Vented Gas Explosion in Small Vessels of L/D of 2.4

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Introduction

Most current vented explosion data in relatively large explosion vessels cannot be predicted using laminar flame propagation models, without including an empirical turbulence factor to make theory and experiments match. However, part of the flame acceleration may be the self acceleration of laminar flames over the large distances involved in large explosion vessels. The generation of flame acceleration due to turbulence created in the venting process should not change significantly with vessel size. The present work uses a small 9L explosion vessel with an L/D of 2.8 with small flame propagation distance to the vent so that self acceleration of the flame should be small [1]. Comparison with laminar flame theory of venting is made to show that turbulence factors are not necessary, as the measured results for open vent explosions are less than those predicted by laminar flame theory. The laminar flame theory assumes a worst case flame area equal to the vessel wall area. US design standards for gas venting are based on compact vessel venting where L/D<2 and in EU standards it is L/D<3 and the present L/D is between these values. The majority of experimental data on venting has either a sphere or a cube with an L/D of 1 and has central spark ignition. Central ignition does not give the worst case overpressure for an L/D of 2 and this is given by ignition on the end wall opposite the vent [2].

Experimental Methods

A small cylindrical vessel of 9 litres volume (0.00948m^3, L=0.460m, D=0.162m and L/D 2.8) was used for vented gas explosion with free venting. Different vent areas were used giving a range of K_v from 2.4-19.3. The L/D of this vessel is close to the L/D of compact vessel as recommended by Bartknecht [3]. The vessel was designed with an L/D of 2, but when the gate valve was added which enabled the mixtures to be made using partial pressures, and then a removable vent orifice support added the length to the orifice face increased the effective L/D to 2.8. This is within the European venting standards definition of a compact vessel (L/D<3). The ignition position was on the centreline of the end wall opposite the vent as this has the worst case overpressure [2, 4] as shown in Fig. 1. Most of the experimental explosion venting data is for central ignition as recommended by Bartknecht [3] but the ATEX Directive in Europe requires the worst case to be considered [5].

The much higher overpressure using end ignition compared with central ignition is shown for a K_v of 9.7 in Fig. 1. This was also found over a range of K_v and for different reactivity mixtures. The reason for the higher overpressures with end ignition is that the distance from the spark to the vent is higher.

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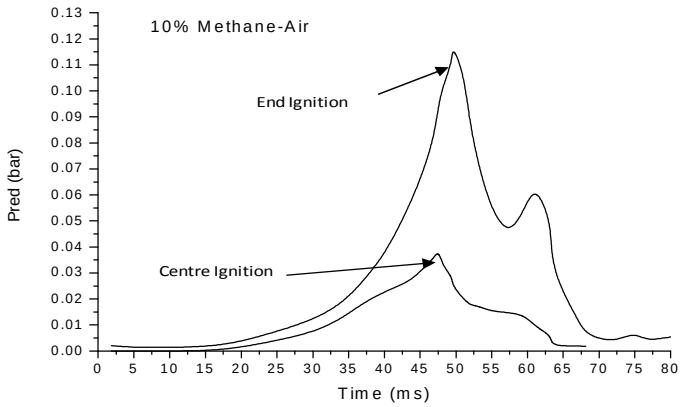

Fig .1 Comparison of end and centre ignition for small vent area, L/D=2.8 and V = 8 litres for a K_v of 9.7.

The vent outflow acts to move the flame in the direction of the vent faster than it moves sidewards. This results in a greater flame area increase with respect to time compared with central ignition, this then gives a higher unburned gas flow through the vent and a faster movement of the flame towards the vent.

Different gas-air mixtures were used for this experimental work including methane-air, propane-air and ethylene-air at the most reactive mixture at Ø=1.05, which is the worst case where the maximum flame temperature occurs. This was done to investigate the reactivity term in the laminar flame venting theory. The flame speed upstream of the vent was measured using the time of arrival of the flame at two thermocouples on the centreline, one close to the spark and one close to the vent. There was also a thermocouple close to the wall on the centreline to record the time the flame arrived at the wall. Piezo resistive pressure transducers were mounted in the end flange on which the spark plug was mounted and a second pressure transducer was mounted on the centreline of the vessel cylindrical wall. A 32 channel 100kHz per channel data logging system was used to record the data.

Free Venting Theory

There are two different approaches to explosion vent modelling suggested in the literature [1]. In both cases the maximum flame area A_f is required to be known at the point of the maximum overpressure. Runes [7] introduced the assumption that the maximum possible flame area is the surface area of the vessel, A_s. However, this should give an over prediction of the mass of unburned gas flow rate, as the flame area is almost never equal to the surface area of the vessel at the point of maximum pressure. In the present work the term $\Delta_{\mathbf{a}}$ has been introduced, which is the flame area as a the fraction of the surface area of the vessel that gives agreement between theory and measurement, with no other turbulence or self acceleration factors.

The first approach to the prediction of the unburned gas mass flow rate assumes that the maximum vent overpressures occurs when the consumption of unburned gas is at its maximum and this is equal to the mass burnt rate at the flame front [8].

Vent maximum unburned gas mass flow rate, $m_b = U_L \Delta_{\mathbf{a}} A_s \rho_u$ (1)

The second approach [7, 9] assumes that the maximum vent overpressure occurs when the vent unburnt gas flow rate through the vent is at a maximum and that this is equal to the maximum unburnt gas displaced flow by the flame front [8].This is given by:

Vent maximum unburnt gas mass flow rate, $m_b = S_g \Delta_{\mathbf{a}} A_s \rho_u = U_L (E\text{-}1) \Delta_{\mathbf{a}} A_s \rho_u$ (2)

where U_L = laminar burning velocity

Δ_a = actual laminar flame area at the maximum overpressure / A_s

A_s = surface area of the vessel,

Sg=velocity of the unburnt gas ahead of the flame

ρ_u= unburnt gas density (1.2 kg/m^3),

E_P= the constant pressure expansion coefficient, where the Stoichiometric value of E_P is 7.5 for methane, 8.1 for propane and 7.9 for hydrogen.

This second assumption assumes that the flame propagates as a sphere in a spherical vessel and all the unburned gas is expelled before the flame exits the vent. The first assumption essentially assumes that there is no flame expansion driving the unburned gas forward, this occurs once the flame is outside the vent and all the expansion is outside and the laminar flame propagates into unburned mixture inside the vessel with continuous expansion of unburned gas outside the vent.. Reality is somewhere between these two extremes and in the present work the second mass flow is used with the flame area correction term Δ_a, to give agreement between the predicted and measured overpressures and is the flame surface area at the maximum overpressure as a fraction of the vessel surface area. This second approach gives a higher predicted unburned gas mass flow rate through the vent and a higher overpressure is predicted, which is in closer agreement with experimental measurements than the predictions using the first method [1].

The overpressure due to the maximum flow rate of unburnt gas through the vent, assuming free venting, can be obtained from the orifice plate flow equation for the vent [1].

$$m_{bmax} = A_{f\ max}\ U_L\ \rho_u = \Delta_a\ A_s\ \beta U_L(E\text{-}1)\ \rho_u = C_d\ \varepsilon\beta A_v(2\ \rho_u P_{red})^{0.5} \qquad (3)$$

where ε = expansibility factor, which is the deviation of compressible flow from incompressible flow for an orifice plate, which is about 0.8 for near sonic flow and 1 for incompressible flow. This factor cannot be predicted and has been experimentally measured for orifice plate flow metering, which will apply here. The vent flow cannot be treated as a nozzle as has been done in most work on venting.

C_d = the orifice plate discharge coefficient, which is 0.61 for large K_v or small vents and about 0.75 for small K_v or large vent areas.

A_v = vent area, m^2

P_{red} = reduced pressure or overpressure in Pa (N/m^2)

β = Turbulence enhancement factor such that the turbulent burning velocity $U_T = \beta U_L$

This now gives:

$$A_v/A_s = \Delta_a\ \rho_u^{0.5}\ \beta U_L(E\text{-}1)\ /\ (C_d\ \varepsilon 2^{0.5}\ P_{red}^{0.5}) \qquad (4)$$

Taking the vent gas compressibility factor ε=1, C_d=0.61 and ρ_u = 1.2 kg/m^3 for the incompressible flow, then Eq. 4 becomes $A_v/A_s = 1.27\ \Delta_a\ U_L\ (E\text{-}1)\ P_{red}^{-0.5}$. Furthermore, considering the vessel volume V in relation to the suface area A_s given as $A_s = C_2 V^{2/3}$, this gives:

$$A_v/V^{2/3} = \Delta_a\ C_2\ C_1\ P_{red}^{-0.5} = 1/K_v \qquad (5)$$

Where $1/K_v = A_v/V^{2/3}$ and the K_v is the vent coefficient of the vessel based on the vent area.

$C_1 = 1.27\beta U_L\ (E\text{-}1)$

C_2 is a constant that is $A_s/V^{2/3}$ and is 4.84 for sphere, 6 for a cube and 5.54 for a cylinder with an L/D of 1, 5.81 for an L/D of 2 and 6.21 for an L/D of 3.

Eq. 4 can be shown to be the similar to that used by Bradley and Mitchenson [10] and the constant is the same if a β of 4.2 is used (1). Eq. 4 is also similar to that used by Swift [11] with all the constants combined into a single constant C. It can be shown that Swift's constants are the same as those predicted by Eq. 4 with a β of 3.6 [1]. The Swift approach has been adopted in NFPA 68 (12) for the vent design for weak vessels with P_{red}<0.1 bar. However, there is no such limitation on the applicability of Eq. 5 as the ε term takes into account compressible flow through the vent. Eq. 5 is also similar to the Bartknecht [3] vent design equation based on vented explosions in a 10 m^3 vessel. For a P_{stat} of 100mb the design equation for the vent coefficient is given in Eq. 6.

$$1/K_v = (.1265 \log K_G - 0.0567)\, P_{red}^{-0.5817} \quad (6)$$

$$1/K_v = a\, P^{-n} \quad (7)$$

However, the data for each gas was correlated by Eq. 7 and the P_{red} exponent was not influenced by the mixture reactivity and the average value was 0.5817. The value of the constant a was 0.167 for methane, 0.200 for propane and 0.290 for hydrogen. These constants are the same as those predicted by Eq. 5 when converted to the same units, but a turbulence factor of 3.3 [1] is required to get agreement in the values of the combined constants in Eq. 8 with the above Bartknecht values [1].

Experimental Results Compared With Laminar Flame Venting Theory

The experimental vented overpressure results are shown as a function of K_v in Fig. 2. The data is compared with the predictions of Eq. 5 with β=1 and Δ_a = 1. The results are less than those predicted by Eq. 5 for laminar flames. Also the experimental results are below the predictions of Swift and Bartknecht There was good agreement with Bradley and Mitcheson predictions with a β=1 and the present prediction, but both were above the experimental results. This was not the conclusion found when Eq. 5 is compared with other vented experimental results for large volume vessels and a β of between 3 and 5 is normally required to get agreement [6, 9 11]

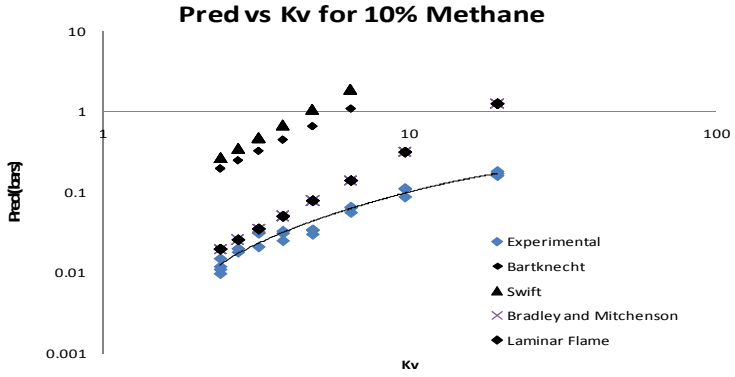

Fig .2 Dependence of Pred on Kv for the small vessel compared with previous correlations.

The difference in the experimental results in Fig. 2 with the laminar flame predictions from Eq. 5 can be used to compute a value for the flame area factor Δ_a. This is shown in Fig. 3 as a function of K_v for methane-air explosions and in Fig. 4 for propane-air explosions. This shows that at low K_v the maximum flame area is closer to the surface area of the vessel at the peak overpressure, but at higher K_v the flame area is a smaller fraction of A_s. This indicates that at small K_v with high vent velocities the flame is accelerated towards the vent and does not propagate to the vessel wall at the same rate it propagates towards the vent.

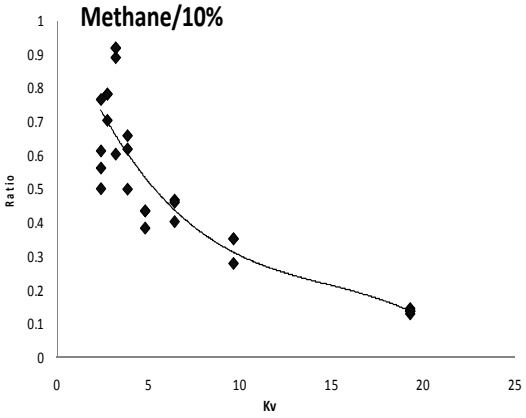

Fig 3. Level of agreement of the Laminar theory with 10% Methane

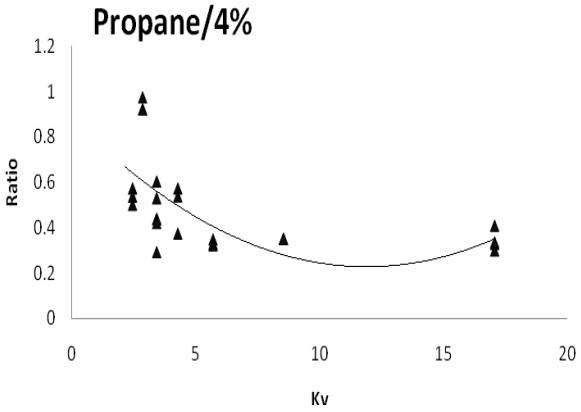

Fig 4. Level of agreement of the laminar theory with 4% Propane

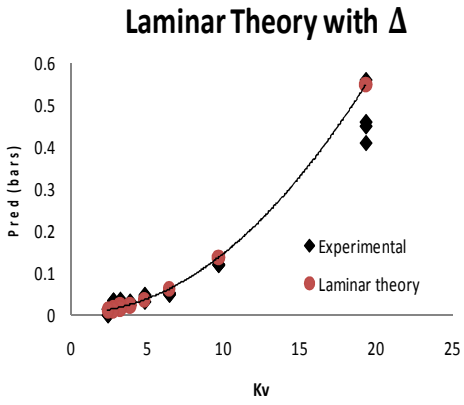

Fig 5. Laminar theory flame with Δ_a for 4% Propane

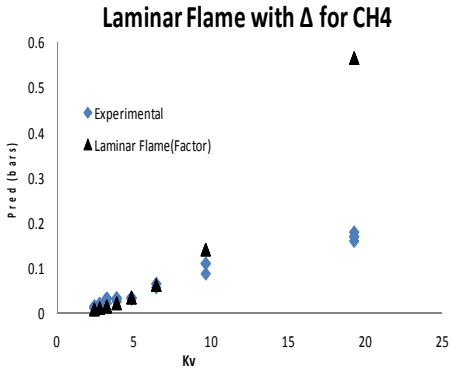

Fig 6. Laminar theory flame with Δ_a for 10% Methane

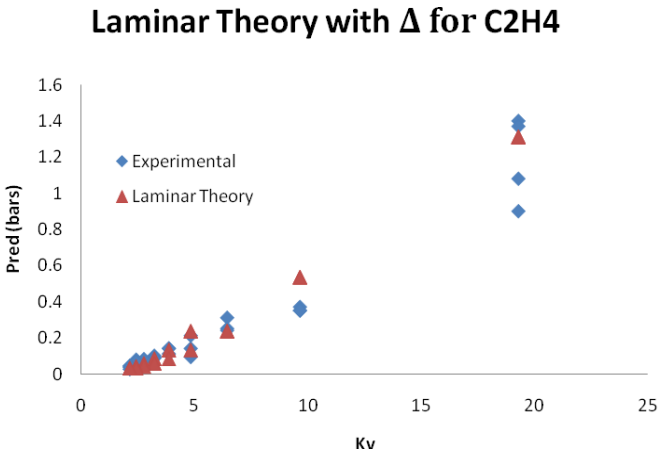

Fig 7. Laminar theory flame with Δ_a for 6.5% Ethylene

The values of Δ_a in Figs 3. and 4 together with equivalent values for ethylene can now be used in Eq. 5 and new predictions made. The agreement of the theory in Eq. 5 with the experimental data from the

present 9 litre vented vessel explosions is shown in Figs. 5-7 for methane, propane and ethylene. These results show that when the vessel is small enough for laminar flame to exist throughout the vented explosions then the laminar flame area is less than A_s but the predictions of laminar flame venting are well supported. It is clear that the higher overpressures recorded in larger vented explosions is due to an increase in the flame reactivity, most likely due to self acceleration rather than turbulence. In future work self acceleration experimental and theoretical data will be examined as a means of enabling the β factor in Eq. 5 to be interpreted as a self acceleration factor. The role of turbulence induced upstream of the vent by the action of the vent flow is likely to be low.

Conclusions

The conventional laminar flame venting theory has been extended to include the flame area as a proportion of the vessel surface area, Δ_a. End ignition was shown to be the worst case compared with central ignition. The use of a small 9 litre vented explosion vessel with an L/D of 2.8 was shown to enable laminar flame venting to be achieved so that β=1. Δ_a was determined for methane, propane and ethylene at their maximum reactivity. This is the first time that a turbulence factor β was not required to give agreement between experimental data and laminar flame venting theory. The results show that the flame is accelerated towards the vent from the spark and only part of the mixture has been burned inside the vessel when the flame emerges from the vent and this decreases as K_v increases. Peak overpressure occurs when the trapped unburned gases in the vented vessel burn after the flame has left the vent. This is not taken into account in the laminar flame model, which assumes that all the unburned gas is expelled through the vent before the flame exits the vent. It would therefore be more correct to take Δ_a as a corrected for deviations of the all the assumptions in the theory from reality.

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