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Fast Turbulent Flames in Duct -Vented Gas Explosion

Rafiziana M.Kasmani[a,b,*], Gordon E. Andrews[a], Herodotous N.Phylaktou[a], Mimi H. Hassim [c], Norazana Ibrahim[b], Roshafima R. Ali[c], Hasrinah Hasbullah[b]

[a] Energy and Resources Research Institute, University of Leeds, LS2 9JT UK
[b] Faculty of Petroleum and Renewable Energy Engineering, Universiti Teknologi Malaysia, 81300 Skudai, Johor, Malaysia.
[c] Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81300 Skudai, Johor, Malaysia
rafiziana@petroleum.utm.my

The influence of vent ducts on gas explosions was investigated with the aim of determining whether the use of larger area of the vent duct than the vent, would reduce the overpressure in vented duct explosion. A 0.2 m^3 cylindrical vessel was used with L/D (length to diameter) of 2, at the limit of applicability of current explosion venting design guidance. Only end ignition was considered in this study with a vent coefficient, K of 16.4. Methane/air mixtures over a range of equivalence ratio, Φ (0.68, 0.84 and 1.05) have been used. Results showed that while there is no significant difference in maximum pressure for larger vent duct as compared to a free discharge vent at lean mixtures, however, a significant increase of overpressure ~ 1.4 bar was obtained in reactive mixtures i.e. Φ = 1.05. This was due to the high unburnt gas velocities induced in the vent duct by the most reactive explosion, creating very high turbulence levels at the vent duct inlet which gave rise to very fast flames and very high back pressures. Flame speeds in the vent duct of up to 500 m/s were measured for the most reactive mixture in the larger vent duct. The results were not predicted by the current US and European vent design guidance.

1. Introduction

Explosion protection using venting for gas and dust explosions are often ducted to safe locations by means of relief pipes in order to discharge the hot combustion product gases safely. Based on the experimental analysis of vented explosions with and without a pipe done extensively by several researchers (Bartknecth, 1993, Ponizy and Leyer, 1999a, b, Molkov, 1994, Kasmani, 2010, 2007a, b) it is known that the explosion overpressure increases substantially if there is an additional of vent duct to be fitted to the vent. Bartknecht (1993) presented a vent design correlation that is offered in NFPA 68 and the European vent design standard. For vented explosions connected to a vent duct, NFPA 68 offers a correlation for vent duct of less than 3 m and in between 3 to 6 m long pipe. However, the design guides give limited guidance on how a vent duct should be designed and the consequences for the overpressure. This is also the work of Bartknecht and is not a function of the pipe diameter (Bartknecht, 1993).
For vented explosions connected to a vent duct, NFPA 68 (2007) and the European Venting standard (2007) gives Eq. (1) and (2) for the increased overpressure, P'_{red}, due to a vent duct of length, L.

$$P'_{red} = 1.24\, P_{red}^{0.8614} \quad \text{for } L < \text{or} = 3\text{m} \qquad (1)$$

$$P'_{red} = 2.48\ P_{red}^{0.5165} \quad \text{for } L > 3\text{m but} < 6\text{m} \qquad (2)$$

where P_{red} is the explosion overpressure for no vent duct attached, as shown in Equation 3 for a 100 mbar static vent burst pressure, P_{stat}.

$$1/K = [0.1265 \text{Log}\ K_G – 0.0567]/P_{red}^{0.5817} \qquad (3)$$

where K_G is the mixture reactivity parameter, bar m/s (55 for methane).
K is the vent coefficient, $V^{2/3}/A_v$, where V is the vessel volume and A_v the vent area.

The results correlated in Eq. (1) and (2) show that the addition of a vent duct greatly increases the explosion overpressure if the pipe is longer than 3 m but has a much smaller effect for vent duct with less than 3 m in length. For example, if P_{red} was 0.4 barg, Eq. 1 predicts that the addition of a vent duct of the same size as the vent would increase the pressure to 0.55 barg and gives P_{red} of 1.54 barg for Eq. (2), respectively. The effect of mixture reactivity is assumed to be taken into account in Equation 1 and 2 by the impact of mixture reactivity, K_G, on P_{red} from Eq. (3). The present work fits the volume, P_{red}, vent coefficient, K, and vent duct length limits of the Bartknecht's correlation (Bartknecht, 1993) and it will be shown that the correlation grossly over predicts the experimental results before any allowance is added for the effect of the vent duct. The increase in P_{red} with the addition of a vent duct is so large that vent ducts cannot be used without increasing the vent area and duct size in order to reduce the overpressure. However, there is insufficient design data for gases to enable this to be done effectively and the physics of the process for gas explosion venting is not well understood. This contrasts with the situation for dust explosions, where a substantial experimental data base exists (Lunn et al., 1988). In order to reduce the violence of explosion and the peak pressure in a free discharge venting, the vent area needs to be increased. However, in the presence of the duct, an increase of venting area and duct diameter does not always allow a decrease in the peak pressure (Ponizy and Leyer, 1999a). By increasing the duct diameter, venting from the vessel through the duct increases and the pressure rise is smaller. However, a further increase in the duct diameter initiates the growth the intensification process, mainly due to the secondary explosion in the duct (burn-up) and the back flow to the vessel as the perturbation induced in the flame propagation is higher (Russo and Di Benedetto, 2007). It is often speculated that using a duct of larger cross section area than the vent would reduce the pressure rise caused by the additional of the duct attached. This is due to the assumption of the flow of unburnt gas out of the vessel would improve and the secondary explosion that takes place in the duct would be less confined. Pressure built-up inside larger duct diameter (vent duct) can be easily relieved and thus, it is less likely to back flow into the main vessel. From the experiments performed on dust explosion, Hey (1991) suggested that the technique using enlarged duct cross section area than the vent area is effective if the duct area/vent area is about ~ 2-2.5 and strictly when P_{red} is less than 0.5 barg. To the authors' knowledge, no experimental work on gas explosion with a vent duct has been carried out on the effect of duct diameter is larger than the vent diameter. In NFPA 68 (2007), this practice cannot be quantified as there is limited data test to provide significant on its effectiveness in reducing P_{red}. The aim of this work is to investigate the effect of larger vent duct diameter at the limit of applicability of compact vessel venting correlations with a length to diameter ratio, L/D, of 2.

2. Experimental material and methods

The experimental set-up is schematically represented in Figure 1. A 0.2 m^3 steel cylindrical vessel with a L/D of 2:1, which closed at the rear end was used, giving a vent diameter of 0.162 m and the vent coefficient, K of 16.4. The primary vessel was closed when the mixture were made up and then opened just prior to ignition using the gate valve. The gate valve acted as an isolator between the primary vessel and the connecting duct and dump vessel. The mixture was prepared using the partial pressure method to an accuracy of 0.1 mbar (0.01% of composition). As this paper focuses on the effect of duct length and diameter on venting explosion, two different duct length (L_d = 0.3 and 1.0 m) and diameters (D_d = 0.162 and 0.315 m) were connected to the primary vessel before discharging into a 50 m^3 dump vessel, as shown in Figure 1**.** This was 250 times larger than the explosion test volume and effectively gave free discharge conditions, but allows for the tests to be carried out under laboratory conditions. Maximum reduced pressure, P_{red} was measured at the P_1 and P_2 was used for the vent duct pressure loss measurement. Flame speeds in the primary vessel and the vent duct were measured from the time of arrival of the flame at an array of thermocouples on the vessel centreline. The average flame speed between two thermocouples was determined and ascribed to the mid-point of the distance between the thermocouples.

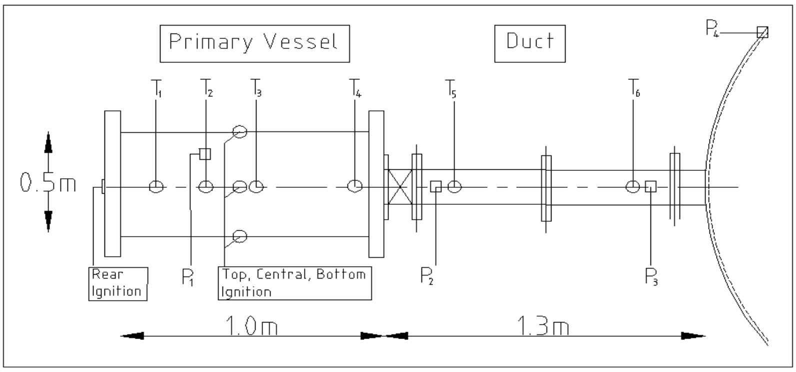

Figure 1: Explosion vessel geometry with location of the pressure transducers and thermocouples.

Three different methane-air mixtures with equivalence ratios, Φ = 0.68, 0.84 and 1.05 were used and only end ignition will be considered in this paper. The flammable mixture was initiated by an electrical spark, which gives 16 J energies for the gas explosion tests. In this experiment, only uncovered vent case was carried out.

3. Results and discussion

3.1 Effect of duct diameter on P_{red}

Figure 2 shows the pressure-time profile inside the vessel at P_1 at Φ =1.08 for different length (L_d) and diameter (D_d) of studied ducts. To be noted that duct length, L_d of 0.3 m and duct diameter, D_d of 0.162 m was used as the base case, considered as a free vent discharge. The results show that the larger pipe diameter (duct area / vent area, A_p/A_v = 3.78) has little effect on the overpressure compared to the duct having the same diameter as the vent opening. This was not agreed with the hypothesis made and did not have a good agreement with the results of Nagy (2000) or Hey (1991). The peak overpressures in the vessel and the duct are shown as a function of the equivalence ratio, Φ in Figure 3.

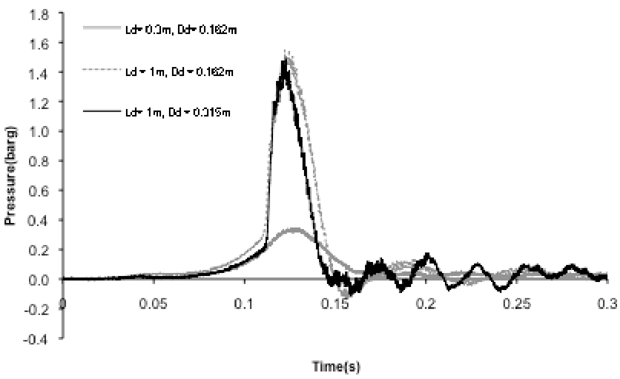

Figure 2 : Pressure time profile for Φ =1.08 at end ignition

This shows that it was only for the most reactive i.e. Φ =1.08 that the larger duct had a high overpressure. For Φ = 0.84, the larger duct had only a slightly larger overpressure than the free vent condition and at Φ = 0.68, the overpressures were in agreement to the duct diameter same as the vent. However, for D_d = 0.162 m, it was observed that the overpressures were always much higher than the free vent (base case) at all equivalence ratios. These results showed that it was only for the most reactive mixture that the larger duct did not solve the problem of the large increase in overpressure and the reasons for this were investigated further. The overpressures in Figure 3 for the most reactive mixture cannot be predicted from the recommended correlations in Eq. 1 and 3. The free vent overpressure is predicted by Eq. 3 to be 5.45 bar compared to the measured value of 0.35 bar. It is clear that Eq. 3 cannot be applied to smaller vessel volumes. If the measured free vent overpressure of 0.35 bar is taken (refer to Fig. 3), Eq. 1 will give P_{red} of 0.5 bar for a duct < 3 m long, well below that measured experimentally. However, if the correlation in Eq. 2 is used, the predicted overpressure is 1.44 bar, closer to the measured results shown in Figure 2 and 3. It can be postulated that Eq. 3 applies for sonic venting conditions as well as long duct pipes. It can be seen that the present results are quite at variance with the correlations for vent design and ducts for Eq. 1 and 3 and further work is recommended on the reliability of these correlations, especially for smaller volumes and high K.

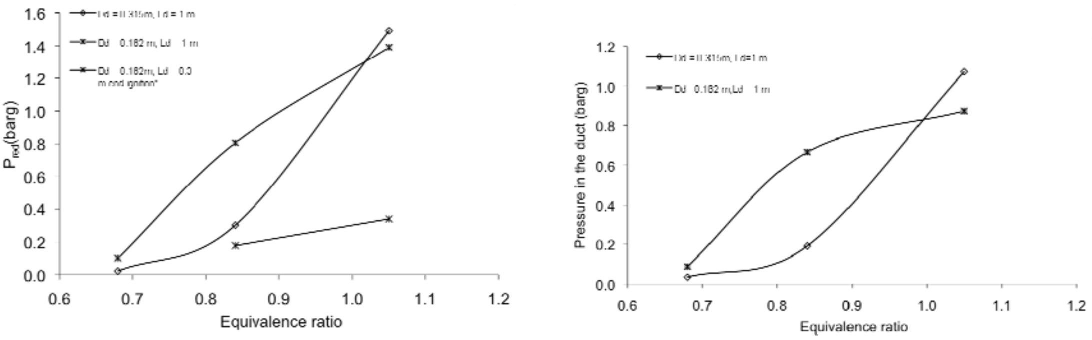

Figure 3: P_{red} in the vessel (left) and pressure in the duct (right) as a function of equivalence ratio

The pressure difference between the main vessel and the duct ($\Delta P_{2\text{-}3}$) is shown in Figure 4 as a function of time, together with the explosion pressure in the duct (P_d). The highest maximum of P_{red} occurred after the flame exited the duct pipe for both vent duct diameters (indicated by t_{in} and t_{out}). This shows that when the flame was in the duct, there was a negative pressure difference, which was higher for the larger vent duct. This will cause the flow to reverse and create high turbulence in the explosion vessel. Much of the unburnt gas mixture remains in the explosion vessel at the time the flame enters the vent duct. The turbulence created by the reverse flame flow from the vent duct into the primary vessel causes a sudden increase in the turbulent burning rate in the explosion vessel and this creates a high rate of vent discharge and pressure rise. The higher overpressure with the larger vent duct was due to the larger negative pressure between the vessel and the vent duct due to the large induced reverse flow as been reported by others (Kasmani et al., 2010, 2007a,b, Ponizy and Leyer, 1999a,b).

3.2 Flame speeds and unburnt gas velocity analysis

The pressure difference between the explosion vessel and the duct in the initial stage of the explosion can be used to compute the mean velocity of unburnt gas, S_g into the duct at the vent entry. Using 0.5 as the dynamic head pressure loss for incompressible flow and the pressure difference of 0.2 bar (refer to Figure 4), S_g in the vent is 258 m/s. However, assuming the sharp edge at the vent will have a contraction coefficient of 0.61, the predicted S_g is 423 m/s. This shows that very high S_g close to sonic conditions was generated at the vent and these will create high turbulence conditions in the duct. The shock waves will be generated and this creates a high backpressure and the subsequent reverse flow back into the explosion vessel (Kasmani et al., 2007a,b, Ponizy and Leyer, 1999a, b). Figure 5 shows that at lean fuel-air mixtures, i.e. Φ = 0.68, there was negligible effect of the duct length or diameter (L/D ratio) on both flame speeds inside the vessel and the duct.

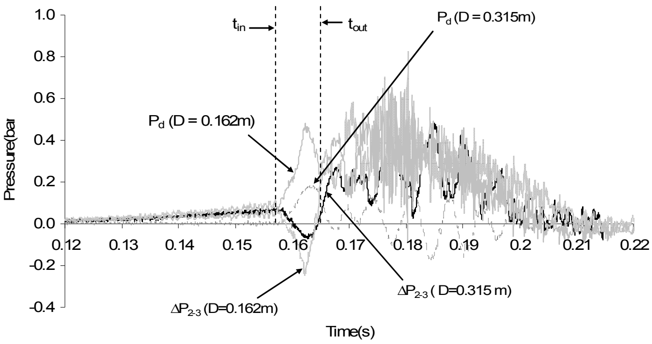

Figure 4: Pressure time histories for the pressure drop across the duct entrance ($\Delta P_{2\text{-}3}$) and pressure inside the duct (P_d) at Φ =1.08

At Φ = 1.08, the highest explosion vessel flame speed of 22.8 m/s occurred for the base case, 19 m/s for D_d = 0.315 m and 16.8 m/s for D_d = 0.162m. The flame speeds approaching the vent were much lower for lean mixtures and hence the induced flow was lower, substantially reducing the overpressure in the duct. The flame speeds in the main vessel approaching the vent were considerably higher than for spherical laminar flame speeds.

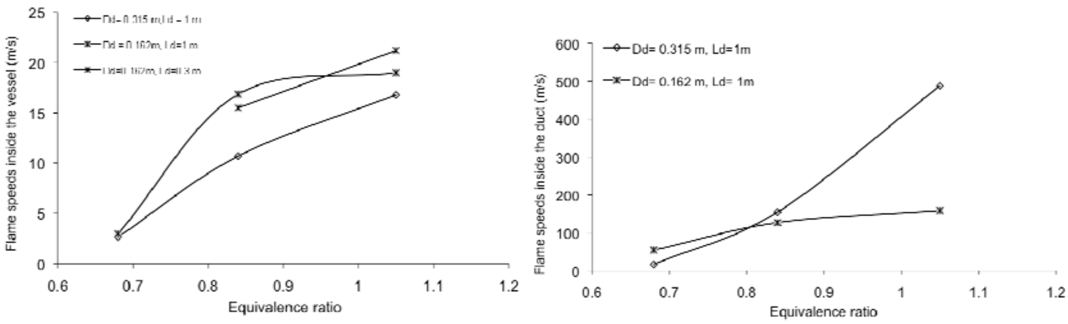

Figure 5: Average flame speeds measured in between T_{v2} and T_{v4} of main vessel (left) and in the duct (between T_o and T_{out})(right) as a function of equivalence ratio.

This condition was due to two factors; self-acceleration of the flame through the cellular flame front mechanism and later, the suction effect of the vent discharge on the flame shape which would draw the flame expansion preferentially in the direction of the vent (Kasmani et al., 2012, 2010). It can be said that these effects gave higher flame speeds for end ignition as the distance to the vent was double that for central ignition. The flame speeds inside the duct were much higher and were similar for both duct diameters, apart from Φ = 1.08; where the larger duct had a much higher peak flame speeds of 490 m/s. The larger vent duct created a flow expansion from the vena contraction at the inlet vent to the duct wall. This flow expansion creates a pressure loss, which apparently bigger in larger duct. More turbulence and a greater flame acceleration of the flame in the larger duct were created, as shown in Figure 5 and discussed in previous section. Further, the lower mean velocities in the larger duct would enable the flame to propagate in regions where there was a local turbulent quenching in the smaller duct (Kasmani et al., 2012, 2010) and this would increase the back pressure, as found experimentally. For leaner mixtures, the velocities were much lower and the turbulence generation was significantly lower as this is proportional to the square of velocity. Hence, the effect of the duct was much lower for the slower burning leaner mixtures. It is significant that many published work on duct-vented explosion that showing larger increase in the overpressure compared with a free vent discharge, were carried out with relatively large values of K. More work on duct has been carried out for dust explosions, but generally with K > 10. It is considered that in view of the limited experimental data in gas explosion on the impact of a duct to the overpressure, K and mixture reactivity (which determines the vent flow velocity), more work is required to understand this type of venting phenomena and to provide more reliable venting design guidance.

4. Conclusion

It has been shown in this work that enlarged vent ducts gave overpressures similar to a free discharge vent for lean mixtures, however, higher P_{red} was observed at Φ =1.08. The cause of the large increase in overpressure for larger vent duct at Φ = 1.08 was due to the high induced unburnt gas velocity towards the vent entrance and in the duct. For K = 16.4, near sonic flow conditions was observed at the vent entry, creating high turbulence and the high reversal pressure, substantially increase the combustion rate of the remaining unburnt mixture and hence, increase the overpressure and flame speed. The present design correlations for venting explosion and vent ducts do not predict the present results and their reliability for small vessel volumes with high K is in doubt.

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