RELIEF OF EXPLOSIONS IN PROPANE–AIR MIXTURES MOVING IN A STRAIGHT UNOBSTRUCTED DUCT

By Z. W. ROGOWSKI,* and D. J. RASBASH, B.Sc., Ph.D., A.R.C.S. D.I.C. (ASSOCIATE MEMBER)*

SUMMARY

Explosions have been carried out in a propane–air mixture moving in a straight unobstructed length of ducting at velocities between 20 and 40 ft/s. Pressures and flame speeds were measured with a number of different distributions of relief vents. The effects of the weight of the cover and the use of magnetically held covers were also investigated. The application of the results to practice is discussed and the ways in which the results may be extrapolated to a wider range of conditions than those actually tested are indicated.

Introduction

A question which frequently arises in industrial practice is the protection against explosions of ducts, and duct systems carrying mixtures of flammable gases and vapours with air. A certain amount of information on the design of explosion reliefs for duct systems was given at the previous symposium,[1] but this information was limited in application since it was based on experiments with gases which were stationary at the moment of ignition. These experiments, however, showed that the development of turbulence within the gas had a marked effect on the violence of the explosion and therefore indicated that a gas originally in motion might explode substantially more violently than a gas which was initially stationary. In many instances in industrial plant the gas at risk is moving through duct systems at speeds of the order of 10 to 60 ft/s. The experiments described in this paper were designed to provide some information which can be applied to such systems.

* Fire Research Station, Boreham Wood, Herts.

Experimental

Apparatus

A difficulty in experimental work of this kind is to provide a high flow rate of an explosive gaseous mixture in such a way that the apparatus used for the purpose would not be damaged by the explosions. In the present apparatus, the difficulty was overcome in a simple manner. The air containing the flammable gas was pulled along the duct by the entrainment action of a water spray. The apparatus is represented diagrammatically in Fig. 1. *AB* represents the test section of the duct which consisted of four lengths of 1 ft square section duct 6 ft long. Air was pulled along this duct in the direction *AB* by means of a spray *S* operating in a further length of duct *BC*, the spray being ejected towards the open end *C*. Flammable gas or vapour was introduced into the air stream within a section *AD*. The top surfaces of the four 6 ft lengths of duct which made up section *AB* were completely open and were flanged in such a way that the openings could be closed to any degree thus allowing a controllable amount of explosion relief at the top of a duct;

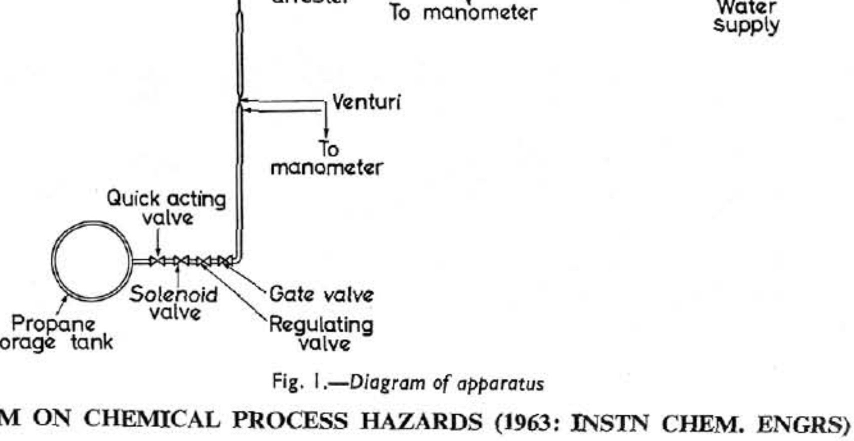


Fig. 1.—*Diagram of apparatus*

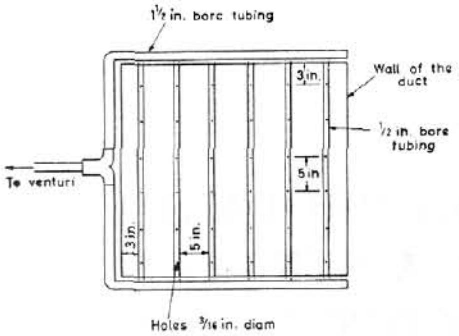


Fig. 2.—*Fuel distributor*

a diagram and further details of this design of duct have been given elsewhere.[1] During experiments these relief vents were covered either with loose covers of various weights or with covers clamped by magnets to the duct.

The fuel was injected into the section *AD* through a distributor which is shown in Fig. 2. It consisted of a series of holes $\frac{3}{16}$ in. in diameter drilled in a battery of pipes held in a framework 2 ft 7 in. square. The holes pointed downstream of the duct. In all experiments a propane-air mixture containing 4·5% of propane was used as the flammable gas. The propane was stored in a vessel of 50 ft^3 capacity at pressures up to 60 lb/in^2 and was injected into the air stream when required by the use of a solenoid valve. The flow rate was controlled by the regulating valve, and gate valve, and measured by a venturi.

The spray used to pull the air along the duct was delivered from a nozzle at rates up to 40 gal/min at 100 lb/in^2; the cone angle was about 45 deg. In this way an air flow up to 40 ft/s could be obtained along the duct. The air flow was indicated by a reference pitot tube situated on the axis of the duct; this pitot had been calibrated in preliminary experiments against the total air flow along the duct. Fig. 3 gives a view of the whole apparatus and shows an explosion taking place.

Provision was made at a number of points along the duct for the insertion of pressure gauges and flame detecting devices for the measurement of explosion pressure and flame speed respectively.

Experimental programme

The main object of the experimental work was to find for systems similar to the one under investigation a practicable

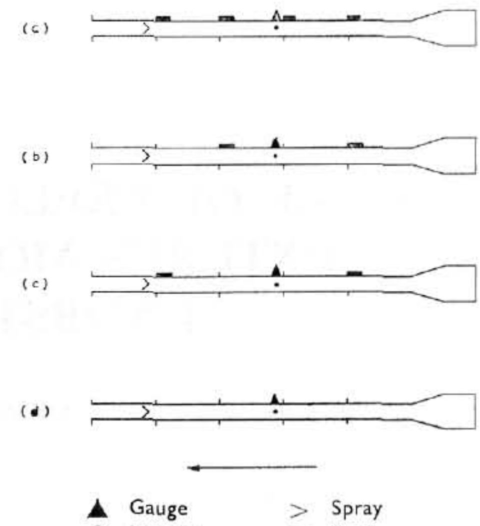


Fig. 4.—*Distribution of relief vents used in tests*

means for providing explosion relief which could keep pressures developed during explosions down to values of about 1 lb/in^2. However these experiments were carried out in such a way as to allow, where possible, extrapolation of the effects of the various factors considered to conditions outside the range of experiments. The main factors investigated were the velocity of the gas, the size and distribution of explosion relief, the weight of the covers on the explosion relief and the effect of holding these covers to the duct by magnets. The distribution of vents are shown diagrammatically in Fig. 4. Most of the experiments were carried out using a distribution of explosion relief with four vents spaced along the working portion of the duct at intervals of 6 ft, Fig. 4*a*. It will be seen that the ignition source was quite near a vent; the reason for this is that preliminary experiments showed that within the range of gas velocities tested the maximum pressure occurred when the ignition source was in the position indicated. A limited number of experiments were also carried out with two vents spaced at 12 ft and 18 ft centres respectively and one experiment with no vents along the top surface of the duct at all. Of course, in all cases the two open ends of the duct at a distance apart of approximately 30 ft acted as explosion reliefs as well, and provided the only explosion relief when there were no openings along the top.

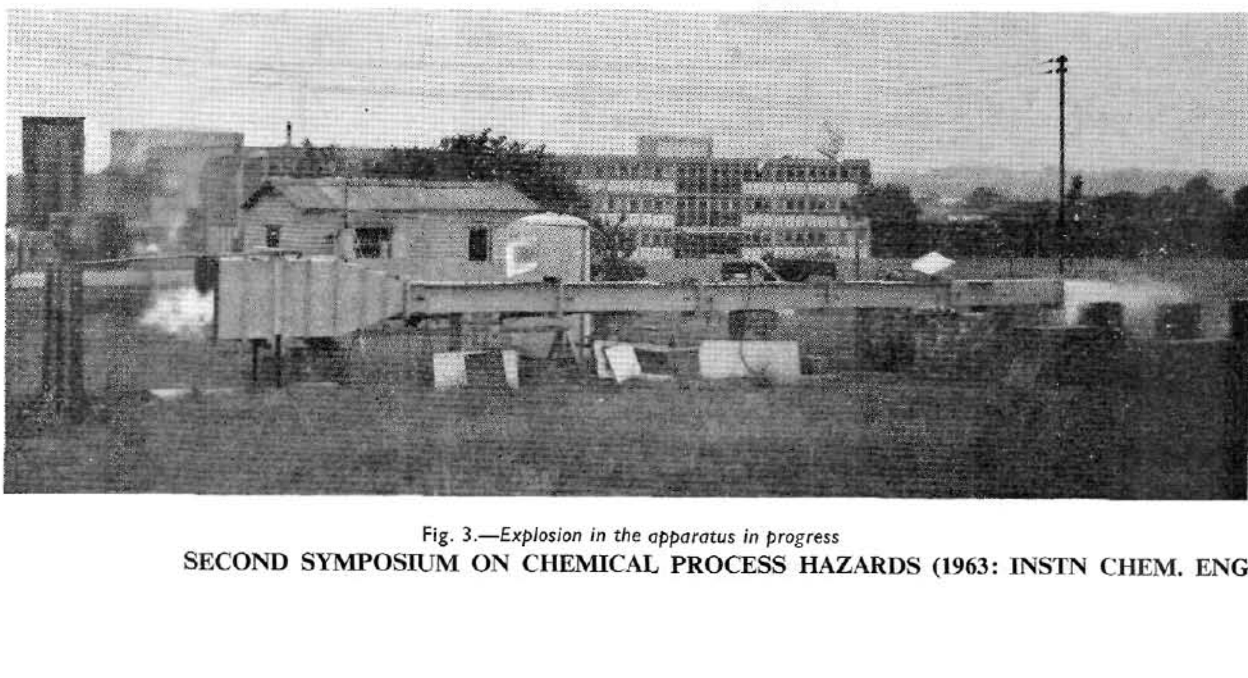


Fig. 3.—*Explosion in the apparatus in progress*

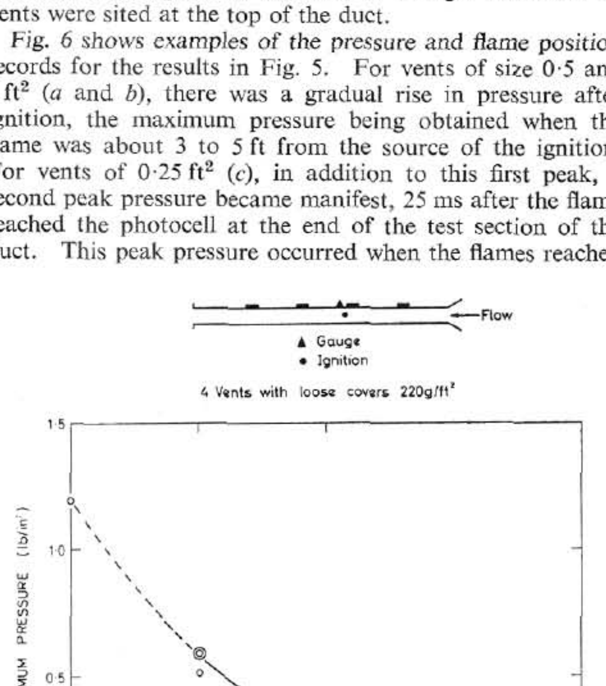
The gas was ignited using an inductive spark sited on the axis of the duct. Three flame detecting probes were placed downstream, and one upstream of the ignition source and a pressure gauge was sited near the ignition source.

Results

Experiments with explosion reliefs at 6 ft spacing

Fig. 5 shows the relation between the maximum pressure and the size of the individual vents spaced 6 ft apart in the top of the duct. Within the range investigated, *i.e.* vent size 0·25 to 1 ft^2, the maximum pressure was inversely proportional to the size of the explosion relief. The results shown in Fig. 5 were obtained with a gas speed of 20 ft/s and for loose covers on the vents weighing 220 g/ft^2 of vent area; tests with vents 0·5 and 1 ft^2 with other weights of cover and other speeds gave a similar relationship between the maximum pressure and the size of vent. The curve shown in Fig. 5 is extended to the pressure obtained in a single test when no vents were sited at the top of the duct.

Fig. 6 shows examples of the pressure and flame position records for the results in Fig. 5. For vents of size 0·5 and 1 ft^2 (*a* and *b*), there was a gradual rise in pressure after ignition, the maximum pressure being obtained when the flame was about 3 to 5 ft from the source of the ignition. For vents of 0·25 ft^2 (*c*), in addition to this first peak, a second peak pressure became manifest, 25 ms after the flame reached the photocell at the end of the test section of the duct. This peak pressure occurred when the flames reached



Velocity of flammable gas 20 ft/s.

Fig. 5.—*Relation between maximum pressure and the vent area*

the fuel feed bars in the section *A D* which acted as an obstacle (see Fig. 1). For this reason the maximum pressure in this second peak was regarded as a spurious phenomena as far as explosion in the non-obstructed test section of the duct was concerned and was ignored. When no vents were placed on the top surface of the duct (*d*), the secondary peak which occurred in the fuel chamber was very high and was followed by violent fluctuations in pressure.

Two examples of the effect of gas velocity on the maximum pressure are shown in Fig. 7. Over the range of velocities tested, *i.e.* 20 to 40 ft/s there was an increase in maximum pressure as the speed of the gas was increased, but as indicated in Fig. 7 the relationship varied somewhat according to the conditions of test and depended on the size of the explosion relief and the weight of the cover. Figs. 8 and 9 show the dependence of maximum explosion pressure on the weight of the cover used for 1 ft^2 and 0·5 ft^2 vents respectively. In all cases there was an increase in maximum explosion pressure as the weight of the covers increased, and within the repeatability of experiments this increase was linear. However, the increase was more pronounced at a velocity of 40 ft/s than at 20 ft/s. In all experiments the force on the cover exerted by the maximum pressure, was far greater—to the extent of between one and two orders—than the weight of the covers.

All the pressure records obtained with 1 ft^2 vents at 20 and 40 ft/s and with 0·5 ft^2 vents at 20 and 30 ft/s were similar in that they showed a steady rise of pressure to a maximum with no sharp peak; Fig. 6 (*a* and *b*) are typical examples. On the other hand the pressure records at 40 ft/s and 0·5 ft^2 vents (Fig. 6*e*) showed a steady slow rise in pressure followed by a sharp rise in pressure to a sharp peak.

Fig. 10 shows the effect of using covers clamped by magnets on the maximum pressure developed. Two sets of covers were used weighing 550 g and 1250 g each. These were clamped to the ducts by magnets with a force of between 9 and 15 lb/ft^2 (4000 to 6800 g/ft^2). Fig. 10 shows the maximum pressure plotted against the velocity of the gas with the two sets of covers; the mean points for loose covers of the same weight interpolated from Fig. 8 are also represented. Over the range of velocities investigated the maximum pressure was directly proportional to the gas velocity for both sets of magnetic covers. Also, in spite of the comparatively strong magnetic force clamping the covers to the ducts, the maximum pressure was on the average only 0·1 lb/in^2 (14 lb/ft^2) greater than the pressure obtained with loose covers of the same weight; this increment in pressure is approximately equal to the magnetic force clamping the covers to the duct.

Fig. 11 shows the flame speed as a function of the position of the flame in the duct for a few experiments with vents spaced 6 ft apart. The distributions for different vent areas were essentially similar in that the flame speed rose on the downstream side of the ignition source to a peak value between 2·5 and 6 ft along the duct. Flame speeds on both sides of the ignition source increased as the vent size was reduced, the weight of the cover increased or as the gas velocity was increased. The maximum speed obtained in any of these experiments within 9 ft of the ignition source on the downstream side was 180 ft/s.

Experiments with explosion reliefs 12 and 18 ft apart

Fig. 12 shows the maximum pressure obtained for different gas velocities with two vents 12 ft apart and 1 ft^2 area. With this arrangement pressures were two or three time as great as with vents of the same size 6 ft apart. Table I shows results of experiments with two vents one square foot in area situated 18 ft apart and Fig. 6 (*f* and *g*) show records of two of these experiments. These results were unusual in two ways. Firstly, the maximum pressure obtained was unexpectedly large in comparison with the maximum pressures obtained with vents 12 ft and 6 ft apart, and secondly, the maximum pressure decreased as the weight of the cover increased. Indeed in all the three experiments listed in Table I the maximum pressure when the flame was in the

TABLE I.—*Maximum Explosion Pressure with Vents 18 ft Apart*

Vent closure	Maximum pressure (lb/in^2)
220 g loose	1·6
440 g loose	1·5
570 g magnets	1·3

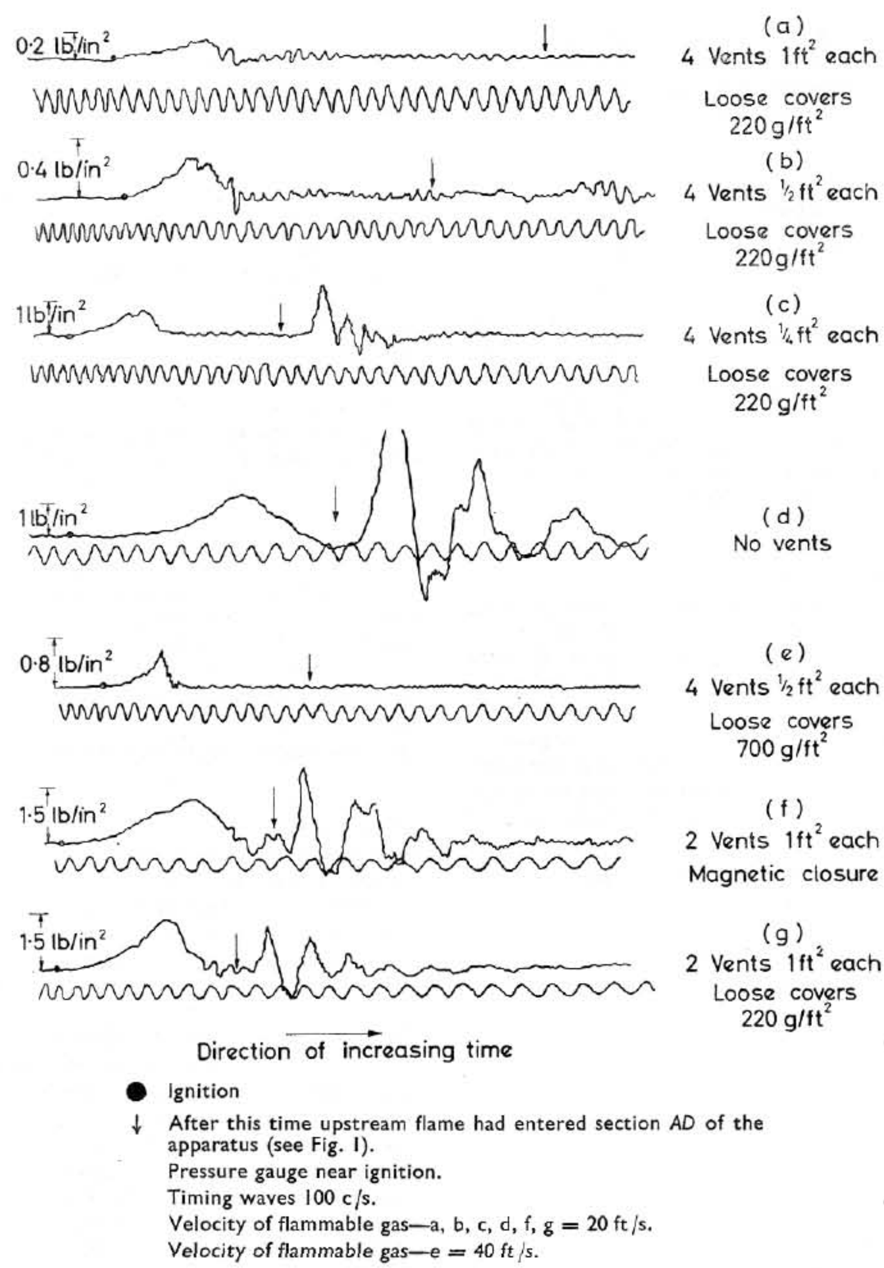


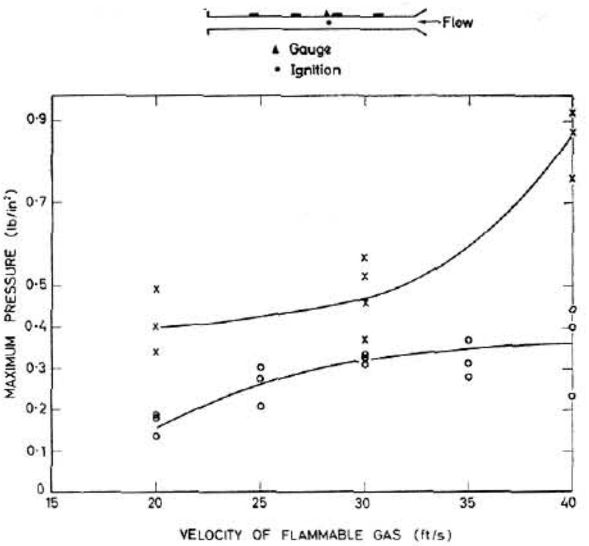
Fig. 6.—*Examples of pressure records*

working section was greater than that obtained when no vents were placed along the top surface of a duct. Also in the three experiments the flame speed reached a high value (360 ft/s) after travelling 7·5 ft from the ignition source.

Discussion

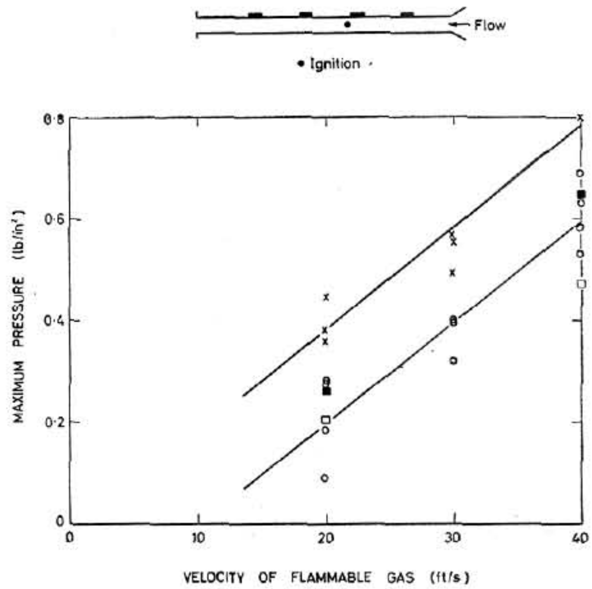
Comparison between moving and stationary gas

Fig. 13 shows a comparison between some of the pressures obtained in the above experiments and the maximum pressures obtained with the flammable gas initially stationary,[2] but in which the conditions of ignition were comparable. It is clear from Fig. 11 that the imposition of velocities of 20–40 ft/s on the gas mixture brought about a marked increase in the maximum pressure. For vent spacings of 6 and 12 ft the maximum pressure was approximately proportional to the initial gas velocity and to the spacing between the vents. There was a sharp increase in the maximum pressure as the spacing between the vents was increased to 18 ft followed by a subsequent slight drop as the spacing was increased to 30 ft; the latter experiment was the one in which there were no explosion reliefs on top of a duct and the only explosion reliefs were those at the ends of the duct. In Fig. 14 the flame speeds obtained with the 18 ft spacing of vents with gases initially moving is compared with those obtained with the gas initially stationary. Here again the effect of initial velocity on the flame speed is well marked. The above phenomena may be ascribed very largely to an increase in the combustion rate due to the initial presence of turbulence in the moving gas stream, although the development of further turbulence at one of the explosion reliefs probably contributed to the high values of maximum pressure and flame speed when vents were spaced 18 ft apart. It was noted that at this spacing the maximum pressure dropped as the weight of cover increased. This may have been due to an increase in the disturbance at the vent as the weight of the cover was reduced.



⊙ = loose covers, 220 g/ft², each vent 1 ft²
× = loose covers, 450 g/ft², each vent ½ ft²

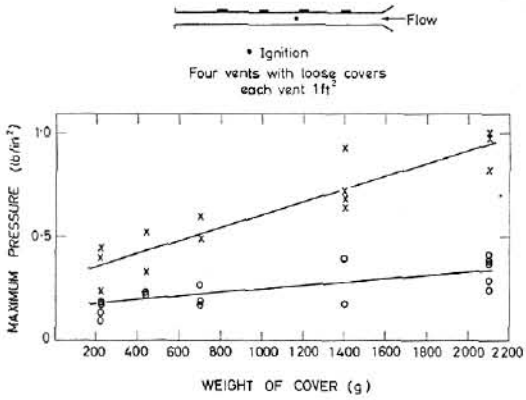
Fig. 7.—*Relation between the maximum pressure and the velocity of the flammable gas*



Covers clamped by magnets:
⊙ = 550 g
× = 1250 g

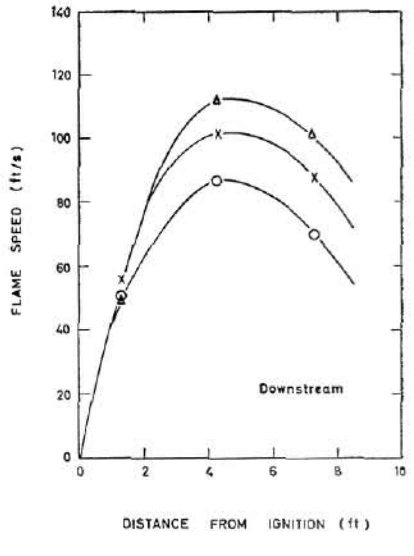
Loose covers:
⊡ = 550 g
■ = 1250 g

Fig. 10.—*Effect of the use of covers clamped by magnets on the maximum pressure*



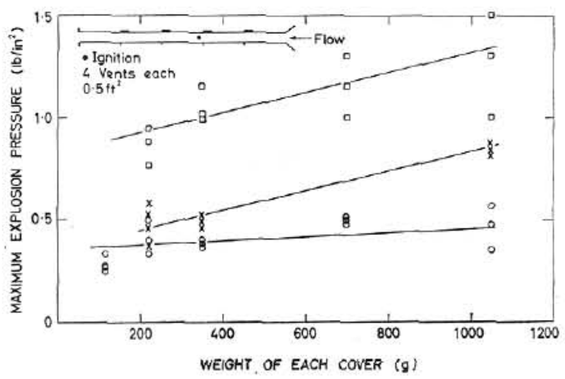
⊙ = Velocity of flammable gas, 20 ft/s
× = Velocity of flammable gas, 40 ft/s

Fig. 8.—*Relation between maximum pressure and the weight of cover*



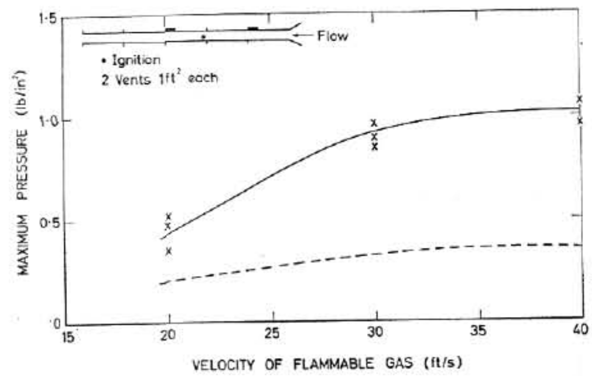
Vent area:
⊙ = 1·0 ft² 4 vents, gas velocity 20 ft/s
× = 0·5 ft²
△ = 0·25 ft²

Fig. 11.—*Flame speed along the duct*



⊙ Velocity of flammable gas, 20 ft/s
× Velocity of flammable gas, 30 ft/s
⊡ Velocity of flammable gas, 40 ft/s

Fig. 9.—*Relation between maximum pressure and the weight of cover*

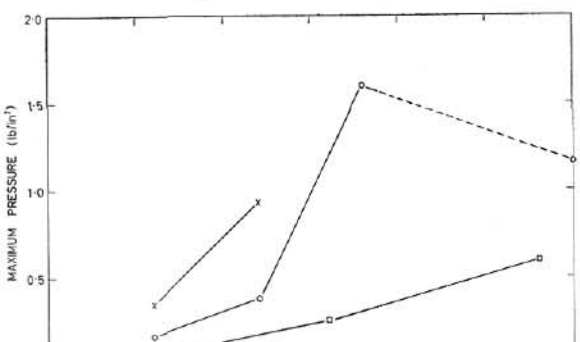


— — —, Curve for vents 6 ft apart from Fig. 7.
———X, Curve for vents 12 ft apart, loose covers, 450 g/ft²

Fig. 12.—*Relation between the maximum pressure and the velocity of flammable gas*

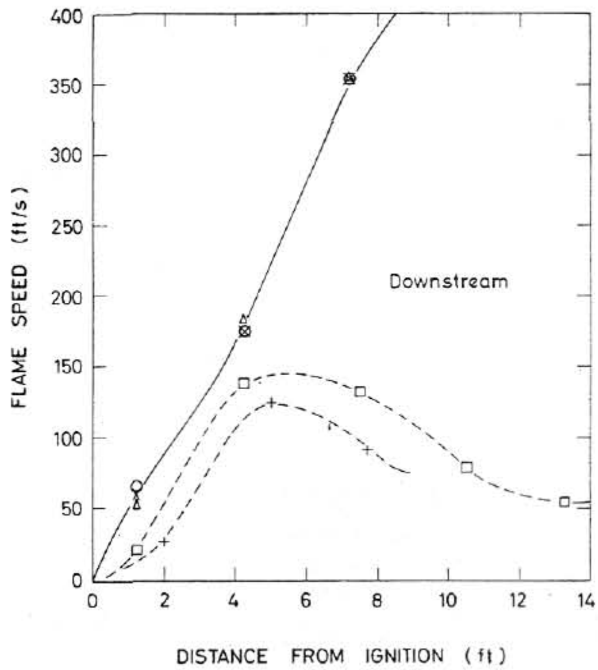
Rates of combustion in moving gases

To help interpret the results obtained in the present experiments it is necessary to have quantitative information on the effect of the turbulence in the moving stream on the combustion rate. Although the present experiments were not designed to give this information, certain of the results obtained, combined with information given elsewhere, did allow a useful quantitative approach to this problem. In these experiments it was noted that the time taken for the flame to reach the first flame detecting point 2 ft 6 in. from the ignition source, was approximately independent of the venting system and depended only on the gas velocity; these times were 0·12, 0·045, 0·036 and 0·029 seconds for gas speeds of 0, 20, 30 and 40 ft/s respectively. On the assumption that the flame moved at the basic turbulent or laminar burning velocity S_B relative to the unburnt gas before the flame reached the walls of the duct, and thereafter for the rest of its passage to the first detection point the flame travelled at a relative velocity S, 3·5 times the velocity S_B, it is possible to estimate the value of S which may be taken as the combustion rate at the flame front moving along the duct. The factor of 3·5 allows for the curvature of the flame travelling along the duct and is based on observed flame speeds when ignition took place near the open end of a similar duct and propagated towards the closed end.[3] Applying this calculation to the ignition of a stationary gas in the 1 ft² ducting, using the time of travel of 0·12 s, gave a value to S of 4·4 ft/s



× = gas moving at 40 ft/s 1 ft² ducting
⊙ = gas moving at 20 ft/s wt of covers, 0–250 g/ft²
⊡ = gas stationary.

Fig. 13.—*Effect of motion of gas on the maximum pressure*



Symbol	Velocity of flammable gas (ft/s)	Weight of cover (g)	Area of each vent (ft²)	Type of cover	Distance between vents (ft)
——— ⊙	20	220	1	loose	18
——— ×	20	440	1	loose	18
——— △	20	550	1	magnetic	18
- - - ⊡	0	220	1	loose	28
- - - +	0	220	1	loose	16

Fig. 14.—*Flame speed along the duct*

or 3·4 times the laminar burning velocity for the propane-air mixture used. This is the expected value if the flame remained completely laminar between the ignition source and the first detection point, and provides some justification of the ratio of 3·5 taken above. For gases moving at velocities of 20, 30 and 40 ft/s the relative velocity S between the flame and the gas moving along the duct was found to be 9·1, 10·6 and 12·8 ft/s.

Most authorities agree that both the intensity of the turbulence and its scale are likely to influence the combustion rate in turbulent systems, but that the effect of these factors will depend on the circumstances of the combustion. For gases moving in an established flow along a duct, the intensity of the turbulence is related directly to the gas velocity, and the scale to the duct diameter. It is therefore to be expected that the combustion rate would depend on these two factors. In a previous paper[3] advantage was taken of the fairly steady conditions of flame speed and pressure which occurred as a flame was approaching the restricted end of a duct to calculate combustion rates at the flame front as a function of the gas movement which had become established ahead of the flame. In this case the rate of combustion was plotted against the Reynolds number of the moving unburnt gas; in the data used the components of Reynolds number $V\rho/\mu$ and D varied by factor of 20, 1·7 and 2·0 respectively. In Fig. 15 this information is reproduced, but in addition the initial burning rates obtained in the present experiments with gas velocities of 20, 30 and 40 ft/s are included. The rate of combustion is expressed as the ratio of S, the rate of combustion at the flame front to S_0, the plane laminar burning velocity, *i.e.* the rate of combustion for a plane laminar flame front stretched

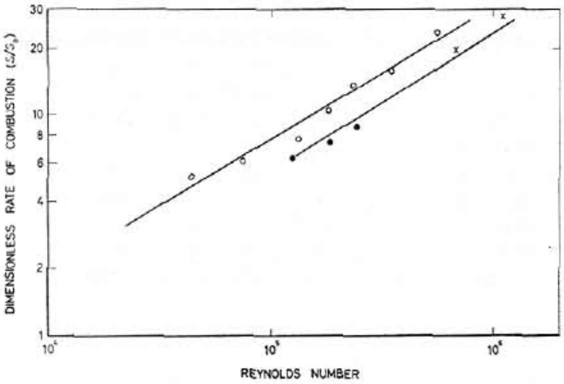


Fig. 15.—*Relation between rate of combustion at a flame front in a duct and Reynolds number of unburnt gas ahead of flame*

across the duct. Fig. 15 indicates that the use of Reynolds number alone does not cover the effect of the diameter (D) on the rate of combustion; in fact the latter is proportional to $(RD^{-0.7})^{0.6}$, or for a given kinematic viscosity to $(VD^{0.3})^{0.6}$ where V is the velocity of the gas. Fig. 16 shows S/S_0 as a function of $VD^{0.3}$ for air at atmospheric conditions; the horizontal line for $S/S_0 = 3{\cdot}5$ is the expected rate of combustion at a flame front moving along a duct under laminar conditions. Extrapolation of the line for turbulent combustion to this line indicates that there is a value of $VD^{0.3}$ below which the contribution due to turbulence is likely to be small.

Using the above information it is possible to compare the results of the present work with results obtained by other authors. Freestone, Roberts, and Thomas[4] report results for explosions in petroleum vapour-air mixtures circulating through a duct 18 in. diameter; ignition took place 3 ft downstream of a pipe 2 in. in diameter where the gas entered the main duct. The value of $VD^{0.3}$ is 66 for the 2 in. diameter inlet and 1·6 for the 18 in. diameter duct; Fig. 16 suggests combustion rates four times laminar, and the same as laminar respectively for these two conditions. Maximum pressures obtained by the above authors in the large duct were about twice as great as the pressures in the same apparatus when the gas was initially stationary. This may have been expected from the foregoing analysis, which also indicates that the turbulence causing the increased rate of

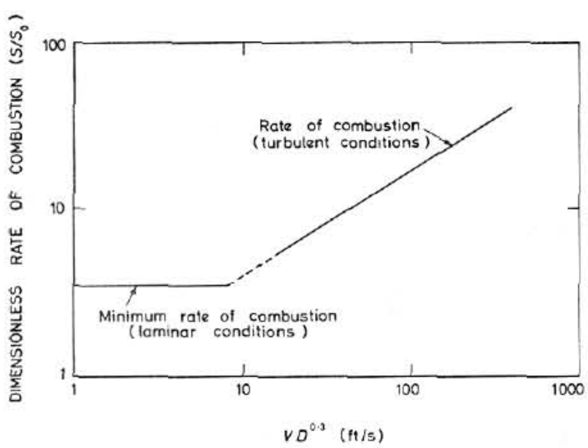


Fig. 16.—*Relation between rate of combustion at flame front and $VD^{0.3}$ ($\rho/\mu = 6100$ ft/s units; atmospheric conditions)*

combustion and pressure rise was almost certainly the injection of the gas at the inlet rather than the motion of the gas in the large diameter duct. Some unpublished results have also been obtained by Palmer at the Fire Research Station for a propane-air mixture flowing smoothly in a duct $2\frac{1}{2}$ in. diameter at a velocity of 20 ft/s. Under these conditions there was no significant increase in flame speed over that of a stationary gas mixture under similar conditions after the flame had travelled a long distance from the ignition source. For these conditions the value of $VD^{0.3}$ is equal to 12·5; Fig. 14 indicates that the combustion rate at the flame front would be about 1·3 times that for laminar conditions and this may not have been sufficient to show any significant effect, particularly in view of the extra turbulence that would be engendered in the gases ahead of the flame after the flame had travelled a long distance even when the gas is initially stationary.

Practical use of results

The results obtained in the experiments may be applied directly for ducts of 1 ft diameter or square section for gas velocities and weights of cover within the ranges tested. If it is desired to keep maximum pressures in an explosion down to about 1 lb/in^2 then vents should not be further than about 12 ft apart if they are equal to the cross-sectional area of the duct, or 6 ft apart, if they are half the cross-sectional area of the duct. Covers used as moving or swinging panels may weigh up to 5 lb/ft^2.

It is useful to extrapolate the results if possible to the much wider range of conditions that can occur in industrial practice, and in particular to extrapolate the following four factors in the ways indicated.

(1) The weight of the cover to larger weights of cover than those tested.

(2) The gas velocity to higher velocities.

(3) The nature of the combustible mixture to those with a greater value of S_0.

(4) The diameter or equivalent diameter of the duct to larger values.

To do this, it is necessary to have some insight into the mechanism by which the maximum pressure is developed. In these experiments the maximum pressure was due to the inertia of the moving gases and vent covers as a result of an acceleration of the flame. Therefore the relation connecting the relevant variables should be of the form:

$$\underset{(PAg)}{\text{Force}} = \underset{(a\rho LA + bM + cY)}{\text{Mass}} \times \underset{(df)}{\text{Acceleration}} \quad . \quad (1)^*$$

Equation (1) predicts that the maximum pressure should increase in direct proportion to the weight of the cover. This was generally observed throughout the tests, the only exception being in the tests with vents 18 ft apart when the maximum pressure was found to decrease as the weight of the cover increased. A reason for this was given above. There is therefore justification in extrapolating linear relationships obtained over a factor of about 2. If the cover is held by magnets, the results indicate that the magnetic forces do not play any part governing the inertia factor. The maximum pressure in these cases may be obtained from the sum of the absolute value of the magnetic force and the expected inertia force due to the mass of the cover.

The other three factors mentioned above will influence the maximum pressure mainly by their effect on the acceleration of the flame.

It may be postulated that this acceleration will depend on:

(1) The initial value of the combustion rate S for a flame front in the duct whether gas conditions are laminar or turbulent.

* *Symbols have the meanings given them on p. 28.*

(2) The rapidity with which the augmented motion of the unburnt gas ahead of the flame gives rise to further turbulence resulting in an increase in the initial combustion rate.

The dependence of the initial combustion rate S on the laminar burning velocity, the gas velocity, and the physical properties of the gas may be obtained directly from the relationship in Fig. 15 and from this the dependence of pressure and acceleration on this rate of combustion may be written as:

$$P_0 \propto f = F(S) = F\{S_0(V\rho/\mu\, D^{0\cdot3})^{0\cdot6}\} \quad . \quad (2)$$

In the present series of tests, taking the results as a whole for the vents at 6 and 12 ft centres, the maximum pressure was proportional to $V^{1\cdot2}$; also the mean acceleration over the first 2·5 ft of flame travel was proportional to $V^{1\cdot1}$. Therefore it is reasonable to state that when the acceleration governing the maximum pressure was controlled by the turbulence in the pipe duct itself this acceleration was proportional to $V^{1\cdot2}$. From this it follows from equation (2) that:

$$F(S) \equiv kS^2 \quad . \quad . \quad . \quad (3)$$

where k is a constant or:

$$P \propto f \propto S_0^{\,2}\, V^{1\cdot2}\, (\rho/\mu)^{1\cdot2}\, D^{0\cdot36} \quad . \quad . \quad (4)$$

Equation (4) provides a basis for extrapolating results to other combustible gases by insertion of the appropriate values of S_0 and ρ/μ and to other speeds by insertion of appropriate value of V. Thus if openings of 6 ft between the vents give a maximum pressure of 1 lb/in^2 at 40 ft/s then a maximum pressure of 2 lb/in^2 would be expected if the gas speed is increased to 70 ft/s. A few tests with an ethylene-air mixture have been carried out and the results support the prediction of equation (4) that the maximum pressure is proportional to the square of the laminar burning velocity; with this gas, as with the propane-air mixture variation of the value of ρ/μ from the value for atmospheric air may be neglected. It should be mentioned, however, that Cubbage and Simmonds[5] found for explosions in drying ovens that the maximum pressure was proportional to the first power of this velocity. It should also be added that if a change is made to a much lighter gas, particularly if it needs to be present at a high concentration to give the stoichiometric ratio, *e.g.* town gas then not only should the new values of both S_0 and ρ/μ be taken into account but also the effect of density on the mass of the gas as indicated by equation (1).

To extrapolate the results to different values of D it is necessary also to take into account the second of the two factors mentioned above, *i.e.* the development of more intense turbulence ahead of the flame. Since in normal pipe flow this turbulence is engendered at the wall the diameter of the duct would be the main factor controlling this phenomenon. Broadly one would expect that if a higher velocity is imposed on a gas column ahead of the flame then the fraction developed of the normal pipe turbulence appropriate to the new velocity will depend on the number of pipe diameters the gas column has travelled with this new velocity. Thus the turbulence encountered by the flame as it passes through this accelerated gas will depend on L/D, or for a given value of L, the maximum pressure or flame acceleration would be expected to be proportional to a function of $1/D$. This is reflected in experiments[3] with initially stationary gas, *i.e.* initial value of $S/S_0 = 3{\cdot}5$, for which maximum pressures were approximately proportional to L/D when inertia controlled the pressure rise, and for which the mean acceleration in the first 2 ft 6 in. of travel was inversely proportional to $(1/D)^{1\cdot3}$ within the range $D = 0{\cdot}25$ to 1 ft. By combining this effect with the dependence of the initial combustion rate on D implied in equation (4) one obtains the result that the maximum pressure should be inversely proportional to approximately the two-thirds power of D provided that the ratio of vent area to the duct cross-sectional area, and the linear distance between vents remain constant.

Extra turbulence may also be engendered at any particular disturbance ahead of the flame. In the present series of experiments the disturbance which could occur when the flame passed an open vent comes into this category. It is difficult to make predictions concerning the extrapolation of this phenomenon although there are good grounds for stating that the maximum pressure would be proportional to the unburnt gas velocity. However, because of the lack of information on this matter it would be unwise to extrapolate the results of the experiments described above by factors greater than about two for any parameter. Turbulence may also be engendered by obstacles in the gas stream; this phenomenon is undoubtedly responsible for the large peaks recorded in some of the pressure records in Fig. 6 as the flames passed over the tubes feeding propane into the air. This aspect is outside the scope of this paper and will be dealt with in greater detail elsewhere.

Symbols Used

A = area of cross-section of duct.
a, b, c, d, k = constants.
D = diameter or equivalent diameter of duct.
f = acceleration of flame.
g = acceleration of gravity.
L = half distance between explosion reliefs.
M = weight of vent cover.
P = maximum pressure.
S = burning rate of flame front moving along duct or relative speed of flame front to the unburnt gas.
S_0 = fundamental laminar burning velocity of the gas.
V = velocity of unburned flammable gas.
Y = a mass term for the air outside the duct and the flammable gas mixture inside the duct beyond the nearest explosion relief, set in motion during the explosion. Y would be a function of the ratio of the area of the vent to the cross-sectional area of the duct.
ρ = gas density.
μ = gas viscosity.

Except where otherwise stated, the above quantities may be expressed in any consistent units in which force and mass are not defined independently.

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