 (cubic chamber) 20.6 to 55.6 (test buildings)
Air flow rate, Qa	-	5.1 to 122
Ventilation patterns	-	Upwards, cross flow, downwards.

N.B. Units are defined in the Nomenclature at the end of the paper.

Ventilated Situation

The tests carried out were designed to determine how the mixing behaviour observed under zero ventilation conditions is modified by the presence of ventilation air. A wide range of ventilation regimes (i.e. flow patterns and air change rates) has been studied. These include not only the basic upward air flow ventilation regime but also the reverse, downward flow condition and an evaluation of the influence of the position of the inlet and outlet ventilators under cross flow conditions. The ranges of the variables studied are shown in Table 1, Column 3.

DISCUSSION OF RESULTS

In this and subsequent sections, it is to be assumed that the discussion refers to a release of buoyant gas unless otherwise stated. However, it is considered that the same general conclusions can be drawn for dense gases, other conditions being similar, except that the total system is inverted (i.e. a buoyant gas release under an upward air flow regime is expected to behave similarly to a dense gas leakage with downward air flow).

Unventilated Situation

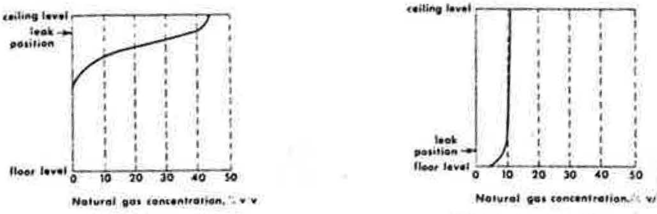
When a gas is released into an enclosure, it will mix with the available air due to the actions of turbulent jet mixing, buoyancy and turbulent interaction with air supplied by ventilation. Gas mixing by molecular diffusion alone is extremely slow in comparison to these other effects and in most practical cases can be ignored. For many situations, the part of the enclosure volume in which turbulent jet mixing is the dominant process is likely to be restricted to a region close to the leakage position. Thus, in an unventilated situation where there is no turbulent mixing produced by ventilation air, the density of the gas released will have a dominant influence on the way in which gas-air mixture accumulates. Consequently, leakages of dense gases, such as propane and butane and flammable vapours such as petrol, would be expected to result in the formation of gas-rich layers near the floor; conversely, buoyant gases such as natural gas would be expected to form layers near the ceiling. This idealised behaviour is illustrated in Figure 1. The results of the experiments carried out under zero ventilation conditions confirm this pattern of mixing and indicate that a

a Dense gas forming a floor layer

b) Buoyant gas forming a ceiling layer

Figure 1 CONCENTRATION PROFILES IN AN UNVENTILATED ROOM
UNIFORM LAYERS OF BUOYANT AND DENSE GASES

well defined layer is formed between the level of the leak and the ceiling (Figure 2). With a leak near to the ceiling, a shallow layer of high concentration is formed, whereas an identical leak nearer the floor fills the enclosure volume between the leak position and the ceiling with a uniform mixture of lower concentration. The higher gas concentration produced by a high level leak, evident in Figure 2, is a consequence of a smaller fraction of the total volume of air in the enclosure being involved in the mixing process.



(a) With high leak position

(b) With low leak position

Figure. 2. TYPICAL EXPERIMENTAL NATURAL GAS CONCENTRATION PROFILES IN AN UNVENTILATED ROOM

An important result of these experiments (as demonstrated in Figure 2) is that, for leaks which occur near the floor, the time taken for uniform conditions to be established within the layer is short. This implies that the time scale over which a gas release can be considered to behave as either a turbulent jet or a buoyant plume is very short. Consequently, it is a misconception to assume (as suggested by Leach and Bloomfield[1]) that, following the onset of leakage, a layer of high concentration is formed at the ceiling which then gradually increases in depth with time. The experimental data show that in practice when a buoyant gas is released some way below the ceiling, although the mechanism suggested by Leach and Bloomfield may operate initially, a layer of essentially uniform concentration is formed very quickly between the point of leakage and the ceiling. Whilst the average concentration will continue to increase, the data demonstrates that the general shape of the concentration profile will be maintained throughout the duration of the gas release, as shown in Figure 3.

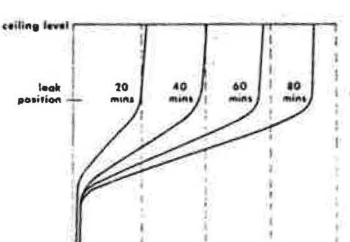


Figure 3 DEVELOPMENT OF A CONCENTRATION PROFILE WITH TIME (UNVENTILATED ROOM)

Both the depth of the layer formed and the degree of mixing which occurs between gas and air can be affected by factors other than the leak position within an enclosure. These include the gas escape velocity, the volume flowrate of gas and the leak orientation.

In Figure 4 the degree of mixing, characterised by the ratio of the maximum gas concentration in the layer to the average gas concentration in the enclosure, is shown as a function of both leak position and orientation. (As better mixing occurs the value of the ratio decreases: perfect mixing corresponds to a value of unity). It is evident from Figure 4 that better mixing is achieved with downward pointing leaks than with either horizontal or upward orientated leaks. As might be expected, a similar trend is observed in the variation of layer depth with leak orientation, as illustrated in Figure 5.

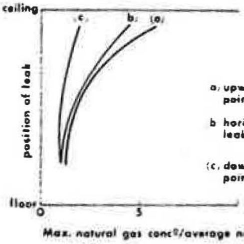


Figure 4 DEGREE OF GAS MIXING CHARACTERISED BY RATIO OF MAXIMUM TO AVERAGE GAS CONCENTRATION AS A FUNCTION OF LEAK POSITION AND ORIENTATION

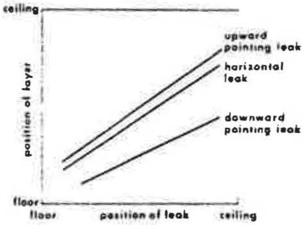


Figure 5 POSITION OF NATURAL GAS LAYER AS A FUNCTION OF LEAK POSITION AND ORIENTATION

Tests in the smaller, rectangular shaped vessel indicated that the position of the source of leakage within an enclosure can have a slight effect on the concentration profile developed, particularly in the early stages of the mixing process. Thus, for the same leak source characteristics, it was observed that initially there was marginally less mixing with the leak source located against the wall of the vessel than when gas was released centrally in the chamber, i.e. the concentration at the ceiling was higher, with less gas present lower down in the vessel, compared with the centrally located leak. However, this slight difference between the two cases diminished with time and with a leak source located half way down the test chamber ($z = 0.5$) the difference in concentration profiles from the two situations was negligible after a gas input equivalent to approximately 5% of the vessel volume. The location (as against the height) of a leak is not considered therefore to have any real practical significance.

The volume flowrate of gas and the gas escape velocity also affect the degree of mixing between gas and air. Higher gas velocities tend to promote more mixing and lead to deeper layers whereas the volume flow rate of the gas released affects the time taken to reach a given concentration - the higher the flow rate, the less time required to reach a specified concentration.

Experiments in a multi-room test building produced results similar to those obtained in the 20.6m^3 test chamber. Thus, it was observed that, if the leak position was below the level of the door lintels, although the room into which gas was released had a slightly higher gas concentration at ceiling level, below the level of the door lintels the gas concentration was similar in each room. In addition, for a leak position below door lintel level, gas initially did not accumulate at ceiling level in the room in which it was released and then pass into adjacent rooms. Only for a leak position higher than the door lintels did the gas build up at ceiling level before spilling under the lintel into an adjacent room. It would appear therefore that the mixing behaviour observed in a single cell enclosure can describe adequately for practical purposes the behaviour of gas released into more complex geometry enclosures.

Ventilated Situation

When ventilation is present, an additional process is available to promote mixing; this is the turbulent interchange between escaping gas and the air supplied by ventilation. In many situations, mixing and subsequent dilution of the gas mixture by the action of ventilation will be the dominant process by which the build up of a flammable gas concentration following an accidental release will be prevented.

Although mechanical ventilation systems are often installed in buildings, in most situations the requisite air change rate is provided by natural ventilation. The driving forces for natural ventilation are (a) the pressure differentials created across a building by external wind forces and (b) buoyancy forces derived from the difference in densities of the atmospheres within and outside a building. Normally, buoyancy driven ventilation derives from a difference in temperature between the air inside a building and that outside but it can be driven by density differences caused by the release of a buoyant gas within a building. The two common patterns of ventilation (i.e. wind driven and buoyancy dominated) are illustrated in Figure 6. Methods for calculating natural ventilation rates of buildings are described in several publications, for example British Standard 5925^2.

a) Air flow generated by temperature difference alone
Upward air flow ventilation

b) Air flow generated by external wind alone
Cross flow ventilation

Figure 6 COMMON PATTERNS OF VENTILATION

The effect of different patterns and rates of ventilation on gas mixing and accumulation have been studied extensively in the 20.6m^3 cubical test vessel. These experiments were carried out under controlled air flow conditions to ensure consistency between tests. However, tests of a similar nature were made also in naturally ventilated buildings to provide a comparison of the pattern of gas mixing and accumulation under more practical ventilation conditions.

Each of the ventilation regimes investigated tended to produce different shaped concentration profiles. This was most obvious between the normal, upward ventilation air flow and the unusual reverse flow situation of a downward air flow. Concentration profiles obtained from the cross flow ventilation regimes tended to approximate to those produced by one or other of the two extremes of upward and downward air flow, depending on the location of the inlet and outlet ventilators. Each of the different air flow regimes is discussed separately below.

i) Upward Ventilation

The experiments with upward ventilation demonstrated that, over a wide range of leak source characteristics and ventilation rates, a steady state concentration profile will be established. The shape of the concentration profile is similar to that obtained under zero ventilation conditions and is maintained as time increases. Typical examples are shown in Figure 7, which indicates that a well defined layer of gas-air mixture, of essentially uniform composition, is formed between the level of the leak and the ceiling with little or no gas being present below the level of the leak.

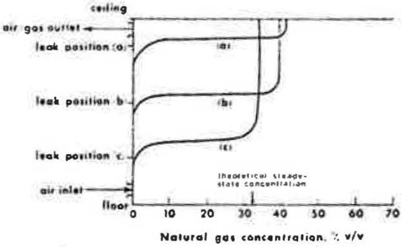


Figure 7 THE EFFECT OF LEAK POSITION ON STEADY-STATE CONCENTRATION PROFILES WITH UPWARD VENTILATION AIR FLOW (NATURAL GAS)

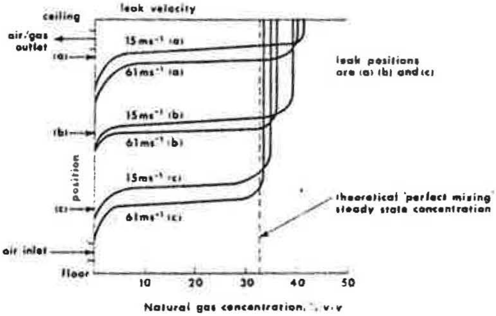


Figure 8 EFFECT OF LEAK VELOCITY AND POSITION (NATURAL GAS) FOR UPWARD FLOW VENTILATION

It was evident from these experiments with ventilation that the nature of the leak source had a similar effect on the degree of mixing as in the unventilated situation. Thus, Figures 7 and 8 demonstrate that better mixing occurs with a lower leak position and higher gas leak velocity.

If perfect mixing between the leaking gas and the ventilation air is assumed to occur, the build up of gas concentration with time is described by the equation:

$$C(t) = 100\,Qg/(Qa + Qg)\left[1 - \exp\left(-\frac{(Qa + Qg)t}{V}\right)\right] \qquad 1$$

The steady state concentration is given by:

$$C_s = 100\,Qg/(Qa + Qg) \qquad 2$$

The value of C_s for the experimental results presented in Figures 7 and 8 is indicated by the dotted line. It is evident that the lower the leak position, the nearer the approach to this 'theoretical' concentration, in other words, the better the degree of mixing. In practical terms, however, for leak sources located below the level of the outlet ventilators, the variation of the steady state concentration from that predicted by equation (2) is not significant.

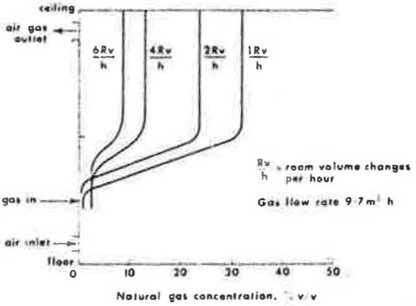


Figure 9 EFFECT OF VENTILATION RATE ON GAS CONCENTRATION - UPWARD FLOW VENTILATION (NATURAL GAS)

The effect of increasing the rate of ventilation - other factors remaining constant - is to reduce the maximum concentration and the depth of the layer of gas-air mixture formed (Figure 9). Overall, the effect of an upward ventilation air flow on gas mixing and accumulation is to reinforce the behaviour observed under zero ventilation conditions.

ii) Downward Ventilation

Although in most practical situations downward air flow would be considered to be an unusual ventilation pattern, it does sometimes occur. For this ventilation regime, buoyancy and momentum forces are acting against each other, consequently it is to be expected that better mixing will result. This is confirmed by the experimental results, Figure 10, which show that a substantial amount of gas can be present below the level of the leak in this situation. In many of these experiments, at steady state conditions, the gas concentration below the level of the leak position approximately equalled the theoretical value given by equation (2). However, the shape of the steady state profile is not established quickly but continually changes as gas accumulates below the level of the leak. Essentially with a downward air flow regime two layers are formed: one of a higher concentration above the leak position and a second with a lower concentration below the level of the leak. This can also be seen in Figure 10.

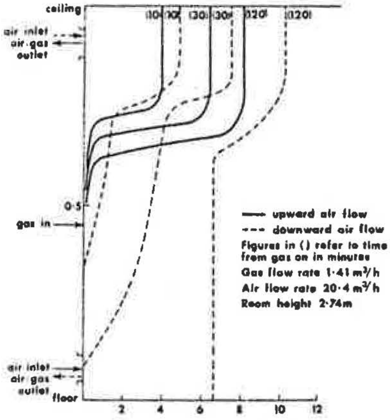


Figure 10 BUILD UP OF GAS CONCENTRATION WITH TIME - CONCENTRATION PROFILES FOR UPWARD AIR FLOW AND DOWNWARD AIR FLOW (NATURAL GAS)

iii) Cross Flow Ventilation

A number of cross flow ventilation patterns have been investigated experimentally. Examples of gas concentration profiles at steady state condition for these various ventilation air regimes are presented in Figure 11. Although the shape of the concentration profile depends markedly on the dispositions of the air inlets and outlets, certain trends important to the practical situation can be identified. Thus, the

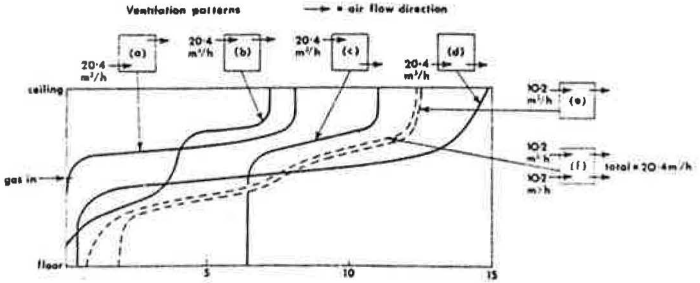


Figure 11 STEADY STATE GAS CONCENTRATION PROFILES FOR DIFFERENT VENTILATION PATTERNS
(Natural gas, flow rate 1·42m³/h for all cases)

lowest concentrations were always obtained with a high level outlet position, irrespective of the location of the air inlet(s). The data also demonstrates that, as might be expected for a leakage of a buoyant gas, ventilation inlets and outlets at floor level only are almost completely ineffective in dispersing mixture accumulation at high level (pattern (d), Figure 11). In fact, the gas concentrations measured with this configuration were very similar to those obtained under zero ventilation conditions. There was a similar effect with other patterns which included a low level inlet and low level outlet. This was especially noticeable with true cross flow conditions, i.e. inlets and outlets at both high and low level (pattern (f), Figure 11). The concentration profile produced under this ventilation condition was very similar to that obtained with inlets and outlets at high level only (pattern (e), Figure 11) but with only half the ventilation air rate.

The data from these cross flow ventilation experiments imply that for a cross flow situation with inlets and outlets at both high and low level, only the air entering at high level plays a part in the mixing process. This result is important in naturally ventilated buildings and suggests that, whilst low level openings are necessary to provide inlets for buoyancy driven ventilation, calculation of ventilation air openings based on wind driven ventilation should be restricted to high level openings only.

PRACTICAL IMPLICATIONS

The main feature to emerge from the experimental study of gas mixing and accumulation is the tendency of buoyant gas releases to result in the formation of high level layers of gas-air mixture, for a wide range of ventilation conditions. This type of behaviour has several important practical implications for the design of natural ventilation systems of buildings.

The formation of a layer inhibits the mixing of gas with the total volume of air in an enclosure and can, for example, radically influence the time taken for an explosive mixture concentration to be reached following a release of gas. Hence, whilst the data from both the controlled air flow studies and the tests in naturally ventilated buildings indicate that, for many practical situations, the perfect mixing equation can be used to determine the steady state gas concentration, in some situations a modification to this formula is needed to describe the build up of concentration to the steady state more accurately. In particular, the data show that for most common patterns of ventilation, the mixing of gas and ventilation air is restricted mainly to the part of the enclosure above the level of the leak. Consequently, the rate of increase in gas concentration can be higher than that predicted by equation (1). This discrepancy can be corrected adequately by using a reduced volume, V^*, in the perfect mixing equation rather than the actual enclosure volume (V), where V^* is the volume of the enclosure above the level of the leak.

For dense gases and vapours, such as propane and petrol, it may still be more appropriate to use the unmodified perfect mixing equation, the reason being that with these substances the tendency will be to form a layer of mixture at low level rather than a high level ceiling layer as is the case with the release of a buoyant gas. Thus, under normal ventilation conditions, the pattern of gas mixing and accumulation subsequent to a leakage of dense gas should correspond reasonably closely to the behaviour of a buoyant gas under a downward ventilation air flow. In this case, the data indicate that gas-air mixture will be distributed throughout the enclosure volume (pattern (c) Figure 11).

Once formed, a layer of rich gas-air mixture is difficult to disperse, relatively high ventilation rates being required to disturb sufficiently the boundary between the layer and the air in order to allow mixing and, therefore, dilution to occur. Hence, a primary requisite of any ventilation system must be to prevent the formation of gas rich layers. The experimental data show that for the most effective dispersal of a leakage of buoyant gas, ventilation openings - certainly the outlets - should be located at high level. Further, data from the cross-flow ventilation studies, with inlets and outlets at both high and low level, indicate that the low level air flow has little or no effect. This suggests that when calculating the ventilation air flow available from wind-driven ventilation, the value of Qa to be used in equation (1) should be based only on the areas of the high level ventilators.

However, this does not mean that openings should not be placed at low level. In normal circumstances, the natural ventilation of a building will be by wind-driven ventilation and the air change rate will be variable since it will be influenced by both wind speed and wind direction. Whilst variations in wind characteristics can be accommodated by distributing openings on all sides of a building, ideally these should also be located both at high and low level. This will then ensure that a reduction in ventilation rate, due for example to a drop in wind speed, can be minimised by the buoyancy driven ventilation that would then occur. (Below a wind speed of about 2 m/s, buoyancy driven ventilation will tend to be more dominant than wind driven ventilation in many situations). The contribution of buoyancy effects to the ventilation can be maximised by ensuring the greatest possible distance between the high and low level ventilation openings. By this means, buoyancy driven ventilation will be available when required and the ventilation air flow rate will depend less on wind characteristics and be less variable than otherwise.

CONCLUSIONS

The main conclusions to be drawn from the experimental study are:

1. Over the wide range of ventilation conditions investigated there is a tendency for gas releases to result in the formation of a layer of gas-air mixture in part of an enclosure, rather than the dispersal of gas throughout the entire volume.

2. The steady-state gas concentration following an accidental release is described adequately by the perfect mixing equation. A modified version of this formula should be used to calculate the build-up of gas concentration to steady state conditions.

3. The most effective dispersal of mixture accumulation is obtained with ventilators placed at high level but to minimise variations in the air flow rate available from natural ventilation systems, ventilation openings should be located at both high and low level on all available faces of a building.

NOMENCLATURE

$C(t)$ - time dependent gas concentration (% gas in mixture)
C_s - steady state gas concentration (% gas in mixture)
Q_a - air flow rate (m^3/hr)
Q_g - gas leakage rate (m^3/hr)
t - time (hr)
V - enclosure volume (m^3)
V^* - enclosure volume above leak (m^3)
v - gas leakage velocity (m/s)
z - leak position in enclosure (dimensionless)

The leak position is defined in terms of the height of the enclosure: a value of $z = 1.0$ indicates a leakage at ceiling level, a value of $z = 0$ corresponding to a leakage of floor level.

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EXPERIMENTAL INVESTIGATIONS ON THE RUN-UP DISTANCE OF GASEOUS DETONATIONS IN LARGE PIPES

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SUMMARY

For the design of installations in which explosive mixtures of flammable gases and vapours with air can occur, the run-up distance in pipes is a significant quantity for safety engineering. For propane/air and ethylene/air mixtures it was measured by varying a number of influencing parameters (such as, for example, concentration of the flammable component, pipe diameter, type and location of the ignition source, pre-volume, turbulence, and pipe blockage). Though the tests carried out do not yet suffice to make a generalized quantitative statement on the run-up distance, some aspects shown by the results are of interest to the application in industrial practice: thus, the strength of the ignition source is of almost no importance, whereas the laminar burning velocity (and thus the maximum experimental safe gap) and, in addition, a volume preceding the pipe plays a considerable role.

INTRODUCTION

Owing to the high, though only short duration momentum, the occurrence of detonations of explosive vapour/air or gas/air mixtures in pipes represents a serious threat to the industrial installations concerned, the more so as they can exceed the stability of the latter /1/. In such cases, it is most interesting from the safety engineering point of view to know under what design conditions (for example, the pipe dimensions) a deflagration can develop into a detonation and, in particular, what run-up distance (distance between location of ignition source and location of deflagration/detonation transition) is necessary for a detonation to take place. Knowledge of the run-up distance is therefore a prerequisite for taking, in particular, constructive measures against the occurrence and effects of detonations and the ensuing high dynamic loads acting on the installations concerned. These protective measures comprise the use of only small pipe lengths or, on the other hand, the use of flame-arresting devices which stop the flame propagation in the case of a detonation (detonation-arresting devices).

To the question in what pipe lengths detonations must be reckoned with, the applicable safety regulations (at least in the Federal Republic of Germany) give no reply or only a very general one. In the "Explosionsschutz-Richtlinien" (Explosion Protection Guidelines) /2/, a pipe length L to diameter D ratio of at least L/D = 5 is given; owing to its necessarily general nature, this limiting value should, however, be regarded as conservative. Moreover, the findings hitherto published with respect to the run-up distance of detonations, particularly in the case of large pipe diameters and under different conditions of installation in industrial plants (for example, the provision of a large volume), are