THEORY OF SUPPRESSION OF EXPLOSIONS BY NARROW GAPS

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SYNOPSIS

The safe gap between the flanges of a flameproof enclosure is shown to prevent the transmission of an explosion by the combined action of the cooling of gas passing through the flange gap, and cooling by the entrainment of cold gas when the hot explosion products emerge from the gap. This counteracts the heat release by burning of the entrained gas. Computer solutions of the equations for heat transfer, entrainment and heat release predict the change in jet temperature with time. The final temperature may be either the maximum flame temperature, denoting ignition, or ambient temperature, denoting a failure to ignite, depending on the initial conditions, one of which is the site of the flange gap. The results enable prediction of the effect on the safe gap of a change in fuel, flange breadth, vessel volume, ambient pressure, and internal ignition position. The same analysis is also applied to a flame trap mounted in the wall of a flameproof enclosure.

Introduction

Wolfhard and Bruszak[1] have described the ways in which an explosion might be transmitted through narrow channels. They demonstrated that two mechanisms were responsible; the flame itself could propagate through the channel, or, if the flame was quenched within the channel, it could be re-ignited by the hot gas emerging from the channel. The lower limit of channel size for active flame propagation is governed by the flame quenching mechanism and the lower size limit for re-ignition is the "safe gap". Since the safe gap is smaller than the quenching distance it is appropriate to study the safe gap when safety from explosion transmission is the main concern. The present paper therefore deals exclusively with the mechanism of the safe gap.

The concept of the safe gap has been in use for many years in ensuring the safety of electrical equipment which might be surrounded by a flammable atmosphere, and the British Standard, *B.S.*229/1957[2] describes the way in which a flameproof enclosure should be constructed. In the appendix to *B.S.*229 is listed the maximum experimental safe gap (MESG) for a representative range of fuels commonly found in the chemical industry. MESG is defined as "*the widest gap which has been found to prevent ignition of the most easily ignited external mixture when the most incendive mixture of the same combustible is exploded inside the test vessel*". The permitted gap is derived from this by the addition of a factor of safety and by classifying fuels into four convenient groups.

Previous researches on this subject have been concerned primarily with the determination of MESG and gave guidance for the formulation of codes of good practice and safety regulations culminating in Britain in *B.S.*229/1957 and its amendments. This work has provided an accumulation of experimental data but attempts to correlate all the data have met with little success. Although several qualitative theories have been advanced there was no means of predicting the combined effects of changes in both the fuel and the test enclosure.

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The effect of an increase in flange breadth could be explained qualitatively by an increase in heat loss from the gas to the flanges.[3] The effect of a change in fuel was calculated by Phillips,[4] other factors being equal, but here heat transfer was ignored. Neither theory could explain all the effects but it was clear that both contained the elements of a comprehensive explanation of the action of a safe gap based on the combined action of heat losses to the flanges, and cooling by entrainment of unburned gas into the jet of hot gas ejected through the gap, which counteracts the heat release by burning of the entrained gas.

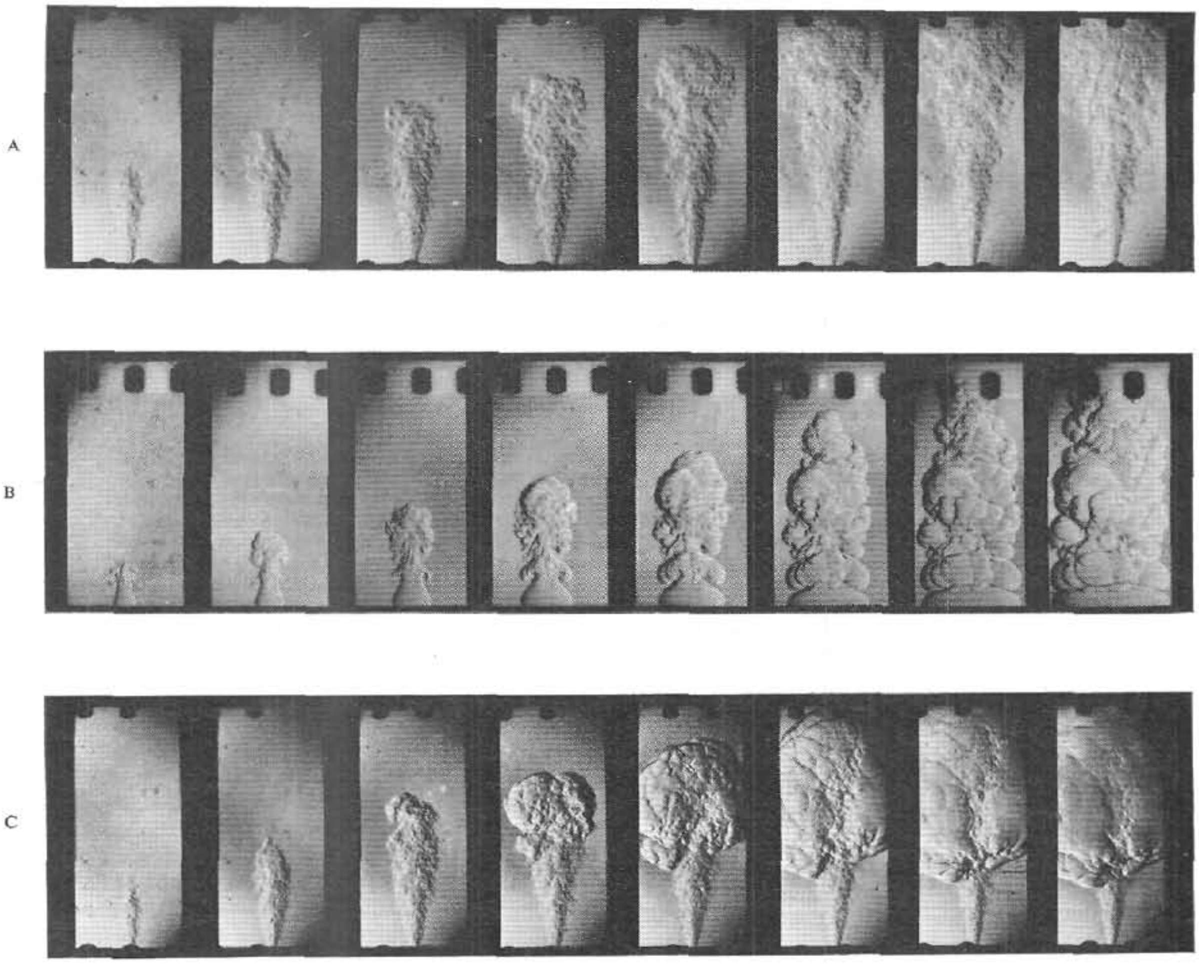
The comprehensive explanation enables predictions to be made concerning the effects both of a change of fuel and a change in the size and shape of the test enclosure.

Overall Concept

Wolfhard and Bruszak[1] showed that ignition could be transmitted through gaps which were too small to permit the propagation of flame. For example, they ignited a mixture of methane and air from an internal explosion of a mixture of nitric oxide and hydrogen through an orifice of 0·8 mm diam although the quenching diameter, which is the minimum size of hole through which flame can propagate, is 15 mm for that mixture. Grove[5] showed that generally for mixtures of common hydrocarbon and air the quenching distance between parallel plates is about twice the safe gap.

Schlieren photographs taken at SMRE have indicated the way in which the external mixture is ignited. It was more convenient to photograph ignitions outside a circular orifice than a long slot; accordingly ignitions were transmitted through a hole 3 mm in diameter at the top of a 250 ml cylindrical explosion vessel. The mixture both inside and outside the vessel was of methane, air and oxygen. The ability to ignite the external mixture was controlled by changing the concentration of oxygen while maintaining stoichiometry.

Figure 1A shows the mixing processes when there is no external ignition. Figure 1B is an ignition. Flame fronts are seen as sharply-defined, rounded surfaces in contrast with the fine structure of turbulent mixing. When the experiment



TOP: No ignition, external mixture air

CENTRE: An ignition, external mixture methane—air

BOTTOM: An ignition, external mixture methane—air adjusted to give 50% ignition probability

Fig. 1.—*Schlieren photographs of a pulsed jet of hot gas (1000/s)*

of Fig. 1B was repeated the external ignition was ignited each time. When the oxygen concentration was adjusted to its critical value, giving only a 50% probability of external ignition, Fig. 1C was the result. Ignition was seen to develop as a ball of fire at the head of the advancing jet of hot gas ejected from the orifice. A flame front first appeared about 50 mm from the orifice. The mathematical analysis of the ignition process must reproduce these general characteristics. The analysis which follows will be described in greater detail by Phillips.[6] A diagrammatic representation of the flange gap and jet together with some of the symbols to be used appears in Fig. 2.

As outlined in an earlier paper[4] ignition can be considered to be the result of mixing and combustion within the hot jet. An energy balance gives:†

$$\frac{\mathrm{d}}{\mathrm{d}t}[m(T-T_u)] = -m\left(1+\frac{a}{f}\right)(T_f-T_u)\frac{RT}{PW}\dot{m}_f''' \quad (1)$$

Inserting:

$$\eta = \frac{T-T_u}{T_f-T_u} \quad . \quad . \quad . \quad (2)$$

and:

$$\psi = -\left(1+\frac{a}{f}\right)\frac{RT}{PW}\dot{m}_f''' \quad . \quad . \quad (3)$$

equation (1) becomes:

$$\frac{1}{\eta}\cdot\frac{\mathrm{d}\eta}{\mathrm{d}t}+\frac{1}{m}\cdot\frac{\mathrm{d}m}{\mathrm{d}t} = \psi \quad . \quad . \quad (4)$$

η is a measure of the temperature of the jet, $(1/m)(\mathrm{d}m/\mathrm{d}t)$ is a measure of the rate of mixing into the jet and ψ is a measure of the rate of burning.

Rate of Combustion

The rate of combustion of fuel, $-\dot{m}_f'''$, is contained in equation (4). The conversion of chemical energy into heat is a result of many reactions involving active species and intermediate products within the flame front but for most applications it is adequate to assume a single step bimolecular reaction between fuel and air, for which Arrhenius gave the rate of reaction;

$$-\dot{m}_f''' = -B\left(\frac{a}{f}\right)C_f^2\exp(-E/RT) \quad . \quad (5)$$

The concentration of fuel, C_f, is related to the proportion of the original fuel already consumed, η_1, by:

$$C_f = \frac{1}{1+(a/f)}\cdot\frac{PW}{RT}\cdot(1-\eta_1) \quad . \quad . \quad (6)$$

† *Symbols have the meaning given them on p. 22*

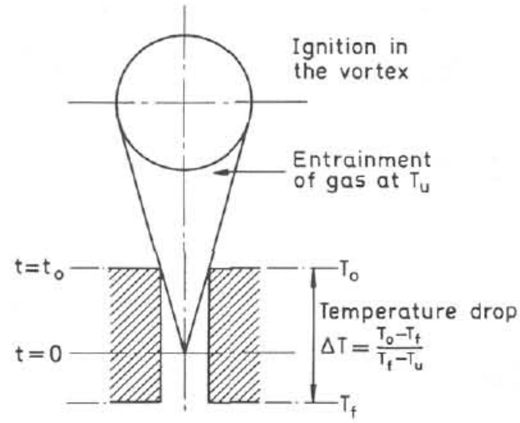


Fig. 2.—*Model of the hot jet*

The jet temperature is derived partly from the jet emerging from the gap, at temperature T_0, and partly by combustion of entrained gas. As heat is lost to the flanges as hot gas passes through the gap, T_0 is less than the maximum flame temperature for the internal explosion. Where $\dot{m}_0$ is the mass of hot gas ejected through the flange gap, and $\dot{m}$ is the total mass, including the entrained mixture, then:

$$\eta_1 = \eta - \frac{\dot{m}_0}{\dot{m}} \Delta T \quad . \quad . \quad (7)$$

where:

$$\Delta T = \frac{T_0 - T_f}{T_f - T_u} \quad . \quad . \quad . \quad (8)$$

Inserting equations (5), (6), (7), and (8) into equation (3):

$$\psi = \frac{BPW}{RT\eta} \frac{a}{f} \frac{1}{1+(a/f)} \times \left(1 - \eta + \frac{\dot{m}_0}{\dot{m}} \Delta T\right)^2 \exp(-E/RT) \quad (9)$$

As the jet emerges from the orifice:

$$\left(1 - \eta + \frac{\dot{m}_0}{\dot{m}} \Delta T\right) = 0 \quad . \quad . \quad . \quad (10)$$

and ψ is zero. At room temperature T, T_u the value of ψ again approaches zero. The maximum of ψ occurs at η having a value of approximately 0·6 although the exact value depends on the fuel and on the initial conditions.

Mixing

Mixing into the jet emerging from a slot is assumed to be governed by the equations of Ricou and Spalding,[7] who examined the entrainment into a circular jet:

$$\dot{m} = K(xM\rho)^{\frac{1}{2}} \quad (11)$$

From this it can be shown[6] that at the head of the advancing jet:

$$\frac{1}{\dot{m}} \frac{d\dot{m}}{dt} = \frac{z}{t} \quad . \quad . \quad (12)$$

and:

$$\frac{\dot{m}_0}{\dot{m}} = \left(\frac{t_0}{t}\right)^z \quad . \quad . \quad . \quad (13)$$

where z is a constant with the approximate value of one.

If the jet is considered to start at a virtual point source within the gap, it takes time t_0 before the jet just fills the gap and starts to emerge. This is the starting time, and the gap size, δ, is related to t_0 by:

$$\delta = \beta v t_0 \quad . \quad . \quad . \quad . \quad (14)$$

when z was given the value one the corresponding empirical value of β was found to be 0·1 by comparing calculation with data on MESG. Trials with a range of values of z confirmed that a change in z can be compensated by a corresponding change in β.

Heat Transfer in the Gap

The Graetz number (the ratio between the thermal capacity of the gas and the convective heat transfer) within the gap is generally low and in this regime the Nusselt number, defining the rate of heat transfer, is constant, independent of the Reynolds number or the Prandtl number. Therefore:

$$\frac{\Delta T}{T'} = \frac{7{\cdot}5\lambda l}{\rho C_p v \delta^2} \quad . \quad . \quad . \quad (15)$$

Both the velocity, v, and the density, ρ, are denoted at the flange exit in conformity with v in equation (14).

The value of the velocity, v, must be determined by dimensional analysis and by comparison with experimental results. The velocity was assumed to depend on the vessel volume, V, the open area of the flange gap, A, the burning velocity of the fuel–air mixture, S_u, and the acceleration due to gravity, g, so that velocity, expressed non-dimensionally as a Mach number, depends on:

$$M = f\left(\frac{S_u^2 V}{gA^2}\right) \quad . \quad . \quad . \quad (16)$$

For very reactive fuels, such as hydrogen, and for all fuels when ignition is at the centre of the test vessel, v was found to be sonic. With central ignition a high explosion pressure is generated before hot gas can be expelled from the gap. With side ignition, and with less reactive fuels, v was considerably less, about 20 m/s for methane in an eight-litre spherical vessel. The form of equation (16) is shown in Fig. 3. Quite large errors, up to plus or minus 50% in the estimation of velocity used in equations (14) and (15) had only a small effect on the calculated value of gap, δ. For methane the difference in velocity between side and central ignition was very much greater than this.

The low velocity of ejection of hot gas for a methane—air explosion with ignition close to the orifice was confirmed by experiment. At the moment of ignition of the external mixture, the internal explosion pressure was less than 0·1 atmospheres. The changes in velocity explain the large difference in safe gap between side and central ignition for methane, whereas for hydrogen there is no difference. As the ratio of open area to volume increases, as it does when the size of a test sphere is reduced, it becomes no longer possible to achieve sonic flow in the gap and the difference between side and central ignition is reduced. This is confirmed by results from the small 20 ml German test vessel.[8]

Solution of the Equations

Equation (4), with the appropriate expressions for the rate of mixing [equations (12) and (13)], the rate of reaction [equation (9)], and with specified initial values of t_0 and T_0 can be solved by computer. Several trials enable a critical value of t_0 to be found which separates ignitions from non-ignitions. A typical plot of the change of temperature with

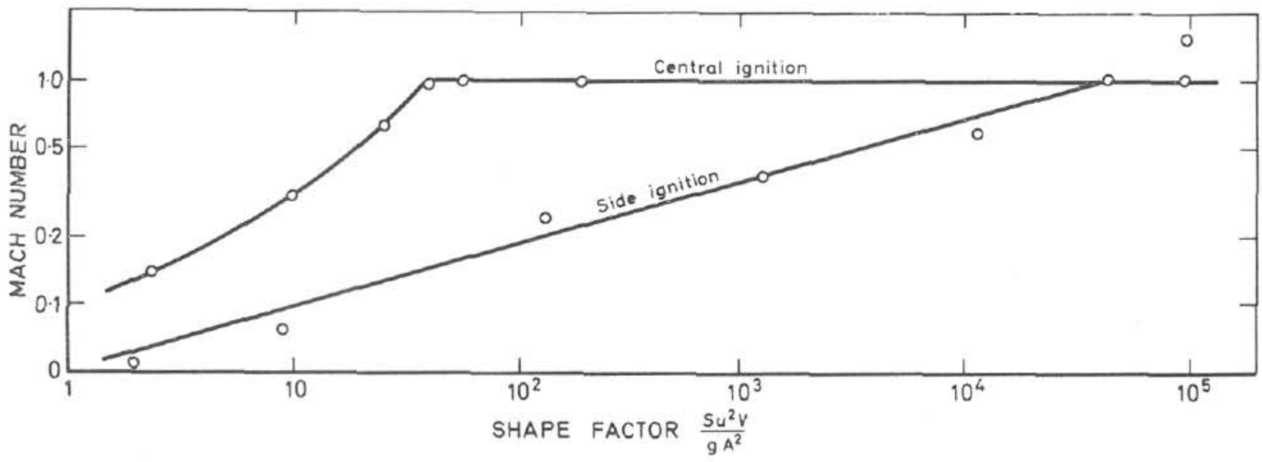
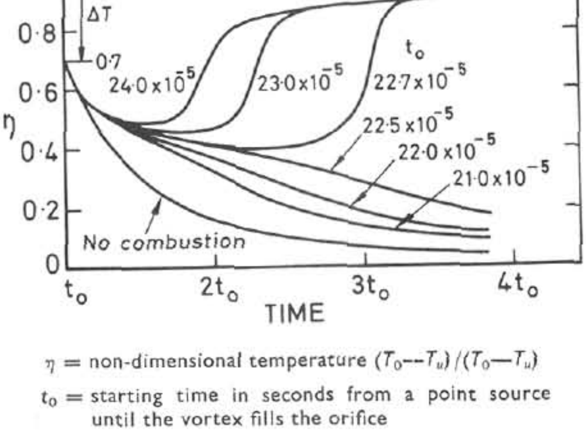


Fig. 3.—*Mach number of the jet at instant of external ignition*

time is shown in Fig. 4. The lowermost line represents a pure mixing process without combustion. The uppermost three lines represent ignitions; the final temperature is asymptotic to the maximum flame temperature. The three lines representing failure to ignite do not follow the pure mixing line but have a higher temperature. The difference represents a zone of burning close to the gap while the jet is still hot. Later, further mixing reduces the temperature sufficiently to quench the flame. This explains the flash of flame that has been observed outside an enclosure even when there is no general external ignition.

Numerous solutions have been found by computer and for a constant ΔT there is a simple relationship between the starting time t_0 and the maximum value of ψ [equation (9)] for $\Delta T = 0$ [equation (15)]. Figure 5 shows a typical family of curves for a range of values of ΔT. For equal velocities and equal ΔT this leads by equation (14), to a simple correlation between MESG and the maximum value of $\psi_{(\Delta T=0)}$. This is the relationship obtained by Phillips[4] using a more direct but less rigorous method. The correlation suggests that for a standard apparatus, other factors being equal there is a direct relationship between MESG and $\psi_{\max\,(\Delta T=0)}$ and this can be used for the estimation of the MESG for a fuel in that particular apparatus (Fig. 6).



η = non-dimensional temperature $(T_0 - T_u)/(T_0 - T_u)$

t_0 = starting time in seconds from a point source until the vortex fills the orifice

$T_f = 2300$ K $\quad z = 2$

$\Delta T = -0{\cdot}3$ $\quad E = 25\,000$ kcal/g mol

Fig. 4.—*Computer curves of jet temperature*

In the earlier paper[4] no reference was made to the effect of breadth of flange or volume of vessel. These can now be introduced by way of their effect on heat transfer from the gas and their effect on the efflux velocity of the hot gas. An increase in flange breadth increases the heat loss ΔT and increases t_0. A reduction in vessel volume increases the ratio of gap area to vessel volume which reduces v but increases ΔT_0. The net result on MESG for vessels in the range 20 ml

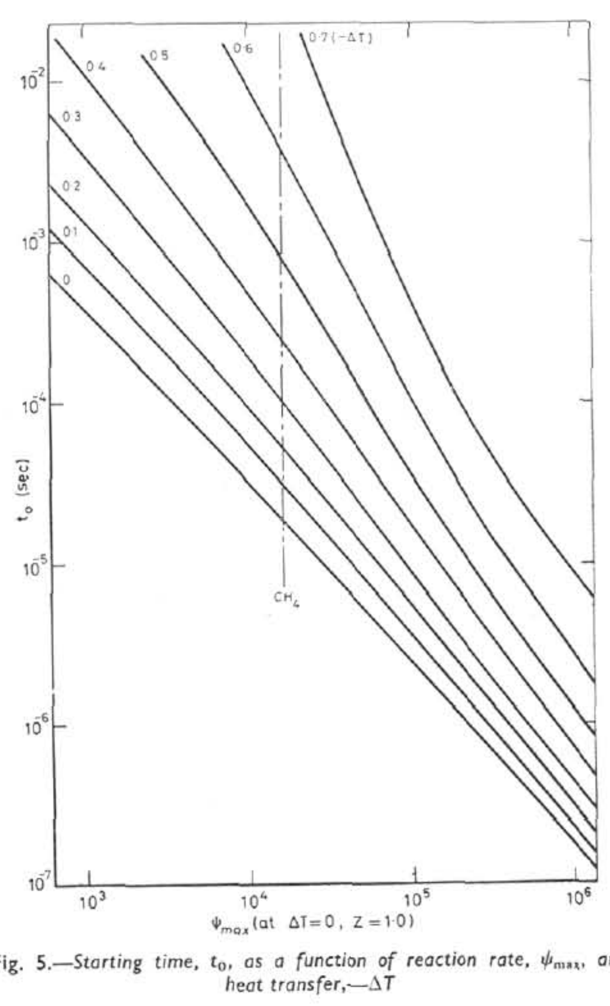


Fig. 5.—*Starting time,* t_0, *as a function of reaction rate,* ψ_{max}, *and heat transfer,*—ΔT

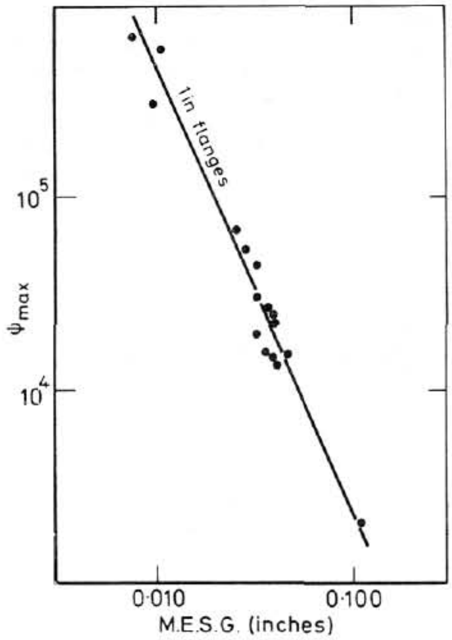
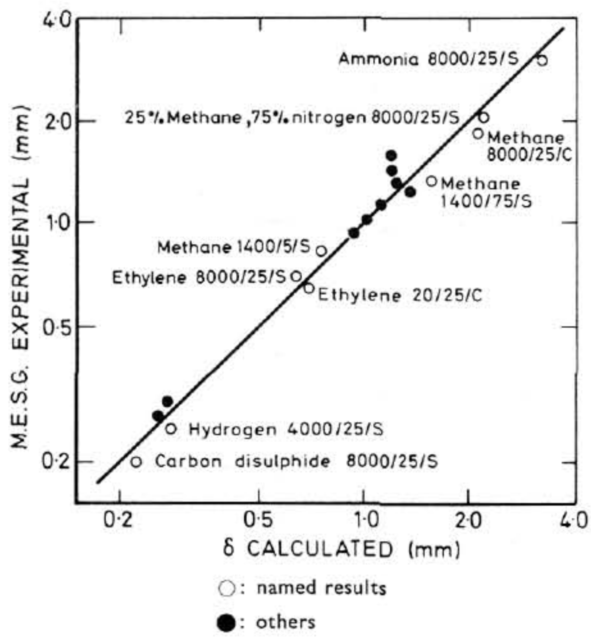


Fig. 6.—*Correlation of MESG (Phillips[19])*

to 8 litres is small for most fuels but for carbon disulphide there is an increase in MESG.

By seeking simultaneous solution to equations (4), (8), (9), (12), (13), 14), and (15) and estimating v from the empirical data of Fig. 3, the MESG for a wide range of variables have been calculated and compared with experiment. Data of experimental determinations came from a wide range of sources; *B.S.*229/1957, *SMRE Annual Reports* for 1965 and 1966, and the work of Nabert,[9] Grobleben,[10] Kotlyarskii,[11] Statham and Wheeler,[12] Jones and Heathcote,[13, 14] Smith and Blackwell,[15] and Smith.[16] The experiments covered fuels ranging from reactive ones such as hydrogen to slowly burning fuels like ammonia. Vessel volumes ranged from 0·02 litres to 8 litres, flange breadths from 3 to 75 mm and both side and central ignition were represented. Some of the results, illustrating the extremes of the range, appear in Fig. 7, from which it is seen that the calculated values are in good agreement with experiment.



The symbol after each gas describes the vessel: 8000/25/C reads "volume 8000 cm^3 sphere, flange breadth 25 mm, central ignition" and 250/12·5/S reads "volume 250 cm^3 sphere, flange breadth 12·5 mm, side ignition".

Fig. 7.—*Calculation of safe gaps taking into account heat transfer and shape factor*

Activation Energy

In applying the calculations the effect of the fuel is felt mainly through its activation energy. The reaction between fuel and air is not simple and involves very many intermediate reactions, each with its own rate and activation energy. However, it has been found convenient in studies of flame propagation and stability to employ a "global" activation energy for an imagined single-step reaction between fuel and air leading directly to the final combustion products. The value of the global activation energy appears to depend partly on the experimental conditions for its determination. In selecting values to use in the calculation of safe gap it is important to find a method of determination at a temperature close to that in the hot jet of products which can just initiate an explosion.

The determinations of Fenn and Calcote[17] are appropriate. They used a method based on Semenov's equation for burning velocity and found that for a wide range of fuels activation energy (cal/g mol) was equal to 16 times the flame temperature (K) at the lower limit of downwards flame propagation. This is a convenient way of estimating activation energy as the flammability range of a fuel is one of the properties usually available in the literature. Another advantage is that from Le Chatelier's rule[18] the flammability of fuel mixtures can be estimated, and hence the global activation energy of the mixture and its safe gap. Using this procedure safe gaps for mixtures of hydrogen, carbon monoxide, methane and nitrogen have been calculated and they are in close agreement with experiment.

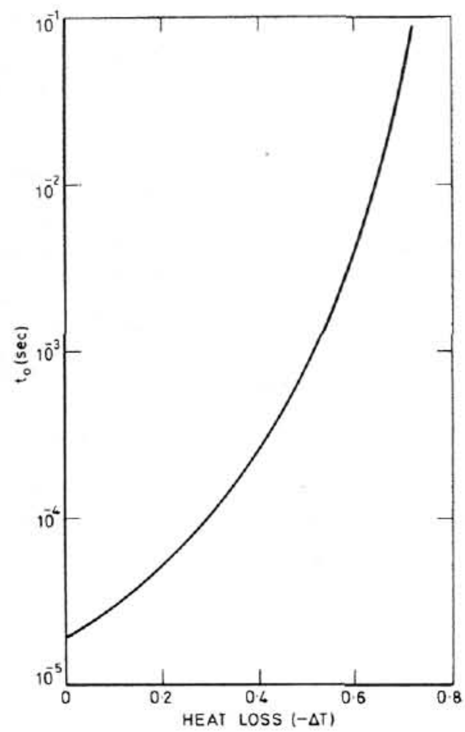


Fig. 8.—*The effect of heat loss, —ΔT, on t_0*

A list of safe gaps based on the more simple relationship between MESG in a standard vessel and the properties of the fuel[4] has been reported by me elsewhere[19] and I used the activation energies of Fenn and Calcote.[17] The list includes 35 fuels, including mixtures, where there is a comparison between calculation and experiment.

Effect of Variables

The effect of barometric pressure is noted in equation (9) but is also present in equation (15) through its effect on density. The analysis correctly predicts the results of Grobleben's experiments[10] with methane, towns gas, and hydrogen, over a pressure range of 0·5 to 3 atmospheres.

Humidity has the effect of reducing the maximum flame temperature so that the rate of combustion is reduced and the safe gap is increased slightly.

A change in vessel size influences the velocity at which gas is expelled from the gap. The variation in gap size for most fuels is small unless the size of the vessel is less than about 20 ml. However, for carbon disulphide the flame speed is low and so, of all the fuels examined with a small vessel, the value of $S_u^2 V/gA^2$ is the least and therefore the effect of a reduction in size is the most for this fuel. Experiment confirms that for most fuels the MESG determined in the 20 ml German test vessel is the same as in an 8 litre sphere (*B.S.*229/1957) but for carbon disulphide the reduction in vessel size results in an increase in safe gap from 0·20 to 0·34 mm.

Flange breadth exerts its influence mainly through equation (15); an increase in breadth of flange results in an increased heat loss to the flanges, and a cooler jet. The exit velocity is also reduced. The safe gap is correctly predicted for a range of gap breadths 3 to 75 mm.

Flame Traps

The same set of equations also explains the behaviour of a flame trap set in the case of a flameproof enclosure. The trap used in experiments was made of crimped metal ribbon and was 12·5 mm in diameter. It was seen to be equally effective in preventing explosion transmission as a single 1·25 mm diameter hole of the same length. Solution of equation (4) revealed that a reduction in the jet temperature function $(T_f - T_0)/(T_f - T_u)$ from 0·79 to 0·55 was sufficient to increase the critical diameter by a factor of 10. If it is assumed that heat transfer is governed by a constant Nusselt number this drop in temperature can be achieved by a 40% reduction in the diameter of the channel. Each channel through the flame trap was in fact roughly equivalent to a 0·75 mm diameter hole, which is about 40% less than the single hole diameter of 1·25 mm. Thus with the safe gap transmission of an explosion is prevented by the combined action of heat losses to the flanges and rapid mixing of the combustion outside the gap and for the flame trap more importance is attached to heat transfer. As the jet temperature is reduced from the maximum flame temperature the critical starting time, t_0, falls, slowly at first but as the temperature is further removed from the maximum, the effect of a further small temperature change on t_0 is greatly increased. (Fig. 8).

Conclusions

The concept of prevention of explosion transmission by the combined action of heat losses to the flanges and rapid cooling by entrainment of gases emerging from the flange gap has enabled almost all of the experimental data accumulated since research on safe gaps was first reported by Beyling[20] to be connected by a single set of equations. This enables predictions and extrapolation of data to be made with confidence. In particular the approach outlined in this paper has permitted critical assessment of proposed apparatus for the experimental determination of safe gaps and classification of fuels. From the simple correlation[4] the safe gaps have been estimated by calculation for a wide range of fuels commonly found in industry.[21] The same approach has explained the behaviour of a flame trap which prevents transmission of an explosion mainly by extracting heat from the hot gases passing through.

Symbols Used

A = area of flange opening.
B = reaction rate constant.
C_f = concentration of fuel (mass per unit volume).
C_p = specific heat at constant pressure.
E = activation energy.
g = acceleration due to gravity.
K = a constant.
l = length (flange breadth).
M = momentum.
m = mass.
$\dot{m}$ = mass flow.
$\dot{m}_f'''$ = rate of consumption of fuel (negative sign denotes that fuel is being used) (mass/unit volume and time).
$\dot{m}_0$ = initial mass flow of the jet (at t_0).
P = pressure.
R = gas constant.
S_u = burning velocity.
T = temperature.
T_f = maximum flame temperature.
T_0 = initial temperature (at flange exit).
T_u = ambient temperature.
T' = log mean temperature.
t = time.
t_0 = starting time.
ΔT = see equation (8).
V = volume.
v = velocity.
W = molecular weight.
z = a constant [equation (12)].
a/f = air/fuel ratio (by weight).
β = a constant [equation (14)].
δ = flange gap.
η = temperature ratio [equation (2)].
η_1 = proportion of fuel consumed.
λ = thermal conductivity.
ψ = reaction rate function [equation (3)].

The above quantities may be expressed in any set of consistent units, in which force and mass are not defined independently.

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The manuscript of this paper was received on 20 *November*, 1970.