GAS EXPLOSIONS IN INTER-CONNECTED VESSELS: PRESSURE PILING

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Evidence from explosions in vessels divided into two compartments which are connected by a small opening, show that ignition in one can propagate into the other producing peak pressures and rates of pressure rise several times greater than in single vessel explosions, an effect referred to as pressure piling. Calculation of these pressures and rates of pressure rise has up to now not been possible. This paper will present a review of the pressure piling hazard including experimental data that can be used to formulate a semi-empirical model for hazard prediction. The relative importance of parameters such as the volume and shape of the chambers, the point of ignition, the size of the connecting tube and the type of gas mixture will be discussed and limitations of available data stated.

Key words

explosions, pressure piling, vessels, explosion pressure, hazard

1. INTRODUCTION

Stoichiometric mixtures of most hydrocarbons in air (initially at atmospheric temperature and pressure) produce explosion pressures of about 8 bar in single vessel. If the vessel is in the form of two chambers connected to each other by a small diameter tube these same mixtures have been shown to produce peak pressures in excess of 35 bar. The explosion of gases in multicompartmented vessels is usually referred to as "pressure piling." Pressure piling was recognised as a special explosion hazard by Beyling[1] when he noticed that enclosures that were divided into separate compartments and connected by small tubes, tended to suffer very violent and destructive explosions.

In the chemical industry interconnecting vessels and pipes handling flammable materials are commonplace and the hazard posed by pressure piling is therefore of considerable relevance.

The first piece of work undertaken specifically to investigate pressure piling was by Grice and Wheeler[2], who were initially working with spheres of up to 8 litres capacity, connected by short lengths of steel tubing 3.2 cm diameter, and a mixture of 9.5% methane in air. The effect of the size of the passage connecting the compartments upon the extent of pressure piling was studied by Brown[3] using a pair of cylinders whose volume ratio was 13.5. The diameter of the connecting tube was varied from 0.64 cm to 2.54 cm, and its length from 6.35 cm to 38.10 cm. The results of this study showed that change in the length of the connecting tube is much less marked than the effect of change in diameter. Indeed, over the range of lengths used the peak pressure remained virtually constant at about 34.5 bar.

A thorough study of the subject was also undertaken by Gleim and Marcy[4]. They worked with a box constructed from steel plate which could be sub-divided into different sections of different volume ratios by partition plates having openings of various sizes. Apart from changing the volume ratios and the size of the hole in the partition plates, they investigated the effect of varying the position of the spark.

The most recent and comprehensive study[5,6] investigated all the parameters important to pressure piling on the same system in order to assess their relative importance and their interrelationship. All the experiments were carried out in a pair of cylindrical chambers connected to each other by a small tube (see figure 1). The larger vessel, referred to as the primary chamber, could be made up by joining any combination of three cylinders whose internal diameter was 30.48 cm and whose lengths were 22.86 cm, 29.85 cm and 45.09 cm. Seven different lengths could be achieved in this way. The small, secondary chamber, was a cylinder whose internal diameter was 15.24 cm, and effective length 38.1 cm. The volume of this vessel could be varied by adjusting the position of a gas-tight piston fitted inside it.

The two chambers were connected to each other by a cylindrical tube whose internal diameter was 7.62 cm and into which pipes of various wall thickness could be inserted, and in this way the internal diameter of the connection was altered. The length of the connection was fixed at 26.0 cm. The gas mixtures used in the course of the experiments were 9.5% methane in air, and 4.05% propane in air, both corresponding to approximately stoichiometric concentrations.

The extensive data from this last study will be used to explain the variables important in pressure piling and to generate an empirical basis for the prediction of maximum explosion pressure.

2. TYPICAL EXPLOSION PRESSURE DATA

The typical form of a pressure-time trace following ignition of a gas mixture is shown in figure 2 where the rise in pressure in both compartments is shown. The maximum pressure in the primary (larger) compartment is P_m, close to the value in a single vessel explosion; the peak pressure P_k occurs in the secondary (smaller) vessel. In the explosion build-up, ignition in the secondary vessel occurs when the pressure in that vessel is P_1 and the corresponding primary pressure is P_Z.

Some typical data for the peak pressure P_k, as a function of the connecting tube diameter (d_c) are shown in figure 3. This covers primary chamber volumes 21.8 and 54.6 litres and a volume ratio of 14.0. As a rule, the peak pressure is reduced with increase in d_c. This is consistent with the data from Brown[3]. For a fixed volume ratio and connecting tube (d_c), an increase the primary chamber volume increases the peak pressure. For example, peak pressure with a primary chamber volume 54.6 litres is typically over twice that with a volume 21.8 litre, both at a volume ratio of 14.0.

Further peak pressure data, this time for a fixed connecting tube diameter, are shown in figure 4, as a function of primary chamber volume. This confirms that although volume ratio between the compartments is important, the scale effect is dominant.

The effect of volume ratio between the connected vessels is more clearly illustrated in figure 5. This shows that in fact P_k peaks at some value of volume ratio and then further increases in the ratio lead to a reduction in pressure.

The data in figures 3 to 5 relates to gas ignition at the centre of the primary chamber; figure 6 shows a comparison between the peak pressure due to central ignition and due to ignition at the extreme (furthest away from the connecting tube). By moving the ignition source in this way, the peak pressure is typically increased by a factor of 1.80.

3. EVALUATION OF MAIN VARIABLES

3.1 Basic Principles

The pressure-time relationship for explosions in single vessels follow the well documented 'S' shape and methods for accurate analytical description are available[7]. The maximum explosion pressures P_f in such explosions, which varies with the type and concentration of the flammable mixture and the initial conditions of temperature and pressure, can be calculated from:

$$P_f = P_o \frac{\overline{T_b}}{T_o} \frac{M_f}{M_o} \tag{1}$$

where P_o is the initial pressure, T_o the initial temperature, $\overline{T_b}$ the mean burnt gas temperature and M_o and M_f are the moles of reactants and products respectively. Approximate values for fuel-air mixtures can be obtained from:

$$P_f = P_o \ (T_f \ / \ T_o) \tag{2}$$

where T_f is the flame temperature of the fuel-air mixture.

Let us now consider a pair of vessels connected to each other by a pipe as shown in figure 1, with both vessels containing the same flammable mixture at a pressure of P_o. If the mixture is ignited in the primary chamber at some point near the centre, the ensuing flame will expand outward from the ignition point causing a simultaneous rise in pressure. This will immediately produce a pressure difference between the primary and secondary chamber causing unburnt gas to be pushed out into the latter chamber. This process will continue until the flame propagates into the secondary chamber itself and ignites the gas within it.

However, whereas the system was originally at a pressure P_o, the pressure in the secondary chamber at the point of ignition will be $P_1 > P_o$. Hence from equation (2), the maximum possible pressure in the secondary chamber will be

$$P_k^{/} = \eta \ P_1$$

where η is a constant for the particular gas mixture and approximately equal to (T_f/T_o). (Strictly, the value of η for the initial mixture (at P_o) will be different to that for the compressed gas at P_1, but the difference is relatively minor). The actual peak pressure experienced by the secondary chamber will be P_k, less than P_k' due to the fact that some gas will be vented back into the primary chamber. Hence in general,

$$P_k = P_k' - \Delta P = \eta P_1 - \Delta P \qquad (3)$$

where ΔP is the reduction in pressure caused by the back-venting.

Even from this simple description of the explosion process, a number of the features observed in experiments can be explained. Consider for example an increase in the length of the primary chamber, the position of the ignition source being in the centre of the chamber. The initial influence of this will be to delay the time at which ignition in the secondary chamber will occur (since the flame will now travel a greater distance). Thus the quantity of gas that will be pushed out from the primary chamber and as a consequence the pre-ignition pressure P_1 in the secondary chamber will be higher than before, causing in turn an increase in the peak explosion pressure.

3.2 Flame Movement in Primary Vessel

When ignition occurs in the primary (large) vessel, the flame grows outward from that point as pressure increases. When the pressure has risen to P_z (and the pressure in the secondary vessel is P_1), ignition in the secondary vessel occurs.

In the experiments by Grice and Wheeler[2] in spherical chambers, some photographs showing flame movement were taken. For central ignition in the larger sphere, the flame travelling towards the smaller, the photographs showed that in the early stages the flame propagated symmetrically in all directions just as it would in the absence of compartmentation. After a few centimetres travel, it displayed a tendency to move more quickly towards the opening into the smaller chamber than in other directions; eventually it very quickly accelerated into the smaller chamber (half the size of the larger one), in which the gas was in a state of turbulence, before the flame in the larger chamber had reached the walls.

It seems that the unburnt gas between the flame front and the connecting tube assumes a velocity similar to that in the connecting tube (which is much higher than in the primary chamber generally) at some point ahead of the entry to the tube and when the flame reaches this point, it is seen to accelerate into the tube and across to the secondary chamber. In fact it could be said that the *effective* entrance to the connecting tube is some distance ahead of the real entrance. This distance, Z say, determines the point at which flame transfer to (and subsequently ignition in) the secondary chamber will result.

The relationship between flame position and pressure is well established for explosions in closed vessel. For example, in a spherical vessel[7]:

$$r_b = r\left(\frac{(P/P_o)^{\chi} - 1}{(P/P_o)^{\chi} - \alpha}\right) \tag{4}$$

where r is the vessel radius and r_b the flame radius at pressure P. (P_o is the initial pressure, α ratio of the burnt to the unburnt gas density and $\chi = 1/\gamma$, where γ is the ratio of specific heats for the unburnt gas).

Thus, if P_z is known experimentally, then from equation (4) the flame position r_b can be calculated. The distance Z from the connecting tube at which flame transfer occurs is therefore:

$$Z = r - r_b\ (P_z) \tag{5}$$

A number of systems were studied in this way[6] and lead to the following empirical relationship:

$$Z = d_c^{1.8} \tag{6}$$

(both Z and d_c being in centimetres). This suggests that Z is strongly influenced by gas flow rate through the connecting tube, itself proportional to d_c^2. Further evidence is available which supports the view that Z is a function only of flow rate though the connecting tube[5]. As the flow rate increases, Z is increased. Using equation (6) and relationships such as equation (4) it is possible to calculate the pressure P_z at which flame flashes across into the secondary vessel, for any diameter of the connecting pipe. These equations, simplified with typical physical properties for stichometric hydrocarbon-air mixtures are[6]:

For spherical vessels (radius r):

$$P_z\ /\ P_o = \frac{-\ 0.265\ (1 - Z/r)^3 - 0.735}{0.602\ (1 - Z/r)^3 - 0.735} \tag{7}$$

For short cylinders (radius r_c)

$$P_z\ /\ P_o = \frac{(0.353/r_c^2L)\ \ (L/2 - Z)^3 - 0.735}{(0.802/r_c^2L)\ \ (L/2 - Z)^3 - 0.735} \tag{8}$$

For long cylinders

These equations relate to central ignition in the primary vessel.

$$P_z/P_o = \frac{0.5\ (L/Z) - 0.0861\ (r_c/Z) - 0.265}{0.0665\ (L/Z) + 0.196\ (r_c/Z) + 0.602} \tag{9}$$

3.3 Pre-ignition Pressure in Secondary Vessel

It is possible to calculate, analytically, the pressure in the secondary vessel (P_1) corresponding to that in the primary vessel (P_z), as the explosion develops. However, this requires considerable computation and so an alternative empirical approach is suggested based on experimental data. Analysis of experimental pressure-time records indicates that the fractional pressure rise in the two vessels is relatively constant for a given set of conditions. That is:

$$\frac{P_1 - P_o}{P_z - P_o} = Constant = \sigma_z$$

This pressure ratio correlates quite well with the parameter:

$$\lambda = \frac{d_c^2\ r}{S_u\ V_o}$$

where V_o is the primary chamber volume, S_u the burning velocity and r the radius of the primary vessel if it is a sphere; otherwise replace r by r_s, given by

$$r_s = [(3/4)\ r_c^2\ L]^{1/3}$$

The reciprocal of λ represents the rate at which the explosion develops (λ has units sm^{-1}); low values of λ (i.e. high velocity) lead to large differences in pressure between the two vessels while at high values (low velocity) pressures are very similar.

The empirical relation between σ_Z, the pressure ratio, and λ is plotted in figure 7.

Note that at $\lambda \sim 0.2$ s/m, σ_z approaches a limit of approximately 0.96 and above this value, pressures in the two vessels are almost equal. The relationship between Z and d_c (i.e. equation 6) is valid only up to this point.

Thus, the compression in the secondary vessel, P_1, may be calculated from

$$P_1 = P_o + (P_z - P_o)\ \sigma_z(\lambda) \tag{10}$$

where σ_z (λ) may be obtained from figure 7 for the relevant equipment geometry.

3.4 Back-venting from Secondary Vessel

Referring back to equation (3) for calculation of P_k, the next step is to evaluate ΔP, the back venting from the secondary chamber. When the flame transfers from the primary to the secondary chamber, the gas mixture that it encounters in the secondary chamber is at a pressure, P_1, higher than when ignition occurred in the primary chamber. Ignition in the secondary chamber causes the pressure within that vessel to rise very rapidly (due to the fact that the gas is in a state of turbulence). As a result, this pressure soon exceeds the level in the primary chamber, causing burnt gas to be vented back into the primary chamber. There is, however, lack of detailed information regarding the combustion process in the secondary chamber. There is uncertainty for example regarding the nature of the turbulent combustion and hence the rate of pressure rise, the transport properties of the gas vented out of the secondary chamber, the gas flow mechanism through the connecting tube and the degree of choking that takes place inside it. In the absence of this information, an empirical approach may be used. Based again on experimental data[6], the back-venting may be calculated from:

$$\Delta P = \left(\frac{2.31}{S_u} \frac{d_c^2}{V_s} \right) P_1$$

where V_s is the volume of the secondary vessel. Combining this with equation (3) leads to the following expression for the peak explosion pressure:

$$P_k = P_1 \left(\eta - \frac{2.31}{S_u} \frac{d_c^2}{V_s} \right) \qquad (11)$$

3.5 Effect of Variations in the Point of Ignition: Qualitative Aspects

The discussion above and indeed the applicability of equation (11) applies only to explosions resulting from gas ignition in the centre of the primary vessel. It is necessary to evaluate the influence of the point of ignition because this can affect the severity of the explosion.

Consider a pair of connected cylinders, the primary one being of length L and radius r_c, where $r_c \ll L$. Suppose the distance from the point of ignition to the primary chamber end furthest from the connecting tube is y, which can be varied from L to zero. When the point of ignition is such that y is nearly equal to L, the pressure in the primary (and in the secondary) chamber will rise by only a small amount when flame transfer occurs (i.e. P_z will be small). Essentially, under these conditions, the flame will expand spherically and when it gets to a distance Z from the connecting tube, it will flash across.

As y is decreased, the distance that the flame has to travel, and hence also the degree of burning that takes placed prior to flame transfer, will increase and consequently so will P_z.

This is illustrated in figures 8a and 8b where the shaded areas represent the volume of gas burnt.

Eventually, as y is decreased to below L/2, a critical point of ignition, y_c, will be reached when all the gas between the point z and the extreme end of the primary chamber will be totally burn at the precise moment of flame transfer. This is shown in figure 8c. If y is decreased still further, the amount of gas burnt prior to flame transfer will be unchanged (see figure 8d) and hence P_z will also be unchanged. Clearly then, if the point of ignition is anywhere between y = zero and $y = y_c$, the value of P_z should remain constant.

The pre-ignition pressure in the secondary chamber, P_1, corresponding with values of P_z is related by the parameter σ_z which is itself a function of λ. In general λ (and σ_z) are functions of the gas mixture and the experimental system only, except that when the flame propagation rate changes (as a result of ignition at one end of a vessel as opposed to the centre, for example) the *effective* burning velocity is altered. This will alter both λ and σ_z. Thus P_1 will increase as the point of ignition is moved away from the connecting tube (during the initial stages as a result of increase in P_z, with σ_z constant, and later for values of $y \leq y_c$, when P_z is constant, due to increase in the value of σ_z).

Hence, unlike P_z, P_1 would not be expected to become constant for y less than y_c. Furthermore, as P_k is proportional to P_1 (assuming equation (11) to be valid) the former should also increase continuously as the ignition point is moved away from the connecting tube.

Experimental verification of the above trends is clearly essential to establishing the credibility of the model. Experimental data with a stoichiometric methane-air mixture using a primary chamber of volume 32.9 litres is shown in figure 9. The diameter of the connecting tube is 1.6 cm , volume ratio 14.0 and the point of ignition was moved along the axis of the primary chamber. Clearly the results relating to P_1, P_z and P_k are all in agreement with the qualitative predictions discussed above.

3.6 Peak Explosion Pressure Due to Ignition at the Extreme End of the Primary Chamber

From a practical view point, it is of interest to know the maximum possible hazard, irrespective of where ignition takes place. In practice this necessitates determining the maximum explosion pressure when the source of ignition is at the primary chamber end furthest from the connecting tube. The analysis for doing such a calculation changes in two ways compared with central ignition: firstly it changes because the explosion develops more slowly, and secondly because the amount of gas burnt in the primary chamber prior to flame transfer increases.

The decrease in the rate of pressure rise in the primary chamber (prior to flame transfer) is reflected in σ_z, which increases slightly. For cylinders of the shape discussed in the last section, (and used in this study) σ_z can be determined in the same manner as for explosions due to central ignition (i.e. from figure 7) provided S_u in λ is replaced by the 'effective' burning velocity $S_{u,eff}$, where:

$$S_{u,eff} = S_u \, 2^{-1/3}$$

to reflect the fact that ignition is at one end[7].

The increase in the amount of gas burnt in the primary chamber (prior to flame transfer), which is the second main effect of moving the point of ignition from the centre of the extreme end of the primary chamber, results in an increase in P_z. The pressure P_z is dependent upon the development of the flame front and its position prior to flame transfer and therefore in order to calculate P_z, the movement of the flame front must be quantified. It is possible to develop simple expressions for end-ignition, similar to the above treatment for central ignition[5]. Alternately, the effect can be incorporated by simply comparing data ignition at the two positions. The data for a range of systems is shown in figure 6 and this indicates that:

$$\frac{P_k \text{ (end ignition)}}{P_k \text{ (central ignition)}} \simeq 1.80$$

Therefore it is possible, for any system, to calculate P_k initially for central-ignition and then modify this value according to the above ratio.

4. APPLICATION OF THE MODEL

1. Basic Procedure

The information required in order to use the empirical model is the following:

(a) dimensions of the primary chamber
(b) diameter of the connecting tube
(c) volume of the secondary chamber
(d) S_u and η, for the unburnt gas at the pre-explosion conditions.

Before proceeding with the calculation it is necessary to decide the likely point of ignition, the centre or the extreme end of the primary chamber being the two points considered in detail in the model. If the ignition point is unknown, then ignition at the extreme end should be taken, this being the most pessimistic.

For central ignition the calculation procedure is the following;

1. Calculate $\lambda = d_c^2 r / S_u V_s$.
   For a cylindrical vessel, replace r by r_s, the radius of a sphere, equivalent in volume to the primary chamber.
2. Using figure 7, evaluate σ_z
3. From equation (6) calculate Z
4. Using the equation appropriate for the primary chamber geometry, evaluate P_z. The simplified equations (which incorporate physical properties of stoichiometric

hydrocarbon-air mixtures) for P_z are the following:

- spherical chambers, equation (7).
- short length cylinders, equation (8).
- long cylinders, equation (9).

5. Evaluate P_1 from the expression

$$\sigma_z = \frac{P_1 - P_o}{P_z - P_o}$$

6. Substitute P_1 into equation (11) to give P_k.

The above procedure cannot be used for $\lambda > 0.2$; see later for further discussion.

If ignition is assumed to be at the end of the primary chamber furthest from the connecting tube, two alternatives are available. The first is to use the above procedures for central ignition and then multiply the value of P_k by 1.80. The second is to apply suitable modifications to the above steps and thus calculate P_k 'rigorously'.

4.2 Comparison with Experimental Results

The explosion pressure predicted by the above procedure can now be tested against experimental data.

Two systems are presented for comparison: 71.4 litre and 54.6 litre chamber, both with a connecting pipe diameter of 1.9 cm. The flammable gas is methane. The values of P_k from equation (11) as a function of volume ratio are shown in figures 10 and 11 together with the experimental results. Good agreement is obtained.

4.3 Explanation for 'Peaking' of Explosion Pressure

It was noted in the experimental data (e.g. figure 5) that the explosion pressure reaches a maximum as volume ratio between the vessels is increased and further increases in the ratio can lead to a reduction. The explanation for this is related to balance between compression of the gas in the secondary chamber (which leads to an increase in the explosion pressure) and the back-venting (which leads to a reduction in pressure). In the example considered above (see figure 11) the explosion pressure is seen to plateau (also predicted by the model).

The point at which this maximum occurs corresponds closely with the pressures in the connected vessels being very similar to each other during explosion build-up. This takes place when $\lambda \geq 0.2$. (This is also the point at which the empirical model for explosion pressure prediction breaks down). This means that the worst configuration can be predicted and is a function of λ and not any individual variable (such as volume ratio).

The diameter of the pipe connecting the two chambers is a particularly important variable. As the diameter is increased, the pressures in the two vessels become more similar (i.e. the partition is less effective) and so the peak pressure is reduced. The smallest size permissible which would still avoid pressure piling may be estimated by reference λ; as λ gets much above 0.2 the peak pressure will fall rapidly.

5. CONCLUSIONS

The equations presented should enable the explosion hazard presented by a pair of interconnected vessels to be assessed from a knowledge of the system geometry and the nature of the flammable gas. Although experimental verification will be necessary, it is expected that the results can be extrapolated to systems somewhat larger than studied at present, possibly up to a volume of a few hundred litres. Within this range, accuracy may be of the order to 10%.

Possible areas of application include electrical equipment casings in flammable atmospheres, and vessels and reactors for flammable gas handling systems such as in hydrocarbon oxidation plants. If the magnitude of the hazard is identified during the design stage, the either the process equipment can be designed to contain the explosion or the phenomenon can be 'designed out' by selecting suitable equipment geometries.

It has been suggested[8] that if the connecting tube as used in this study is replaced by a short orifice type connection, the system behaviour could be substantially altered due to the difference in turbulence that this would cause compared with tube. The fact that varying the length of the connecting tube[3] from about 6 cm to 38 cm had no effect upon the explosion behaviour and that the degree of turbulence in the secondary chamber is so large even with a tube connection that it behaves almost like a stirred reactor, suggests that changing to an orifice type connection should have little or no effect. However, this also needs to be confirmed experimentally.

Another feature that would particularly benefit from further analysis is the mechanism of flame transfer from the primary to the secondary chamber. The complexity of this process is probably not adequately reflected by the model described.

SYMBOLS USED

d_c diameter of connecting tube
L length of cylinder (primary chamber)
M_f moles of burnt gas (products)
M_o moles of unburnt gas (reactants)
P absolute pressure
P_1 pressure (absolute) in secondary chamber just prior to ignition in it
P_f peak pressure (absolute) in a single vessel explosion
P_k peak pressure (absolute) in the secondary chamber
P_o initial pressure (absolute)
P_k' $P_1\eta$
P_m maximum pressure in primary chamber
P_Z pressure in primary chamber just before ignition in secondary vessel

ΔP $P_k^{/}$ - P_k
R universal gas constant
r radius of a sphere
r_b distance of flame from point of ignition during a spherical explosion
r_c radius of cylinder
r_s $[(3/4)\ r_c^2 L]^{1/3}$ i.e. radius of sphere equal in volume to a cylinder
S_u fundamental burning velocity
$S_{u.eff}$ 'equivalent' value of S_u which can be used in spherical explosion equations to represent 'non-spherical' explosions
T_o initial (unburnt gas) temperature
T_b burnt gas temperature
T_f flame temperature
$\overline{T_b}$ mean temperature of burnt gas
V_o volume of primary chamber
V_s volume of secondary chamber
V_R volume ratio = V_o/V_s
η P_f/P_o

REFERENCES

1. Beyling, E., 1960, Glückauf, 42: 97-99 and 129-138

2. Grice, C.S.W. and Wheeler, R.V., 1929. Papers, Safety-in-Mines Res. Bd. No. 49, (HMSO, London).

3. Brown, T.J.A., 1959, Tech Rep. Br Elec Allied Ind Res Assoc, D/T 109

4. Gleim, E.J., and Marcy, J.F., 1952, Rep Investig. U.S. Bur Mines. No. 4904

5. Singh, J., 'Gas Explosions in compartment Vessels: Pressure Piling', Chem.Eng. Res. Des., Vol 62, Nov. 1984.

6. Singh, J., 1977, PhD Thesis (University of London, British Library Ref. No. D24652/78).

7. Singh, J., 1983, "The Calculation of Explosion Parameters in Non-spherical Vessels, simplified equations and applications," J. Loss Prev. Proc. Ind., Vol 1, Jan. 1988.

8. Fitt, J.S., The Chemical Engineer, No. 368, p. 237.

FIGURE 1: TYPICAL SETUP FOR PRESSURE PILING EXPERIMENTS

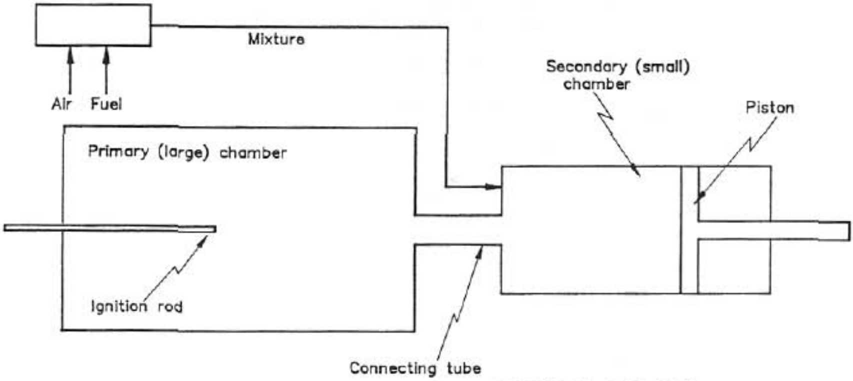


FIGURE 2: A TYPICAL RECORD OF AN EXPLOSION IN COMPARTMENTED VESSELS SHOWING THE VARIABLES MEASURED

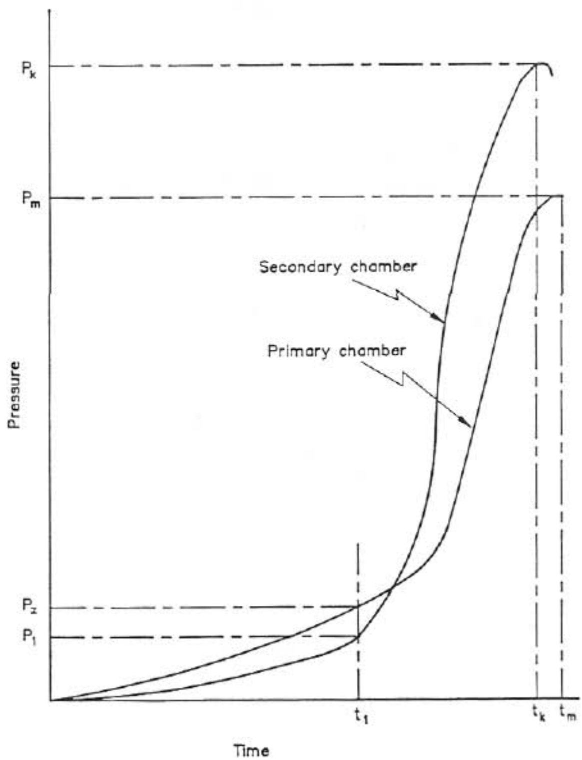


FIG 3 : EXPLOSION PRESSURE Vs CONNECTING TUBE DIA.
(TEST GAS : STOICHIOMETRIC METHANE-AIR)

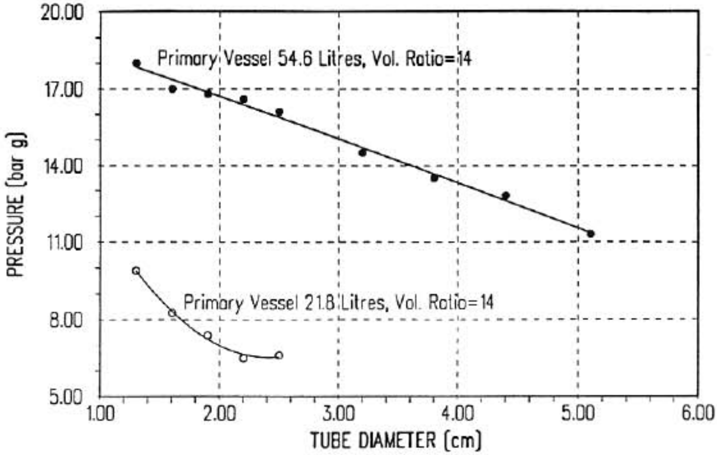


FIG 4 : EXPL. PRESSURE Vs VOLUME OF PRIMARY VESSEL
(GAS : STOICHIOMETRIC METHANE-AIR)

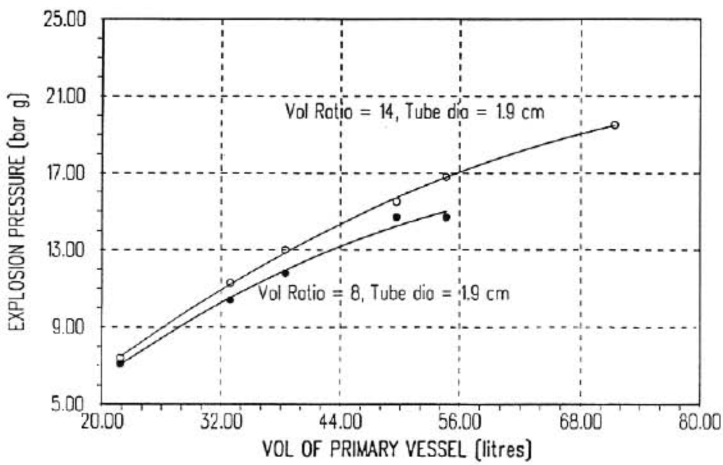


FIG 5 : EXPLOSION PRESSURE Vs VOLUME RATIO
(PRIMARY VESSEL VOLUME = 54.6 Litres)

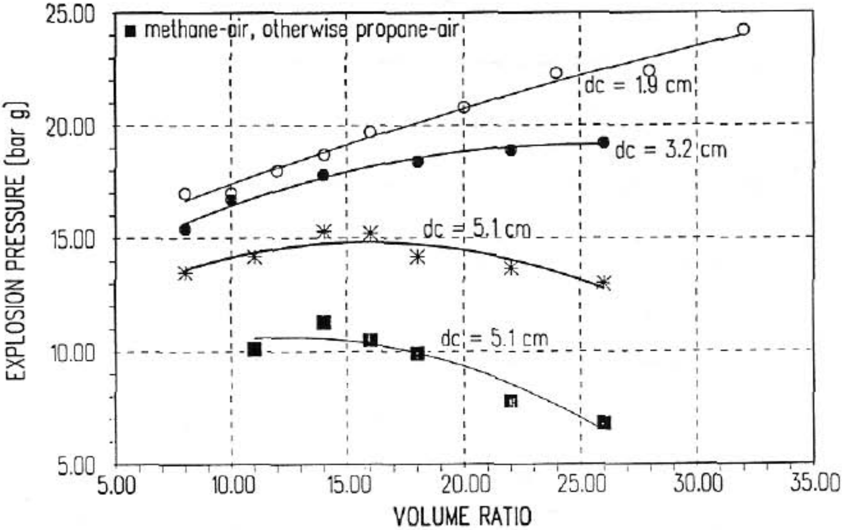


FIG 6 : EXPLOSION PRESSURE AT RANGE OF CONDITIONS
EFFECT OF IGNITION POINT IN PRIMARY VESSEL

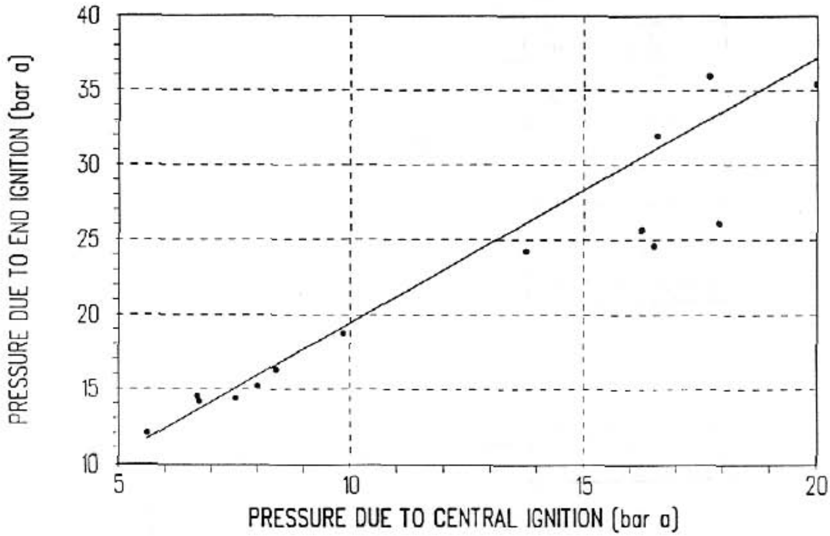
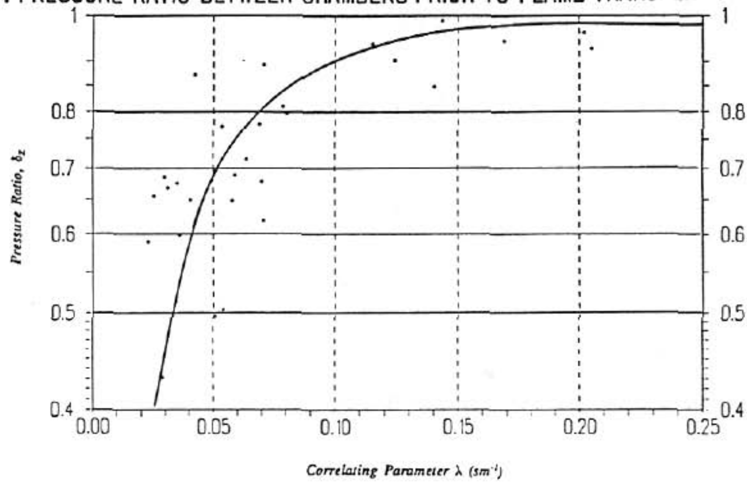


FIG 7 : PRESSURE RATIO BETWEEN CHAMBERS PRIOR TO FLAME TRANSFER



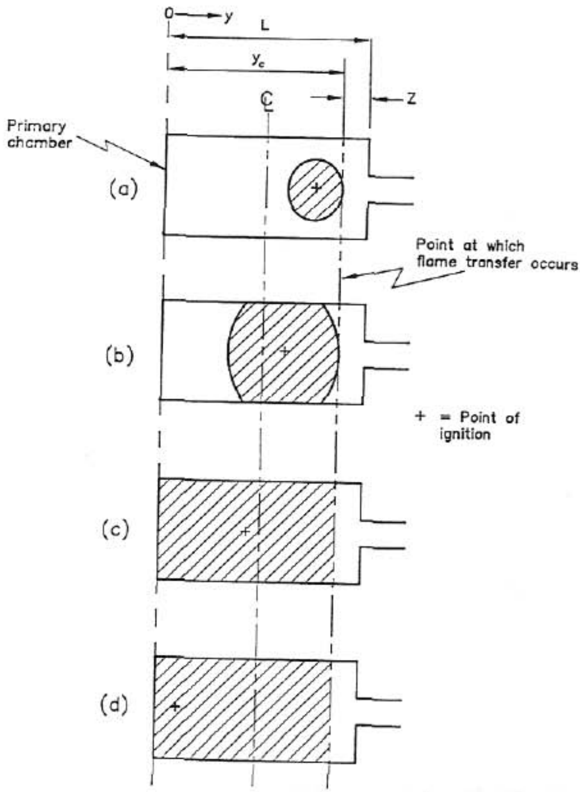


FIGURE 8: EFFECT OF THE POSITION OF THE SOURCE OF IGNITION ON THE DEGREE OF COMBUSTION PRIOR TO FLAME TRANSFER

FIG 9 : EFFECT OF CHANGE IN POINT OF IGNITION

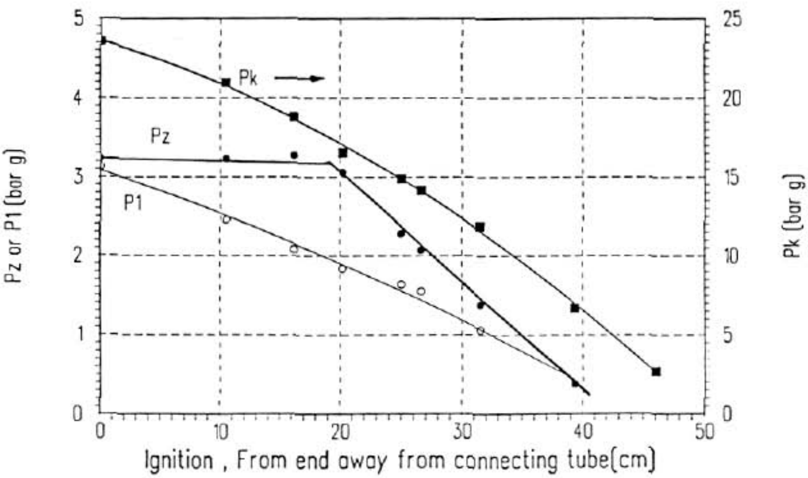


FIG 10 : COMPARISON OF PREDICTED & CALCULATED DATA
(Primarary Chamber Volume = 71.4 Litres)

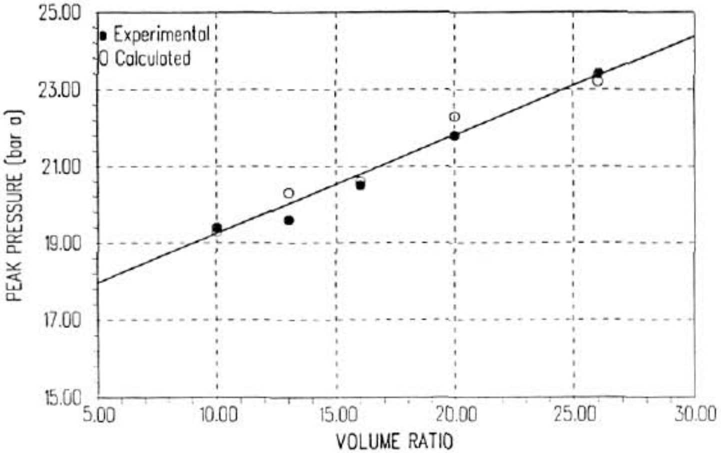


FIG 11 : PREDICTION OF PEAK EXPLOSION PRESSURE
(Primary Chamber Volume = 54.6 Litres)