The Influence Of Vessel Volume And Equivalence Ratio In Vented Gas Explosions

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Experiments of vented gas explosions involving two different cylinder vessel volumes (0.2 and 0.0065 m^3) were reported. It was found that self-acceleration and larger bulk flame trapped inside the vessel are the main factor enhancing the overpressure attained in 0.2 m^3 vessel. There was about 2 to 7 times increase in ratio of pressure and flame speeds on both vessels at the same equivalence ratio and K which can be considered as turbulent enhancement factor, β. Hot spot or auto ignition is responsible to the deflagration to detonation.

Keywords: vented gas explosion, self acceleration, turbulent enhancement factor, hot spot

1. 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 (Bradley and Mitcheson, 1978b, Chippett, 1984, Molkov, 1995, Runes, 1972), the impact on venting at different vessel volume is not recognized in the current guideline offered by NFPA 68 (NFPA68, 2007) and European Standard (2007). Both guidelines rely on the vent correlation first published by Bartknecht (Bartknecht, 1993) 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. However, Kasmani et al (2006) 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 $K<\sim5$. 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 could be accounted for by the turbulent enhancement factor, β term in the burning velocity equation. The present work aims to provide further understanding in this unclear area of gas vented explosion.

2. Experimental Equipment

In this study, two different cylindrical vessel volumes were used (Figure 1): 0.2 and 0.0065 m^3. 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.

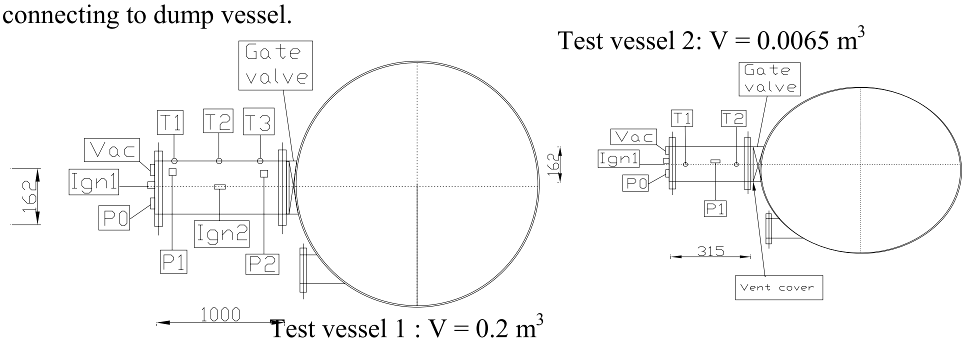

Figure 1 Rig configuration for vented gas explosion

The gate valve was closed when the mixture were mixed homogeneously and then opened just 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 arrival of the flame 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 and only end ignition was considered in this experiment. 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). 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.

3. Results and discussion

3.1 Impact of the overpressure on vessel's volume

Kasmani et al (2006) showed that at high K with sonic venting (P_{max} > 900 mbar), the self acceleration is likely to have already occurred at the smaller volume. The findings were confirmed in this work as illustrated in Table 1. From the table, it can be said that in vessel volume of 0.2 m^3, it is obvious that self-acceleration is the important feature in increasing the P_{max}. It can be postulated that the ratio of P_{max1}/P_{max2} indicates on how fast the flame accelerates inside bigger vessel. To further justify whether self-acceleration plays important factor in determining the final P_{max}, ratio of average flame speed, S_{favg} of Test vessel 1 and Test vessel 2 was calculated (Table 1). The flame speed at which the flame front propagates through gas/air mixtures during an explosion determines the rate at which burnt gases are generated (Harris, 1983). The ratio of P_{max} and flame speeds on both vessels also shows that there was about 2 to 7 times increase in both parameters in larger vessel at the same equivalence ratio and K and this constant value can be considered as β. These β values were agreed reasonably with previous investigators (Bradley and Mitcheson, 1978b, Chippett, 1984, Pasman et al., 1974, Swift, 1984) on determining the turbulent factor in venting explosion.

Table 1 Summary of experimental P_{max} and average flame speed, S_{favg} for Test vessel 1 and 2 for K = 16.4. The ignition position was end ignition.

Gas/air	**Φ**	**Test vessel 1 P_{max1} (barg)**	**Test vessel 2 P_{max2} (barg)**	**Ratio = P_{max1}/P_{max2}**	**Test vessel 1 S_{favg} (m/s)**	**Test vessel 2 S_{favg} (m/s)**	**Ratio = S_{favg1}/A_{favg2}**
CH_4/air	0.80	0.18	0.12	1.50	15.51	6.15	2.5
	1.00	0.35	0.19	1.84	18.83	8.21	2.3
	1.05	0.34	0.17	2.00	22.78	7.51	3.0
	1.26	0.06	0.08	0.75	8.35	4.60	1.8
C_3H_8/air	0.8	0.14	0.03	4.67	11.04	6.15	1.8
	1.0	0.54	0.47	1.15	20.01	10.91	1.8
	1.13	0.68	0.30	2.27	24.05	8.90	2.7
	1.38	0.35	0.25	1.40	15.37	6.32	2.4
	1.5	0.14	0.23	0.61	11.89	5.90	2.0
C_2H_4/air	0.6	0.04	0.078	0.51	6.57	3.41	1.9
	0.7	0.21	0.23	0.91	12.25	5.70	2.1
	0.8	0.50	0.72	0.69	23.06	11.23	2.1
	1.0	3.06	1.25	2.45	28.11	13.61	2.1
	1.4	1.42	1.30	1.09	28.61	12.49	2.3
	1.6	0.79	0.40	1.98	19.31	7.40	2.6
H_2/air	0.34	0.015	0.027	0.56	5.31	2.11	2.5
	0.41	0.11	0.057	1.93	22.47	4.78	4.7
	0.48	0.28	0.17	1.65	44.69	8.66	5.2
	0.51	0.52	0.25	2.08	53.62	10.11	5.3
	0.54	2.3	0.37	6.21	85.10	12.68	6.7

This work supported the observation reported by McCann et al (1985) that flame cellularity is appeared in the early stage of the explosion in larger volume compared to the smaller volume and hence, influence the mass burning rate and P_{max} inside the vessel. It is known that rich mixtures are known to be more susceptible to develop surface instabilities (flame cellularity) which would lead to higher burning rates and hence higher flame speeds and this is supported with the flame speeds recorded by the fuel rich mixtures compared to those at near stoichiometric in methane, propane and ethylene-air mixtures. However, hydrogen-air mixtures were not supported the argument made. This observation implies that venting is effective at lower H_2 concentration (Φ < 0.41) but not in higher concentration in the case of smaller vent area i.e. high K. It shown the high ratio of S_{favg1}/ S_{favg2} in which can be explained with the mass burning rate of the flame to increase due to faster flames, rather than due to the larger flame area and also due to the larger bulk flame left trapped inside the vessel that triggering subsequent combustion inside the vessel and hence, increase the overpressure attained.

3.2 Deflagration to detonation in test vessel

The deflagration to detonation situation was only observed for hydrogen/air mixture in Test vessel 2 as clearly illustrated in Fig. 2 and for hydrogen/air ($\Phi > 0.51$) and ethylene/air at $\Phi = 1.0$ (Fig. 4) in Test vessel 1. The significant 'spikes' pressure was observed at a time when the leading flame front had already left the vessel as shown in Fig. 2 and occurred only for few milliseconds ~ 3 ms. From Fig. 3, the onset of the denotation spike occurred at $\Phi = 0.76$ with $S_f = 28.6$ m/s in hydrogen/air mixtures. Noting that it is a lean concentration with $S_f < 1970$ m/s (Chapman-Jouguet (CJ) flame speed) and the length of the vessel is shorter (L = 0.315 m) for Test vessel 2, the onset of deflagration to detonation should not happened theoretically (Dorofeev et al., 1995, Moen et al., 1985) but Fig. 3 demonstrated the opposite results. Taking into account that the explosion initiated by a weak source (a standard automotive spark plug with a 16J), there is only a very low probability that a deflagration to detonation will occur in a manner similar to that observed in elongated tubes. It can be thought that the external explosion might cause this phenomenon to happen. However, Fig. 3 showed that this does not occur as there is no significant pressure difference between pressure inside the vessel and the dump vessel to eradicate the external explosion effect. A major feature of the explosions is that there are substantial proportions of the original flammable mixture in the test vessel after the flame left the test vessel and eventually, these unburned gases trapped in the corner regions were auto-ignited.

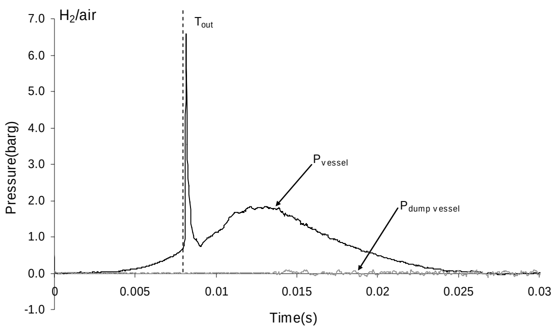

Figure 2 Pressure time history for maximum pressure inside the vessel (P_1) and pressure inside the dump vessel (P_6) at stoichiometric hydrogen/air in Test vessel 2.

Both hydrogen and ethylene can produce fuel/air clouds which are more sensitive to detonation (Moen et al., 1985). As been studied previously (Dorofeev et al., 1995, Moen et al., 1985), the deflagration to detonation mechanism can be instantaneously occurred from turbulent flame acceleration. Fast flame acceleration towards the vent causes most of the unburnt gases trapped at the corner region of the vessel and both top and bottom of the vessel. Since high value of K i.e. small vent area, flow restricted is experienced towards the venting of burnt gases which in turns promotes the turbulent jet initiation prior to the vent. A sudden venting can give rise to flame instabilities and consequently to more intense mixing of combustion products and reactants (Dorofeev et al., 1995). The effect of fast turbulent mixing of hot combustion products with reactant, flame shock interaction and flame instabilities causes the auto-ignition of the unburnt pockets of mixture inside the vessel or by specific, ‘hot spots’, leading to the explosion responsible for transition to a developing detonation.

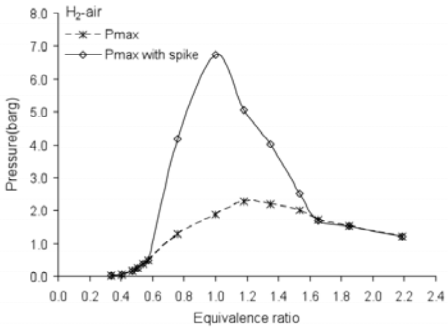

Figure 3 Maximum pressures with and without spike traces in hydrogen/air explosion in Test vessel 2.

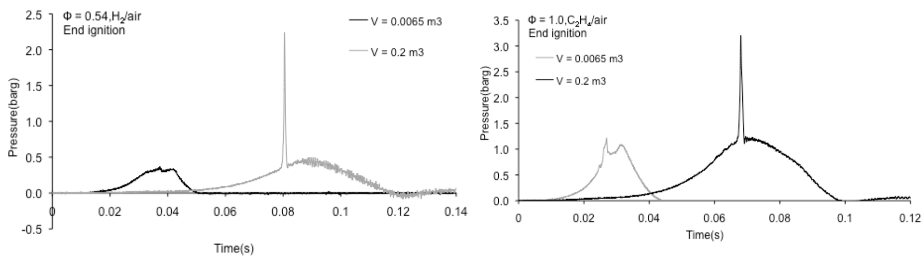

Figure 4 Pressure-time histories for hydrogen-air (left) and ethylene-air mixtures(right)

This argument is supported by the time of flame arrival in the corner region of the Test vessel 1 at the spark end, where a flame arrival thermocouple was located as shown in Table 2. The results showed that the time of the flame arrival in this corner region was very close to the time of the pressure spike’s occurrence for end ignition. It is considered that the corner region is not a high turbulence zone and hence, the auto ignition point or hot spot is the best described for the observation. Similar observation is reported for large scale test using 35 % H_2/air concentration where the localised explosion occurred inside the vessel after the outflow of flame in venting explosion (Dorofeev et al., 1995).

Table 2 Time of flame arrival for Test vessel 1

Fuel/air	Ignition position	Time of spike (s)	Time at the corner region (s)	Time the flame left the vessel (s)
H_2/air	End	0.08 – 0.082	0.088	0.077
C_2H_4/air	End	0.067-0.07	0.062	0.054

4. Conclusion

1. Self accelerating and larger bulk flame trapped inside the vessel are the main factor increasing the overpressure attained in 0.2 m^3 vessel.

2. Autoignition is the main factor of the appearance of spiky pressure traces on reactive gas mixtures. It can be said that fast turbulent mixing of the combustion products and reactants initiates the 'hot spot' or auto-ignition leading to the deflagration to detonation condition inside the test vessels.

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