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THE INFLUENCE OF VESSEL VOLUME AND EQUIVALENCE RATIO IN VENTED GAS EXPLOSIONS

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Abstract. 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. The comparison with previous work has shown over-prediction results as compared to the present study.

Keywords: Vented gas explosion; self acceleration; turbulent enhancement factor; hot spot

1.0 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.

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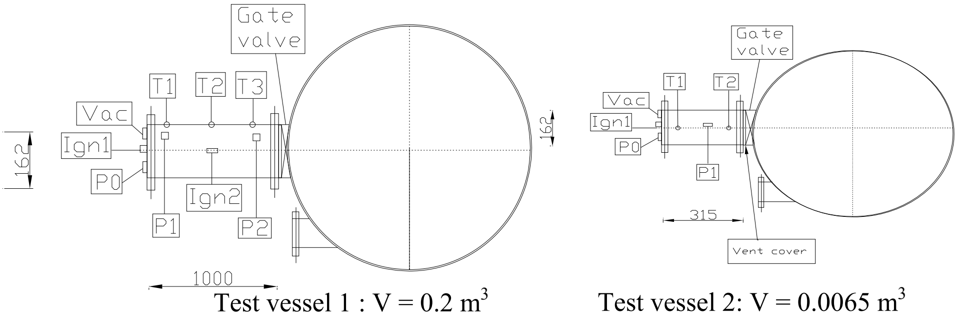
However, Kasmani *et al.* (2006) demonstrated that there is a volume effect in K that is not included in the Bartknecht's equation and is likely associated with flame self-acceleration due to the development of cellular flame for subsonic venting at $K<{\sim}5$. The net effect is an increase in burning 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 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.

2.0 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.

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 which 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 Figure1).



Test vessel 1 : V = 0.2 m^3

Test vessel 2: V = 0.0065 m^3

Figure 1 Rig configuration for vented gas explosion

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 $\Phi = 0.3$ 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 program, 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.

3.0 RESULTS AND DISCUSSION

3.1 Impact of the Overpressure on Vessel's Volume

Kasmani *et al.* [11] 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. Vessel 1 has much higher overpressures and flame speeds (x2-3) than Vessel 2, by a factor of 1.8 for methane and 2.4 for ethylene. For propane, it showed that the peak pressure ratio of 3.2 is attained when **Φ** is 1.3 in the larger vessel and 1.06 in the smaller 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 [12]. 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 [2, 3, 8, 13, 14] on determining the turbulent factor.

This work supported the observation reported by McCann *et al.* [15] 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.

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

However, hydrogen-air mixtures were not supported the argument made below. 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. 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 Position of the Flame When the Peak Overpressure Occurs

A feature of the results in Figure 2 is that the peak overpressure occurs well after the flame has left the vent for both central and end ignition. The vertical lines in Figure 1 are the flame arrival times just upstream of the vent. Similar results were also found in Vessel 2 for methane with end ignition as shown in Figure 3 and for propane, ethylene and hydrogen as shown in Figure 4. This indicates that the peak overpressure is caused by the external explosion. However, this was not the case as there was no external pressure rise and Vessel 1 had a thermocouple mounted close to the wall on the centreline and this showed that the peak overpressure was associated with the internal flame reaching the wall. The venting physics involve a flame accelerating towards the vent, pulled there by the 'suction' effect of the vent outflow. 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.

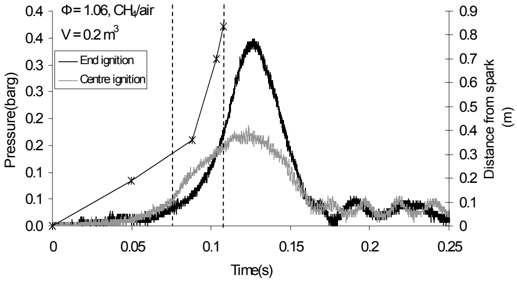


Figure 2 Methane/air at Φ=1.06 in Vessel 1 with end and central ignition

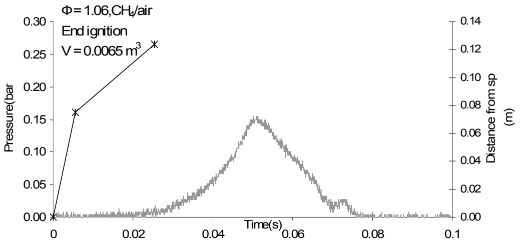


Figure 3 Methane/air Φ=1.06 Vessel 2 with end ignition. x is the time of flame arrival as a function of distance from the spark

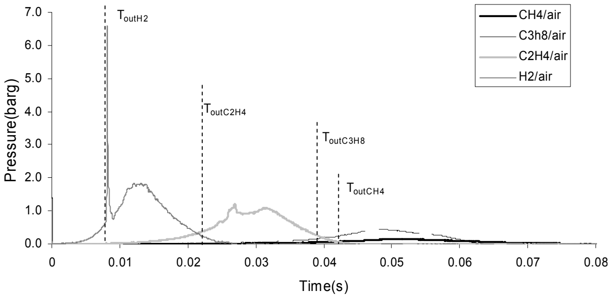


Figure 4 Methane, propane, ethylene and hydrogen/air Φ=1 vented explosions, with time of arrival at the vent marked. Vessel 2

3.3 Flame Speed Upstream of the Vent

The flame speeds upstream of the vent for methane/air explosions are shown in Figure 5 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 for end ignition, this is 9 times the 2.6 m/s flame speed for a spherical methane/air laminar explosion [16]. The flame speeds are plotted as a function of distance from the spark for **Φ** =1.06 in Figure 6. Also shown in Figure 6 is the expected influence of flame self acceleration due to the development of cellular flames.

This is based on the results in NFPA 68 [1]for K_G as a function of vessel volume, translated into normalized K_G with the value for 5 litre vessels and plotted against the vessel radius. These normalized results were then multiplied by the spherical flame speed of 2.6 m/s for small diameter flames. The results in Figure 6 show that the initial flame acceleration in the vented explosions did follow the self-acceleration trend. However, there was a sudden flame acceleration when the flame was 0.3 m from the vent for central ignition and 0.6m from the vent with end ignition. It is considered that this is the action of flow ‘suction’ from the vent flow. With central ignition there is no vent flow until significant mass has been burnt and this requires the spherical flame to be large. 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 this turbulence that results in the fast combustion of the trapped mixture in the outer part of the vessel.

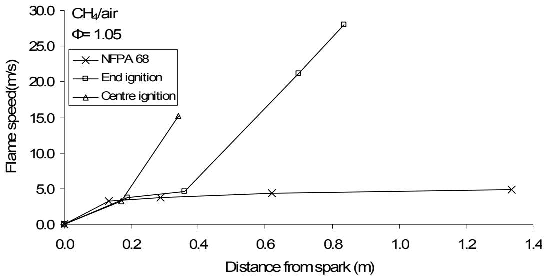


Figure 6 Methane/air peak flame speeds for **Φ** =1.06 plotted as a function distance from the spark for end and central ignition. Vessel 1

3.4 Small Explosion Vessel 2

The overpressures and flames speeds in the smaller vessel for the same K of 16.4 are shown in Figure 15 and 16 for all four gases. The peak overpressures are compared with those of Vessel 1 as shown in Table 1 above, which also compares the various predictions from previous experimenters (refer to Table 2). It should be noted that only Molkov [4] prediction did include the 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. The method of Bradley and Mitcheson [2, 17]is the closest to the present measured results in Vessel 1.

Table 2 Comparison of measured data with other published correlations

Gas/air	Experimental data (bar)	Bartknecht [10]	Swift [18]	Bradley & Mitcheson [2, 17]	Molkov [4]
CH_4/air	0.35 Vessel 1	5.44	12.43	1.163	2.09
C_3H_8/air	0.53 Vessel 1	7.45	20.92	1.46	2.26
C_2H_4/air	3.06 Vessel 1	10.92	20.92	3.35	3.07
H_2/air	-	14.57	-	42.72	4.16
CH_4/air	0.19 Vessel 2	5.44	12.43	1.163	1.15
C_3H_8/air	0.47 Vessel 2	7.45	20.92	1.46	1.36
C_2H_4/air	1.25 Vessel 2	10.92	20.92	3.35	2.32
H_2/air	2.28 Vessel 2	14.57	-	42.72	4.44

4.0 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. The suction effect occurred at the vent entry creates a rapid turbulent explosion of the unburned mixture trapped in the vessel after the centre line jet flame has been vented.

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REFERENCES

[1] *European Standard :Gas Explosion Venting Guidance EN 14994:2007*. 2007.
[2] Bradley, D. and A. Mitcheson. 1978b. The Venting of Gaseous Explosions in Spherical Vessels.II-Theory and Experiment. *Combustion and Flame*. 32: 237-255.
[3] Chippett, S. 1984. Modelling of Vented Deflagrations. *Combustion and Flame*. 55: 127-140.
[4] Molkov, V. V. 1995:Theoretical Generalization of International Experimental data on Vented Gas Explosion Dynamics. *Physics of Combustion and Explosions*. 165-181.
[5] Molkov, V. V. 2001. Unified correlations for Vent Sizing of Enclosures at Atmospheric and Elevated Pressures. *Journal of Loss Prevention in the Process Industries*. 14: 567-574.
[6] NFPA68, *NFPA 68: Guide for Venting of Deflagrations: 2002*. 2002. National Fire Protection Association.
[7] Razus, D. M. and U. Krause. 2001. Comparison of Empirical and Semi-Empirical Calculation Methods for Venting of Gas Explosion. *Fire Safety Journal*. 36: 1-23.
[8] Runes, E. 1972. *Explosion Venting*. Plant Operations & Loss Prevention. 6: 63-71.
[9] Siwek, R. 1996. Explosion Venting Technology. *Journal of Loss Prevention in the Process Industries*. 9(1): 81-90.
[10] Bartknecht, W. 1993. *Explosions Schultz*. Berlin: Springer-Verlag.
[11] Kasmani, R. M., *et al.* 2006. Sefl-Accelerating Gas Flames in Large Vented Explosions that Are Not Accounted for in Current Vent Design. In *Proceedings of the 2nd International Conference on Safety and Environment in Process Industry*. Naples, Italy.
[12] Harris, R. J. 1983. *The Investigation and Control of Gas Explosions in Buildings and Heating Plant*. London: E&F N Spon Ltd.
[13] Pasman, H. J., T. M. Groothuizen, and H.d. Gooijer. 1974. *D*esign of Pressure Relief Vents. Loss Prevention and Safety Promotion in the Process Industries:Edited by C.H.Buschmann. 185-189.
[14] Swift, I., 1985. Venting deflagrations-Theory Practice. Plant/Operational Progress, 1984. 3(2): 89-93.
[15] McCann, D. P. J., G. O. Thomas, and D. H. Edwards. Gasdynamics of Vented Explosions Part I: Experimental Studies. *Combustion and Flame*. 59: 233-250.
[16] Andrews, G. E. and D. Bradley. 1972. Determination of Burning Velocity : A Critical Review. *Combustion and Flame*. 18: 133.
[17] Bradley, D. and A. Mitcheson. 1978a. The Venting of Gaseous Exploisons in Spherical Vessel 1-Theory. *Combustion and Flame*. 32: 221-236.
[18] Swift, I., 1983. Gaseous Combustion Venting- a Simplified Approach. 4th International Symposium on Loss Prevention and Safety promotion in the Process Industries. 3(82): F21-F37.
[19] Dorofeev, S. B., A. V. Bezmelnitsin, and V. P. Sidorov. 1995. Transition to Detonation in Vented Hydrogen-Air Explosions. *Combustion and Flame*. 103: 243-246.

[20] Moen, I. O., *et al.,* 1985. Transition to Detonation in a Large Fuel-Air Cloud (Brief Communication). *Combustion and Flame*. 61: 285-291.

[21] Ng, H. D. and J. H. L. Lee. 2007. Comments on Explosion Problems for Hydrogen Safety. *Journal of Loss of Prevention in Process Safety.*