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Experimental Investigation of Vessel Volume and Equivalence Ratio in Vented Gas

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***Abstract*—**An experiment of vented gas explosions involving two different cylinder vessel volumes (0.2 and 0.0065 m^3) was reported, with equivalence ratio (Φ) ranged from 0.3 to 1.6. Both vessels were closed at the rear end and fitted at the other side with a circular orifice plate that gives a constant vent coefficient ($K = A_v/V^{2/3}$) of 16.4. It was shown that end ignition gives higher overpressures than central ignition, even though most of the published work on venting uses central ignition. For propane and ethylene, it is found that rich mixtures gave the highest overpressures and these mixtures are not considered in current vent design guidance; which the guideline is based on mixtures giving the maximum flame temperature. A strong influence of the vessel volume at constant K was found for methane, propane, ethylene and hydrogen-air explosions. It can be concluded that self- acceleration of the flame, which is dependent on the distance of a flame from the ignition and the 'suction' at the vent opening are significant factors affecting the vent flow during explosion development in vented gas explosion. This additional volume influence on vented explosions is not taken into account in the current vent design guidance.

***Keywords*—**Equivalence ratio, ignition position, self-acceleration flame, vented gas explosion.

I. Introduction

EXPLOSION venting is widely accepted as the effective protection measures against gas and dust explosions. Even though experimental and modeling work in this area has been extensively investigated and many correlations associated with the venting design were developed [1]- [9], the impact on venting at different vessel volume is not recognized in the current guideline offered by NFPA 68 [6] and European Standard [1]. Both guidelines rely on the vent correlation first published by Bartknecht [10] which indicated that the same vent area is required irrespective of the vessel volume. The $V^{2/3}$ dependence of overpressure in Bartknecht's equation on the vessel volume is a characteristic of spherical or compact vessel explosions, where the flame remains spherical during most of the flame propagation period during the venting process. If the spherical flame propagates at a constant rate, irrespective of the vessel volume, then there should be no other dependence of P_{red} on volume, other than K. For methane and propane, these were undertaken in a cubic vessel of 10 m^3 and the results for hydrogen were obtained in a 1m^3 spherical vessel [10]. For methane and propane the vented explosion overpressures were lower at any other volumes less than 10 m^3 and greater (60 m^3), as previously discussed by Kasmani et al. [11]. The design equations in the European Standards [1] are Bartknecht's equations for the above vessel sizes. These design equations grossly over predict the overpressures for explosion venting in vessels smaller than 10m^3, as shown in Bartknecht's results [10] and further illustrated in the present work. The ATEX Directive [12] applies to all vessels that have an explosive atmosphere, irrespective of its volume. The present work presents new data on vented explosion in vessels of small volume as well as demonstrating the failure of the Bartknecht Equation to predict this data. Analysis of the flame position data is used to suggest that the additional volume effect is related to the vent 'suction' effect and associated flow turbulence.

However, Kasmani et al [11] demonstrated that there is a volume effect in K that is not included in the Bartknecht's equation and is likely associated with flame self-acceleration due to the development of cellular flame for subsonic venting at K<~5. The net effect is an increase in burning velocity, S_u and mixture reactivity, K_G, which has not been accounted for in venting design guidelines. In principle, the effect is similar to that of vent induced turbulence and the turbulent enhancement factor, β term in the burning velocity equation should be accounted in this manner. The present work presents new data on vented explosion in vessels of small volume as well as demonstrating the failure of the Bartknecht's correlation [6] to predict this data. Analysis of the flame position data is used to suggest that the additional volume effect is related to the vent 'suction' effect and associated flow turbulence.

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II. Materials and Method

In this study, two different cylindrical vessel volumes were used; 0.2 and 0.0065 m^3 (refer to Fig. 1). Both vessels have a length to diameter ratio (L/D) of 2, complying the compact vessel as described in NFPA 68 and European Standard guideline. Both vessels were closed at the rear end and fitted at the other side with a circular orifice plate given a constant vent coefficient, K (= $A_v/V^{2/3}$) of 16.4, simulating as a vent before connecting to dump vessel. The gate valve was closed when the mixture were mixed homogeneously before opening

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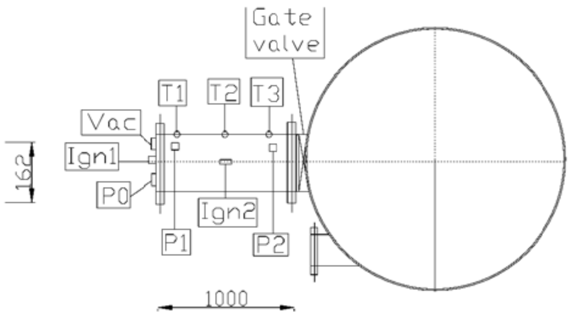
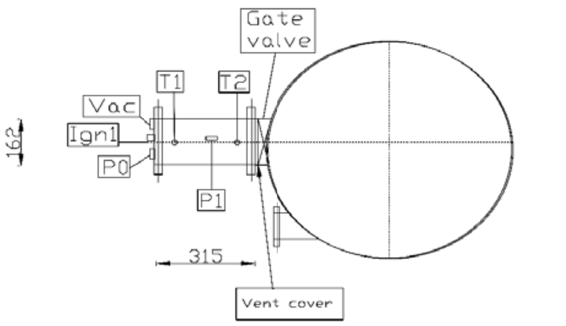
prior to ignition. For maximum reduced pressure, P_{max}, this was taken from P_1 pressure transducer as it located at the centre of the vessel for both test vessels. Flame speeds in the primary vessel were calculated from the time of flame arrival at an array of thermocouples on the vessel centerline (symbols as T_1-T_3 in Fig.1). The ignitor was a 16 J spark. Lean and rich mixtures of methane-, propane-, ethylene- and hydrogen-air were investigated with equivalence ratios of Φ = 0.3 to 1.3. Fuel-air mixtures were prepared using the partial pressure method, to an accuracy of 0.1 mbar (0.01% of composition). All the data was recorded on a 32 channel 100kHz per channel data acquisition system. As part of the experimental programme, three repeat tests were performed at each condition and these demonstrated good consistency and reproducibility, with peak pressures varying by less than ± 5 % in magnitude.



Test vessel 1: V = 0.2 m^3



Test vessel 2: V = 0.0065 m^3

Fig. 1 Rig configuration for vented gas explosion

III. Results and Discussions

A. Effect of the Ignition Position

A comparison of the pressure-time records for methane and propane air explosions in Test vessel 1 was made for central and end ignition. The result shown in Fig.2 is for the pressure-time profile at Φ =1.06. Fig.3 shows the maximum overpressure v. Φ for methane/air. Both figures show that end ignition results in a higher overpressure than the central ignition by about 60%. This was found for all the tests that will be discussed later, apart from for rich mixtures where central ignition resulted in higher overpressures. The reason for the higher overpressures with end ignition was considered to be the higher 'suction' flame velocities induced by the vent, which are discussed below.

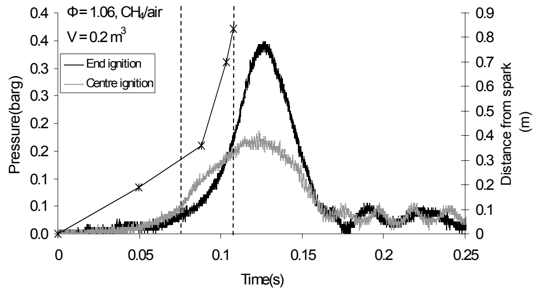


Fig. 2 Pressure time profile for methane/air mixtures at Φ = 1.06. Test vessel 1

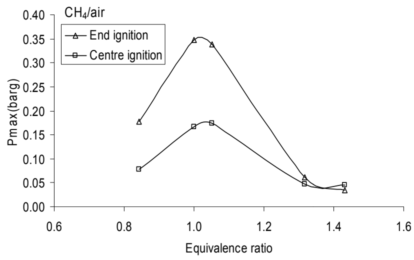


Fig. 3 Maximum overpressure, P_{max} v. equivalence ratio, Φ for central and end ignition for methane/air mixtures. Test vessel 1

A feature of the results in Fig. 2 showed that the peak overpressure occurs well after the flame has left the vent for both central and end ignition. The vertical lines in Fig. 2 are the flame arrival times just upstream of the vent. Similar results were also found in Test vessel 2 for methane/air mixtures with end ignition as shown in Fig. 4 and for propane, ethylene and hydrogen as shown in Fig. 5. This indicates that the external explosion has a significant contribution on triggering the peak overpressure yet; this was not the case as there was no external pressure rise. Test Vessel 1 had a thermocouple mounted close to the wall on the centre line and showed that the peak overpressure was associated with the internal flame reaching the wall (showed by the time of flame arrival on thermocouples). The venting physics can be explained by the flame accelerating towards the vent, pulled there by the 'suction' effect of the vent outflow.

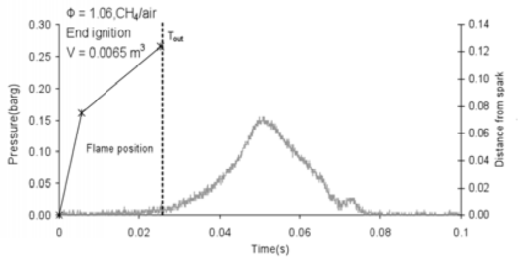


Fig. 4 Methane/air Φ=1.06 at Test vessel 2 with end ignition. * the time of flame arrival as a function of distance from the spark

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This left most of the unburned mixture trapped in the outer part of the vessel. Peak overpressure occurred when this trapped mixture burnt rapidly, forcing high velocity gases out of the vent.

The substantial proportions of the original flammable mixture in the test vessel after the flame has exited the vessel and trapped at the corner region inside the vessel would be larger for central ignition than for end ignition as it takes longer time for the combustion to take place before reaching the maximum pressure as suggested from Fig. 4. The direction of unburned gas flow, due to gas expansion behind the flame front, was preferentially in the axial direction towards the vent, where the unburned gases are displaced. The induced flow through the vent, ahead of the flame leads to a significant increase in flame speeds and expansion ratio of the main vessel. If the ignition is initiated at the end wall of the vessel, it resulted in an elongation of the flame shape with a corresponding increase of its flame area and thus, increasing the burning rate and flame speed eventually. In the case of centrally ignited, the flame will be in spherical vessel initially before progressively being stretched on one side towards the vent and thus, reducing the flame area as postulated by Ferrara et al [13] and Kasmani et al [14]. In case of central ignition, there is an indication of higher quantity of residual unburned mixture in the vessel whereas almost complete combustion occurred at end ignition that eventually leads to higher peak pressure.

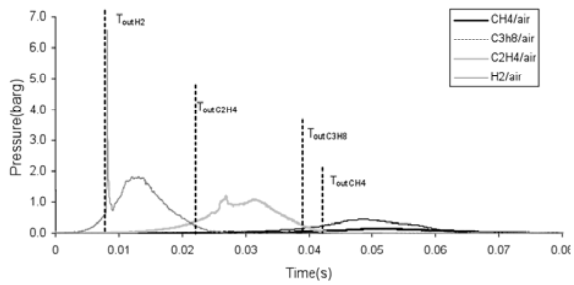

Fig. 5 Pressure-time history for different fuel/air mixtures at Φ = 1.0 at end ignition. Test vessel 2.

B. Flame Speed Upstream of the Vent

The flame speeds upstream of the vent for methane/air explosions are shown in Fig. 6 for central and end ignition. These show higher flame speeds for end ignition and the peak flame speed for Φ =1.06 was 23 m/s, about 9 times of 2.6 m/s flame speed for a spherical methane/air laminar explosion [15]. The flame speeds are plotted as a function of distance from the spark for Φ =1.06 in Fig. 7. Fig. 7 is also shown the expected influence of flame self-acceleration due to the development of cellular flames. This is based on the results in NFPA 68 [6] for K_G as a function of vessel volume, translated into normalized K_G with the value for 5 litre vessel and plotted against the vessel radius. These normalized results were then multiplied by the 2.6 m/s value of the spherical flame speed for small diameter flames. The results illustrated in Fig. 7 show that the initial flame acceleration in the vented explosions did follow the self-acceleration trend. However, sudden flame acceleration was spotted when the flame was 0.3m from the vent for central ignition and 0.6m from the vent with end ignition. It is considered that this is due to the action of flow 'suction' from the vent flow. For centrally ignited explosion, there is no vent flow until significant mass has been burnt and this requires the spherical flame to be larger. For end ignition, there is more time for the flame to develop before it is influenced by the vent flow. A flame speed of 23 m/s will have an unburned gas flow of 87 % of the flame speed if the process was adiabatic and this would give a jet velocity towards the vent of about 20 m/s. This jet velocity, of roughly the diameter of the vent, creates a shear region with the surrounding stationary mixture and this generates turbulence, which further accelerates the flame. It is due to the turbulence that results in the fast combustion of the trapped mixture in the outer part of the vessel.

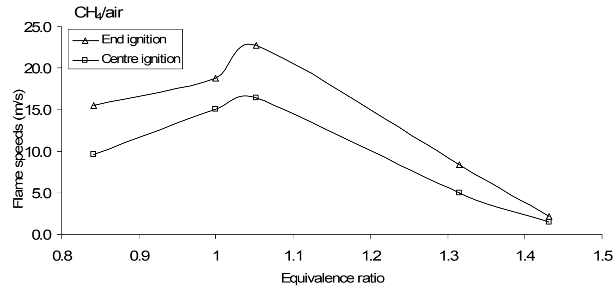

Fig. 6 Methane/air peak flame speeds upstream of the vent as a function of Φ for Test Vessel 1.

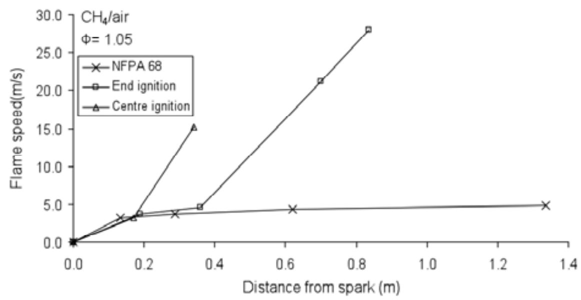

Fig. 7 Methane/air peak flame speeds for Φ=1.06 plotted as a function of distance from the spark for end and central ignition for Test Vessel 1.

C. Propane, Ethylene and Hydrogen Results

The equivalent results to those for methane were obtained for propane, ethylene and hydrogen and are shown in Fig. 8-10 for Test Vessel 1. These results show that for mixtures up to Φ = 1.06 at end ignition gives the highest overpressure. Fig. 11 shows high vent 'suction' flame speeds, with 30 m/s for propane. For mixtures richer than Φ =1.2, central ignition becomes the worst case for overpressure and flame speed upstream of the vent. Hydrogen mixtures richer than Φ = 0.6

were not investigated as the overpressure was already very high. It is clear that K = 16.4 is too large for a value of K in order to be suitable for hydrogen explosion risks. This observation implies that venting is effective at lower H_2 concentration ($\Phi < 0.41$) but not in higher concentration in the case of smaller vent area i.e. high K. The reason for the high overpressures and flame speeds for rich mixtures have to be related to Lewis numbers influences, which are highest for rich propane air mixtures and rich ethylene air mixtures. However, it is difficult to know why the same acceleration does not occur with end ignition position.

The most important feature of these results is that for propane and ethylene, the worst-case vented explosion is at Φ =1.3 and not at Φ = 1.06, where all the current venting explosion data has been determined. This indicates that the current design procedures for venting may not include the worst case for propane and ethylene.

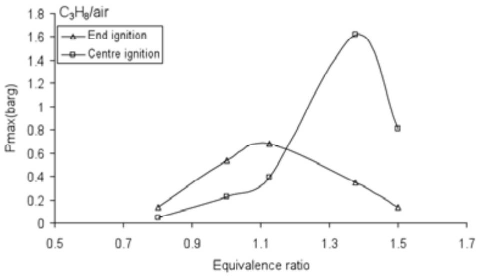

Fig. 8 P_{max} v. equivalence ratio, Φ for propane/air mixtures

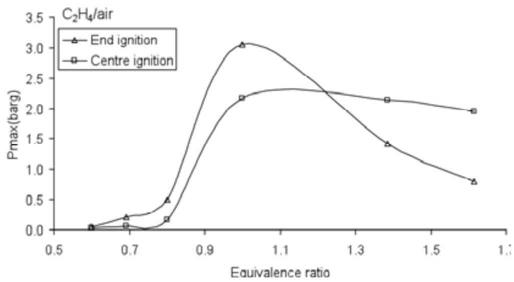

Fig. 9 P_{max} v equivalence ratio, Φ for ethylene/air mixtures

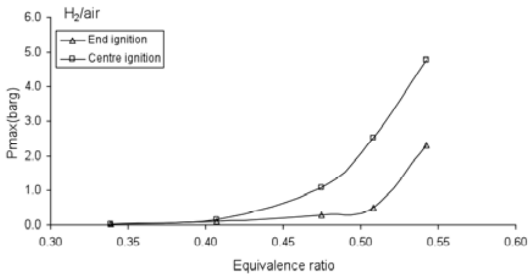

Fig. 10 P_{max} v. equivalence ratio, Φ for hydrogen-air

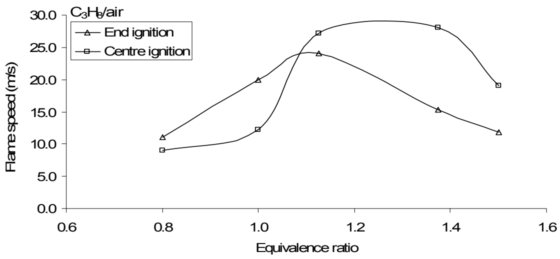

Fig. 11 Flame speeds for propane/air mixtures

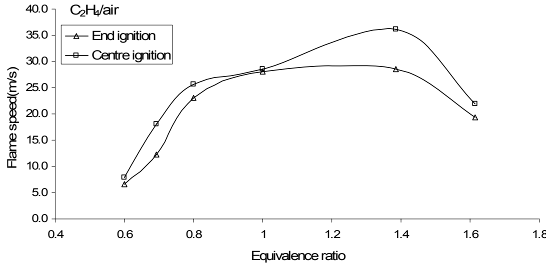

Fig. 12 Flame speeds prior to the vent for ethylene/air mixtures

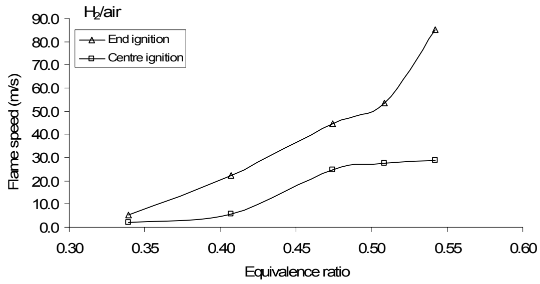

Fig. 13 Flame speeds prior to the vent for hydrogen/air mixtures

D. Explosion in Test Vessel 2

The overpressures and flames speeds in the smaller vessel for the same K_v of 16.4 are shown in Fig. 14 and 15 for all four gases. The peak overpressures are compared with Test Vessel 1 and also to those correlations from NFPA [6], Bradley and Mitcheson [2] and Molkov[5] as listed in Table 1. Test Vessel 1 has much higher overpressures and flame speeds (2-3 times) than Test Vessel 2, by a factor of 1.8 for methane and 2.4 for ethylene.

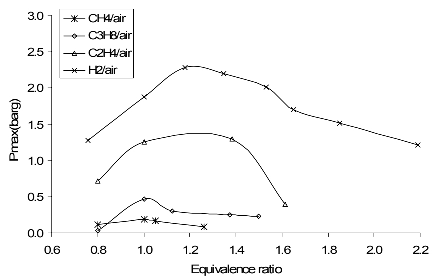

Fig. 14 Maximum pressure P_{max} for different fuel/air mixtures as a function of equivalence ratio.

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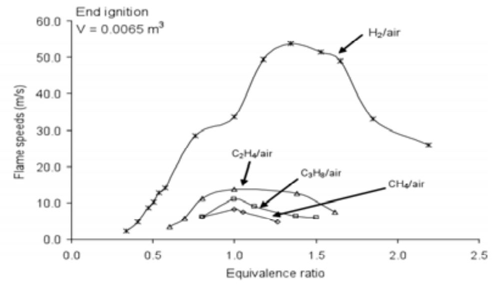

Fig. 15 Flame speeds for the four gas/air as a function of equivalence ratio.

Propane peak overpressure at $\Phi = 1.13$ is 0.68 bar in the larger vessel and 0.3 bar in the smaller; the peak pressure ratio is then 2.27. However, only the predictions of Molkov [5] include an influence of vessel volume at constant K, but these predictions are much too high for P_{red}. All the predictions have a major over prediction of the present results, as they are calibrated against explosions in larger volumes. Only Bradley and Mitcheson [2] and Molkov [5] are closest to the present measured results in Test Vessel 1.

TABLE I
EXPERIMENTAL DATA AND CALCULATED EQUATIONS FOR TEST VESSELS AT $\Phi = 1.0$

Gas/air	Experimental data (bar)	Bartknecht Eq (bar)	Swift Eq (bar)	Bradley and Mitcheson Eq (bar)	Molkov Eq (bar)
Test Vessel 1					
CH_4/ air	0.35	5.44	12.43	1.163	2.09
C_3H_8/ air	0.53	7.45	20.92	1.46	2.26
C_2H_4/ air	3.06	10.92	20.92	3.35	3.07
H_2/ air	-	14.57	-	42.72	4.16
Test Vessel 2					
CH_4/ air	0.19	5.44	12.43	1.163	1.15
C_3H_8/ air	0.47	7.45	20.92	1.46	1.36
C_2H_4/ air	1.25	10.92	20.92	3.35	2.32
H_2 /air	2.28	14.57	-	42.72	4.44

IV. Conclusion

The volume of a vented explosion has a very significant influence on the overpressure for a constant K. This is not included in vent design guidance and leads to gross over prediction of the required vent area for small volumes. The peak overpressure occurs after the flame has left the vent and is caused the 'suction' jet of the vent that creates a rapid turbulent explosion of the unburned mixture trapped in the vessel after the centerline jet flame has been vented.

Acknowledgment

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