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VENTED GAS EXPLOSION IN A CYLINDRICAL VESSEL WITH A RELIEF PIPE

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Abstract. A study of vented explosions in length/diameter (L/D) of 2 of cylindrical vessel with a duct pipe (L/D = 6) is reported. The influence of vent burst pressure and ignition locations on maximum overpressure generated inside the vessel, flame speeds and unburnt gas velocities ahead of the flame were systematically investigated. Propane and methane-air mixtures with equivalence ratio, Φ of 0.8 to 1.6 have been used. Results show that rear ignition exhibits higher maximum overpressures and flame speeds in comparison to central ignition. It is confirmed that prior to the flame entry to the duct, the flow is chocked due to the sonic flow created at the duct entrance.

Keywords: Vented explosion; vent burst pressure; ignition location; sonic flow

Abstrak. Kajian tentang letupan gas/udara di dalam tangki silinder dengan panjang/garis pusat adalah 2, dilaporkan di mana tangki silinder bersambung dengan paip dengan panjang/garis pusat ialah 6. Kajian ke atas kesan tekanan koyakan penutup ventilasi dan kedudukan pencucuh dijalankan untuk mengetahui nilai tekanan maksimum di dalam tangki, halaju nyalaan gas serta halaju gas tak terbakar. Gas propana dan metana di dalam udara digunakan dalam kajian ini dengan kadar persamaan gas/udara antara 0.8 hingga 1.6. Keputusan kajian menunjukkan bahawa tekanan dan halaju nyalaan udara di dalam tangki silinder adalah lebih tinggi jika kedudukan pencucuh berada jauh dari ventilasi berbanding jika pencucuh berada pada bahagian tengah tangki. Selain itu, sebelum gas dialirkan keluar ke bahagian paip, aliran gas dihalang untuk memasuki bahagian paip disebabkan oleh aliran sonik yang terbentuk pada bukaan paip.

Kata kunci: Letupan gas; tekanan koyakan penutup ventilasi; kedudukan pencucuh; aliran sonik

1.0 INTRODUCTION

In venting, vent devices for gas and dust explosions are often ducted to safe locations by means of relief pipes in order to discharge the hot combustion product. Based on the experimental analysis of venting explosion with and without a pipe, It is known that the severity of the explosion is likely to be double or 12 fold increase with the presence of a duct with respect to simply vented vessels [1–4]. The maximum pressure, $P_{\max}$ in the vented enclosure will, after onset of venting, be the result of the combustion

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process and the flow flame propagation of unburnt as well as burnt mixtures through the vent opening [5]. Further, the pressure generation and flame front propagation during vented explosion in vessels are also strongly affected by large number of parameters: turbulence level of the mixture, ignition source location and vent area size. Several phenomena were identified as affecting the increase of $P_{\max}$ such as secondary explosion in the duct (burn-up), frictional drag and inertia of the gas column in the duct, acoustic and Helmholtz oscillations [2]. The study by Iida *et al.* [6] mentioned that flame was found to extinguish or hesitate in the channel before passing through in some cases, depending on the equivalence ratio of the mixture, the channel width and the flame inflow velocity. Other studies supported the above hypotheses by using relatively narrow ducts with a sharp vessel-duct area [3, 6, 7]. It showed that the flame front entering the duct can be temporarily extinguished due to stretch and cooling through turbulent mixing with unburned gas which brings about stronger burn-up (i.e. with higher pressure amplitudes) during re-ignition [8].

Bartknecht [9] presented a vent design correlation considering the vent bursting pressure, P_v and this correlation is used as a vent design guideline in NFPA 68 [10] and European Standard [11]. For vented explosion connected to duct pipe, NFPA 68 offers correlation for pipe less than 3 m and in between 3 to 6 m long pipe. The effect of bursting vent on pressure development in vented explosion have been studied by several workers [2, 3, 12–14], only limit at stoichiometric fuel concentration. It is found that the peak pressure inside the vessel during duct-vented gas explosions did not result from the external explosion and when the flame is propagating in the duct as reported by Kasmani *et al.* [15] and being postulated by Lunn *et al.* [16]. This observation has been reported by Ferrara *et al.* [17, 18], inheriting the condition using simple duct pressure loss theory. It is considered that variation of the mass burn rate and flame speeds of the flame approaching the vent have a strong influence on the vent flow and hence, the subsequent combustion behaviour. A major feature of the explosions is that there are substantial proportions of the original flammable mixture in the test vessel after the flame has exited the vent duct. This is larger for central ignition than for rear ignition. Kasmani *et al.* [15] also showed that the faster mass burn rate approaching the vent as P_v increases causes sonic flow in the vent and hence choked flow. This prevents there being any outflow from the duct until the pressure has risen in the vessel to drive the burnt gases out. In some cases, this condition leads to a period of mixed burnt gas and unburnt gas venting with micro explosions and detonations in the vent duct. This phenomena has been detailed by Ferrara *et al.* [17, 18].

To our knowledge, little consideration on the effect of the mixture reactivity is published in literature even for the open vent gas explosions. In this paper, the effect of mixture reactivity from lean to rich fuel concentration will be presented and investigated in terms of $P_{\max}$, flame speeds, S_f and unburnt gas velocity ahead of the flame, S_g. The presence of bursting vent is found to be one of the important factors in generating the $P_{\max}$. The opening/breaking of the vent would delay or hinder the venting process, causing the maximum burning rate increasing due to the bulk flame area compressed towards the vent and hence, the rates of pressure rise increases as well as the pressure inside the vessel in comparison to the open vent mechanism. At low opening vent pressure P_v, the resistance to flow expansion out of the chamber to the duct is less than at higher P_v. At higher P_v, since the vent opened at a relatively late stage, when the total flame area had increased significantly compared to the lower P_v case, the rate of burned gas production exceeded the rate of unburned gas venting which in turn caused a continuation in pressure rise within the vessel [19].

2.0 EXPERIMENTAL DETAILS

To conduct the experiments, a 0.2 m^3 steel cylindrical vessel with length: diameter of 2:1 connecting with 1 m length duct pipe was utilized as shown in Figure 1. The vessel is closed at the rear end and fitted at the other with a circular tube with diameter of 0.162 m, simulating the vent (initially covered) and its discharge duct (length = 1 m, diameter = 0.162 m) connecting to the dump vessel which has a volume of 52 m^3. A constant vent coefficient, K_v (= $V^{2/3}/A_v$) of 16.4 was used for this test series with diameter of orifice plate, d = 162 mm. Four vent covers of different types of papers and plastics sheets with bursting pressure (P_v) of 79, 178, 209 and 424 mbar were used and located behind the gate valve. The gate valve acted as an isolator between the primary vessel and the connecting duct. The vent covers were clamped between the circular stainless steel for support and flanged between the opening vent and the duct pipe. For the

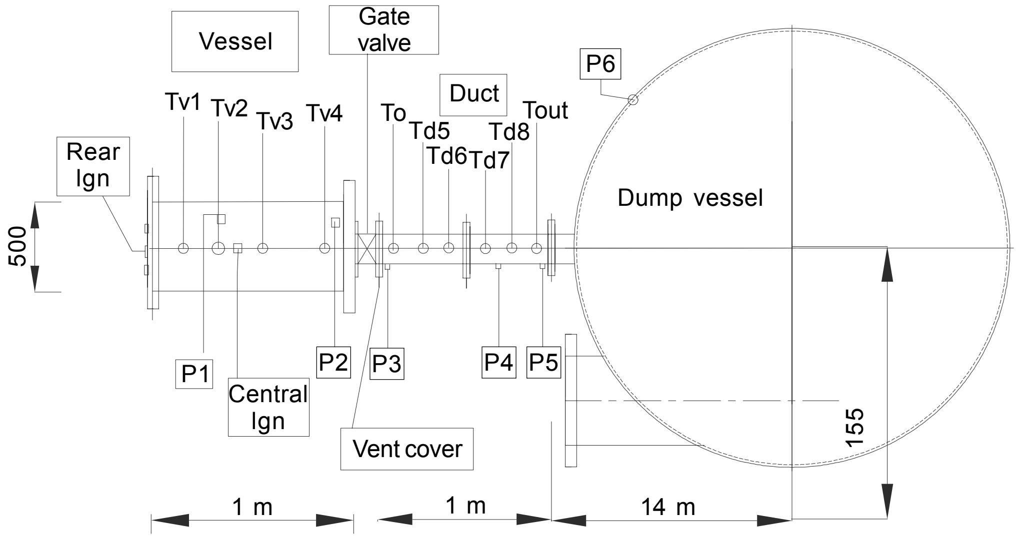

Figure 1 Vessel geometry

purpose of this test, the dump vessel volume was sufficient to allow these results to be applicable to an explosion vented to the atmosphere.

For maximum reduced pressure, P_{max} was measured from P1 pressure transducer and P2 pressure transducer will record for vent dynamic bursting pressure and duct pressure loss measurement. Flame speeds were recorded from the primary vessel and duct from an array of thermocouple's flame arrival times output, positioned along the centre line. The flammable mixture was initiated by an electrical spark which gives 16 J energies for the gas explosion tests. Ignition was positioned at the rear wall and central to the vessel, each along the centre line opposite to the entrance to the duct Lean to rich limits concentration by volume of propane and methane-air (Φ = 0.8 to 1.6) were investigated for both rear and central ignition tests. Fuel-air mixtures were prepared using partial pressure method, to an accuracy of 0.1 mbar (0.01 % of composition). Ignition was then initiated immediately after opening the gate valve. For the repeatability and reproducibility purpose, three repeated tests were performed at each condition.

3.0 RESULTS AND DISCUSSION

3.1 The Influence of Static Vent Burst Pressure, P_v on Maximum Pressure, P_{max}

The variation of the maximum over pressure with static vent bursting pressure, P_v, value is shown on Figure 2 with central and rear ignition for stoichiometric propane and methane/air mixtures. Figure 2 shows an increase in P_{max} with P_v that is approximately linear, as has been found in vented explosions with no vent duct [9, 20–22]. However, the trends are far from consistent and it is apparent that the effects are different for propane and methane as well as for rear and central ignition. There are several unusual features in the results: a decrease in P_{max} with P_v for propane up to a P_v of 180 mbar; completely different trends for methane than for propane which showed that methane gave worst condition for central ignition position than propane; the results with no static vent burst pressure and an initially open vent [17, 18] show different trends to those with 100 mbar vent burst pressure in relation to the sensitivity of P_{max} to the ignition position, which is larger with a static vent burst pressure on propane and the effect is reversed for methane once a vent is in position. None of these effects are reflected in any vent guidance [10, 11] or have been reported by others.

Another interesting feature that shown in Figure 2 is the influence of P_v on P_{max} for methane-air explosion is not much pronounced either at rear or central ignition and this behaviour similar to initially open vent ignition as reported by Ferrara *et al.,* [17, 18]. However, this trends also apparent to stoichiometric propane-air ignited at central but propane with rear ignition shows a much larger influence of P_v and for all cases, the effect of P_v on P_{max} below 220 mbar is much more complex than a linear constant dependence on P_v.

Figure 2 also illustrates a comparison with the experimental correlation of P_v effect on P_{max}, in the absence of a vent duct, based on the work of Bartknecht [9] and for the duct pipe effect, correlation excerpted from NFPA 68 [10] is used. This shows the classic linear effect that has been reported by others [9, 20–22] and yet, the results gave gross overestimation compared to experimental data obtained. The relative deviations, δ [23] between the calculated and experimental P_{max} given by $\delta = 100\ (P_{max,cal} - P_{max,exp})/P_{max,exp}$ is between 289% to 318 % for initially open vent and averagely about 199 % to 248% for all P_v ignited at central and rear wall respectively in methane-air compared to NFPA 68. For propane-air, 241% to 273% deviations are marked for initially open vent and average of 284% to 622% deviation for rear and centrally ignited explosion respectively at all P_v. This observation showed clearly that correlation given in NFPA standard [10] is overly conservative for the vented gas explosion and this argument is supported by Ural and DeGood *et al.,* [21, 24] when comparing their measured peak pressures with those predicted by the NFPA 68 correlation.

3.2 Flame Speeds and Flame Vent Velocities

It is suggested that the induced flow through the duct plays an important role in the final severity of the explosion. This flow is driven by the flame expansion and propagation in the main vessel as shown in Figure 3, 4, 5 and 6.

Those figures report the average flame speeds measured in second half of the main vessel (between Tv2 and Tv4 in Figure 1) and unburnt gas velocity in the duct just

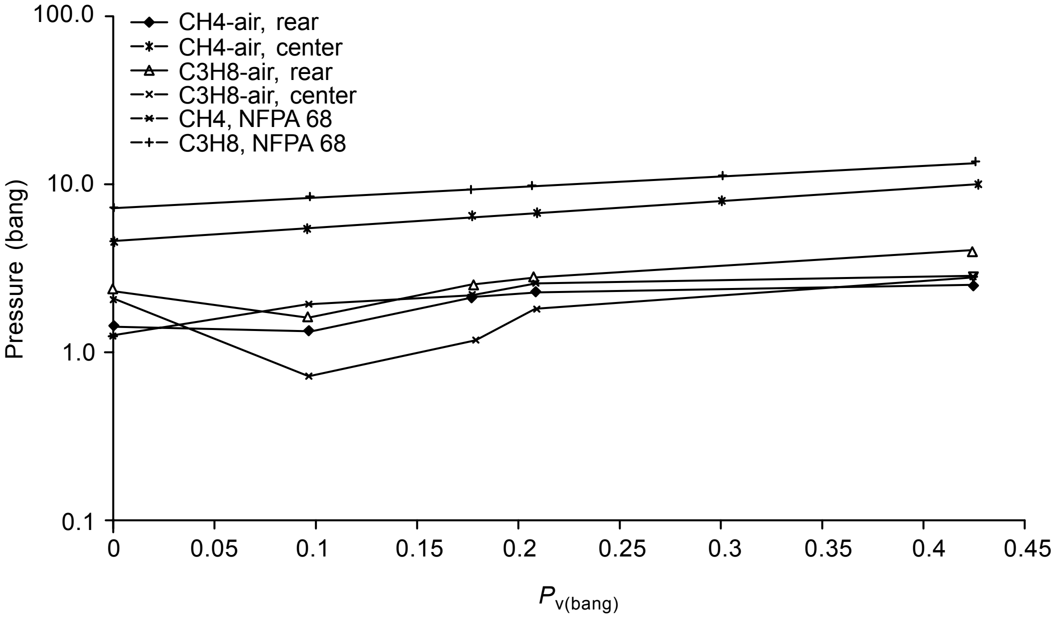

Figure 2 P_{max} vs. P_v on stoichiometric propane-air and methane-air

prior the flame entry as a function of fuel concentration at different P_v for centrally and rear wall ignition. Simple momentum conservation law is used to predict the unburnt gas velocity, S_g in the duct prior to the flame entry. For propane-air at Figure 3, the main vessel flame speeds is initially at 19 m/s for $\Phi = 0.8$ before increasing to maximum value of 234 m/s ($\Phi = 1.34$) at $P_v = 424$ mbar. The maximum flame speeds at all P_v exhibits highest value at 5.5 % propane concentration ($\Phi = 1.34$) but different trend is observed for initially open vent result. The maximum flame speeds of 52 m/s obtained at $\Phi = 1.13$. As expected, similar observation is obtained for centrally ignition (refer to Figure 4) and resulted lower flame speeds at all P_v and $\Phi = 1.34$ where 145 m/s is the highest value. Rich mixtures are known to be more susceptible to developing surface instabilities (flame cellularity) which would lead to higher burning rate and hence higher flame speeds [17]. The faster flame speeds with rear ignition can be explained based on the flame propagation mode. The burnt gases are only allowed to expand in one direction from rear ignition site, resulting in an elongated hemispherical flame with larger surface area and hence, faster expansion compared to centrally ignited flames. Further, the faster mass burn rate approaching the vent as P_v increases causes sonic flow in the vent and results in chocked flow.

Higher flame speeds reflect higher unburnt gases velocities ahead of the flame that will cause higher turbulence field in the initial section of the duct [18]. This can be observed from unburnt gas velocity, S_g in the duct prior to the flame entry results. For propane-air explosion, S_g increases corresponding to P_v and equivalence ratio up to $\Phi = 1.34$ and deceases at very rich propane concentration ($\Phi = 1.63$).

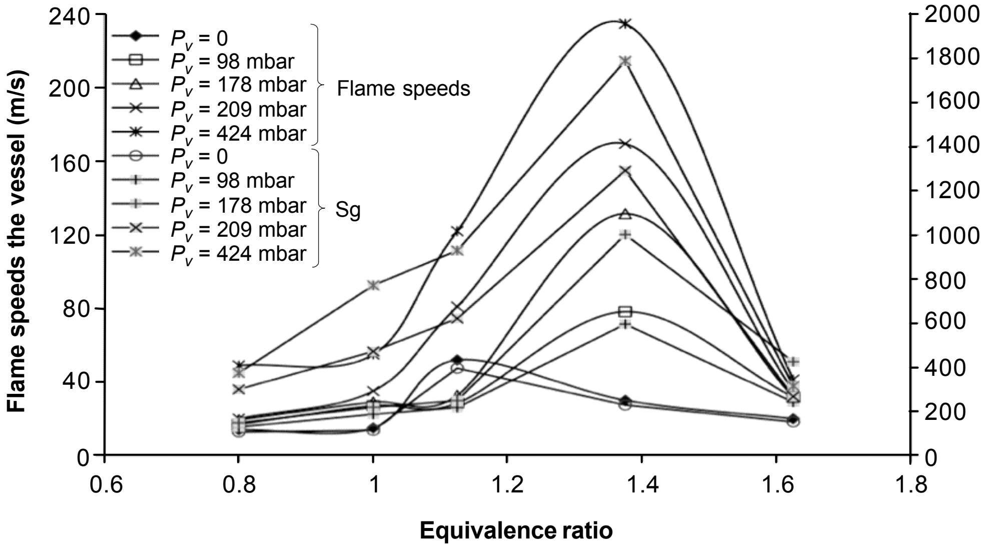

Figure 3 Flame speeds and unburnt gas velocity in the duct just prior to the flame entry as a function of Φ for propane-air at rear ignition

The maximum S_g values attained are 1787 m/s and 1100 m/s for rear and central ignition respectively and both occurred at Φ = 1.34 (refer to Figure 3 and 4). Those velocities are slightly higher than speed of sound in gases at adiabatic temperature; 889 m/s for methane and 892 m/s for propane. Interestingly, about 78% for rear ignition and up to 98% for central ignition increase in S_g at highest P_v in comparison to initially open vent result. This observation can be explained with the effect of vent bursts. Vent rupture generates a pressure wave and rapid acceleration of the gas in the vent duct. The vent bursting also generates turbulence upstream of the vent as well as pressure waves that propagate and interact with the flame. Both effects result in the generation of turbulence and the acceleration of the flame upstream of the vent. However, inconsistent trend is observed for methane-air explosion. At rear ignition, maximum flame speeds marked at 39 m/s at P_v = 209 and Φ = 1.06 instead of occurring at highest P_v i.e. P_v = 424 mbar as showed in propane-air profile (refer to Figure 5). As expected, maximum value of flame speeds occurred at rich fuel mixture (Φ = 1.06) for methane-air mixture.

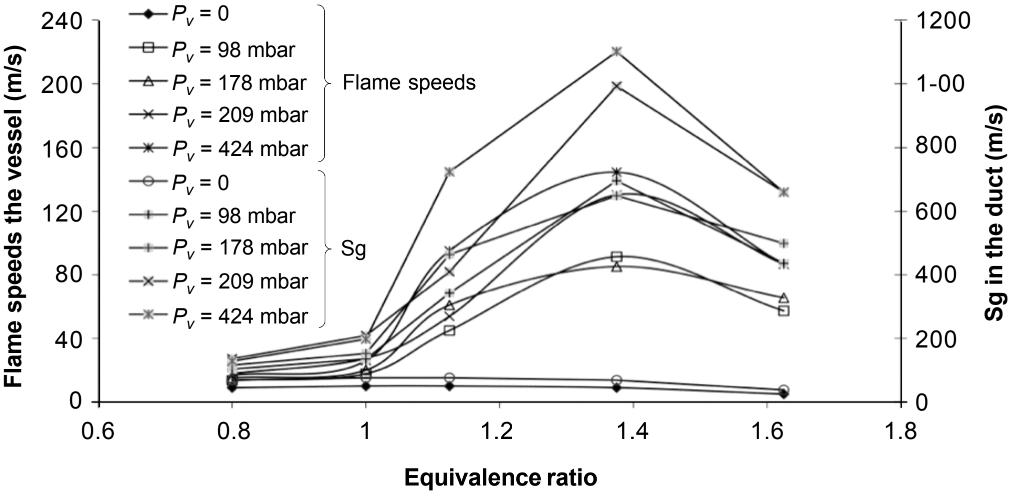

Figure 4 Flame speeds and unburnt gas velocity in the duct just prior to the flame entry as a function of Φ for propane-air at central ignition

Interesting unusual feature marked on centrally ignition methane-air explosion: maximum flame speeds of 52.32 m/s is marked at P_v = 424 mbar and Φ = 1.06. However, only at P_v = 424 and initially open vent reached highest flame speed at Φ = 1.06 while others marked the highest flame speeds values at stoichiometric methane-air explosion (Figure 6). As explained above, the rear ignition methane – air explosion tests would produce highest value of flame speeds as same as propane but, central ignition gave higher value of flame speeds. Since flame speeds at central ignition exhibits the highest value, highest S_g value of 399 m/s is denoted at central ignition instead of 276 m/s at rear ignition.

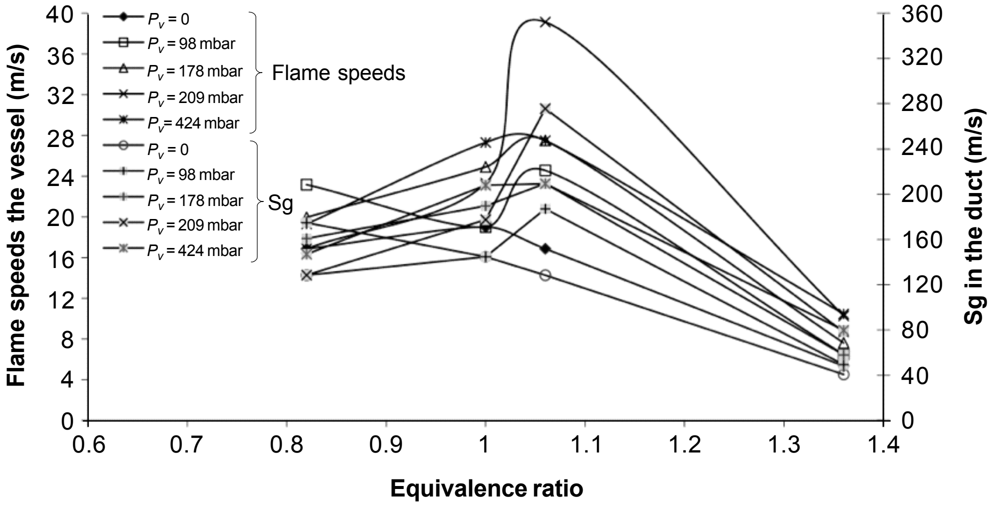

Figure 5 Flame speeds and unburnt gas velocity in the duct just prior to the flame entry as a function of Φ for methane-air at rear ignition

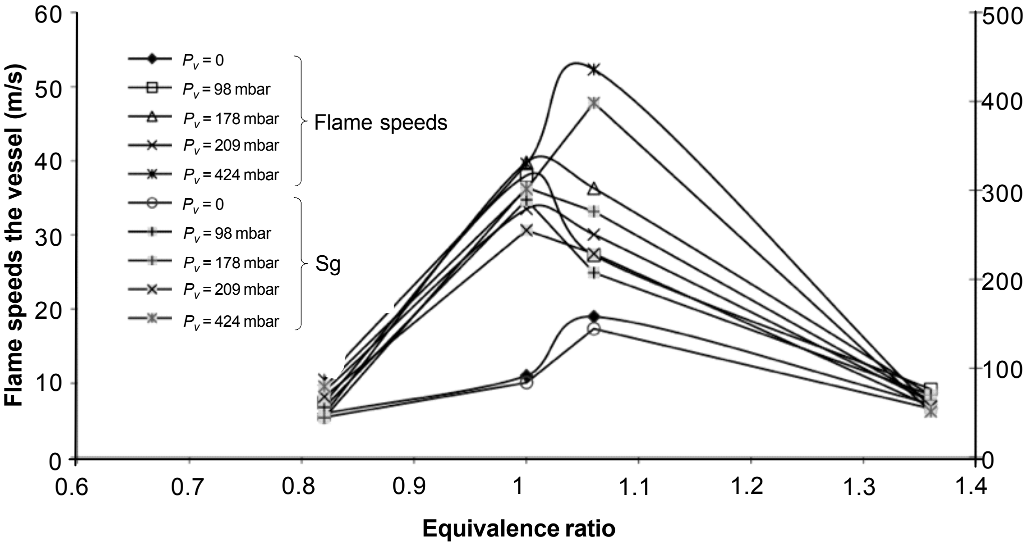

Figure 6 Flame speeds and unburnt gas velocity in the duct just prior to the flame entry as a function of Φ for methane-air at central ignition

3.3 Maximum Pressure on Equivalence Ratio Effect

P_{max} measured in all tests presented in this paper are given in Figure 7, 8, 9 and 10 as a function of equivalence ratio. In Figure 7, it is apparent that initially open vent exhibits higher P_{max} for propane-air at central ignition from $\Phi = 0.8$ to 1.12 at $P_v = 98$ mbar and 178 mbar. For rear ignition case, the trend is similar at $P_v = 98$ mbar but P_{max} is almost identical for P_v = 178 mbar and initially open vent test (Figure 8). However, for rich propane concentration (Φ = 1.4 and 1.6), $P_{\max}$ at different P_v is higher than $P_{\max}$ of initially open vent. For both rear and central ignition, maximum $P_{\max}$ value obtained are 5.7 barg (Φ = 1.35 at P_v = 209 mbar) and 4.7 barg (Φ = 1.35 at P_v = 424 mbar) respectively. As the propane concentration increases, the combustion time becomes shorter and less time is available for gases in the vessel to flow out before combustion

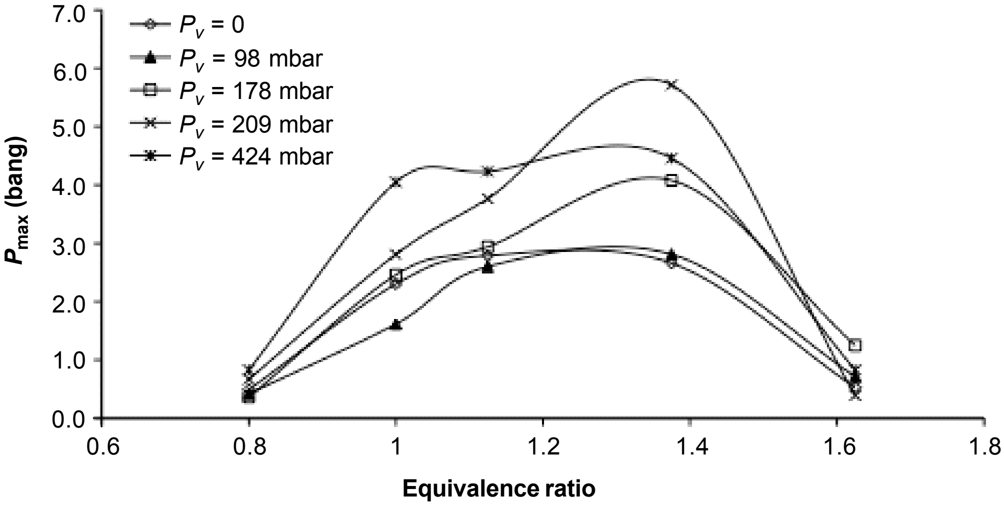

Figure 7 Propane-air at rear ignition

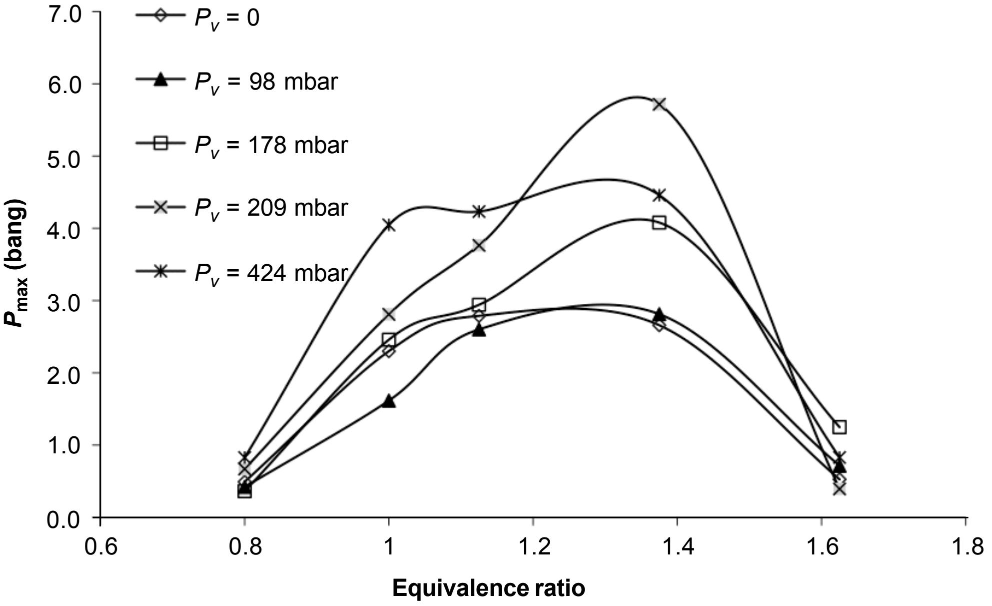

Figure 8 Propane-air at central ignition

is complete [22]. At rear ignition, greater distance from the spark ignition to the vent, allowing the flame to travel longer at the centre line of the vessel and creating larger flame area. Subsequent from this, the flame cellularity is likely to occur. It has been shown experimentally that as the radius of the flame increases, unstable regime is developed upon a combination of the flame linear instability theory and fractal analysis where the rate of radiative heat loss from the burned gases will become important and increase in flame speed [25, 26]. In the case of central ignition, very little unburned mixture has been vented from the vessel due to the rapid onset of burned gas venting following the vent ruptured.

In the explosion literature and practice, the presence of the vent cover could delay the venting process due to the breaking of the vent cover itself by stopping any flow in the duct prior to the vent bursting. The action of the vent further distorts the flame shape from hemispherical as the flame develops preferentially in the direction of the vent, where the unburnt gases are displaced. Since the size of the flame becomes larger prior to the vent opening, its mass burning rate is greater than for an initially open vent. In the case of sonic condition (P > 900 mbar), it causes the vent pipe to choke and theoretically, the vent flow is a linear function of the internal vessel pressure. Thus, the internal vessel pressure increases until the mass of vented gases reduced the vent flow to subsonic and lower pressure occurs. The major disturbance causing the increase of vessel pressure is due to the increase of combustion rate by promoting an increase in turbulence by the subsequent turbulisation (by the physical back-flow into the vessel) and by the interaction of the shock pressure waves with the flame frame.

For very large vent burst pressures, it is anticipated that the higher jet velocities and their sudden generation when the vent cover bursts will generate more turbulence in the duct and higher duct velocities will results with consequently higher overpressure.

For methane-air explosion, Figure 9 showed that rear ignition exhibits similar trend as propane-air explosion as $P_{\max}$ gives maximum value of 2.9 barg at $\Phi = 1.06$. Surprisingly, the pressure development corresponding to equivalence ratio between $P_v = 98$ and initially open vent is identical and this is similar to pressure profile at $P_v = 209$ mbar and $P_v = 424$ mbar centrally ignited methane-air explosion (Figure 10). Further, significant difference between $P_{\max}$ at all P_v with $P_{\max}$ at initially open vent is observed for a central ignition in methane-air explosion. This unusual behaviour did not demonstrate on propane-air pressure development profile. The possible reason for this identical pressure profile for methane-air between lower P_v and open vent would be that at 'smooth' breaking, acoustic instabilities [14, 27, 28] that present after the vent ruptured is not strongly exhibited compared to higher P_v i.e. $P_v = 424$ mbar and propane-air pressure profile (Figure 7). In this case, different fuel reactivity causes the significant different in rate of flame acceleration along the centreline of the vessel [19]. Further, at higher P_v, since the vent opened at a relatively late stage, where the total flame area had increased significantly compared to the lower P_v case, the rate of burned gas production exceeded the rate of unburned gas venting which in turn caused a

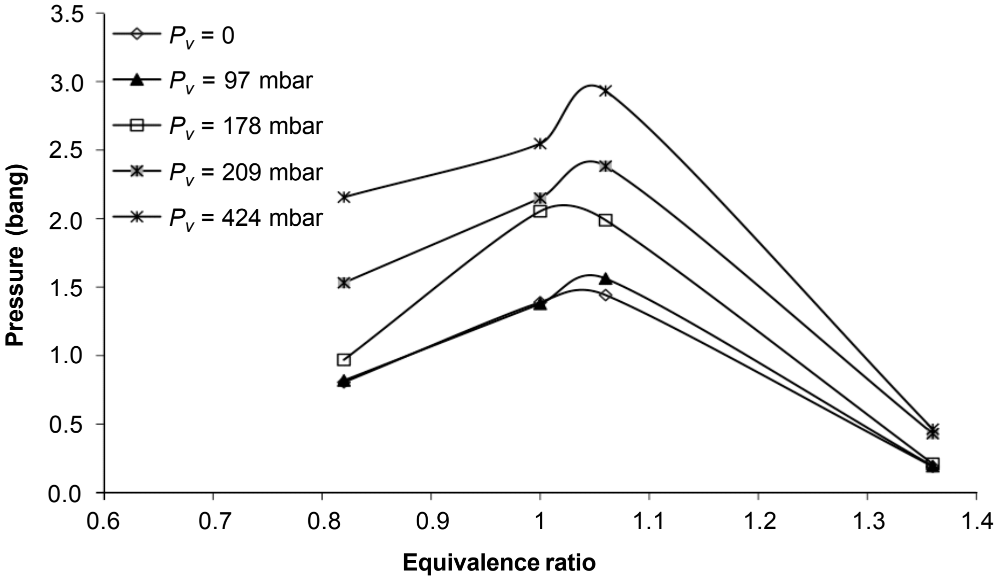

Figure 9 Methane-air at rear ignition

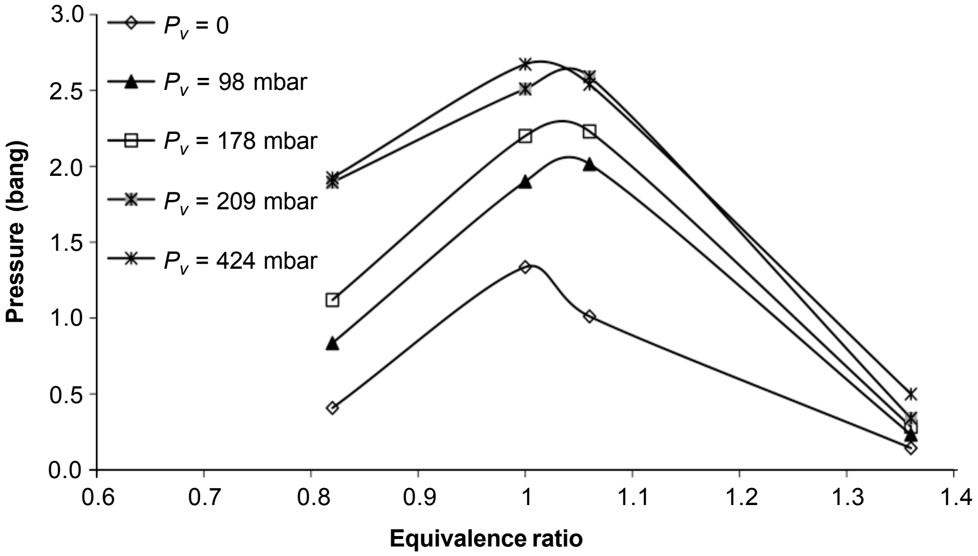

Figure 10 Methane-air at central ignition

continuation in pressure rise within the vessel [6]. Also, increasing P_v leads to a decrease in the time interval between significant pressure peaks due to increased combustion rate [14]. Overall, the results of present study confirm previous finding regarding vented gas explosion connected to relief pipe. Increases in vent static pressure leads to increase in maximum pressure generated inside the vessel due to flame distortion from vent breaking and flame acoustic instability.

Further, higher flame speeds inside the vessel relative to laminar burning velocity and the gas velocities ahead of the flame creates ‘blocked’ passage at the vena contraction of the pipe orifice, leading to sonic flow flame propagation that also contributes to the increase in $P_{\max}$.

4.0 CONCLUSION

The essential features of propane and methane-air mixture in vented explosion in a presence of duct pipe have been presented. The analysis of the flame speeds and unburnt gas velocity propagation prior to the duct entrance supported the arguments that those two factors are the important phenomena leading to the severity of vented explosion mechanism. The higher flame speeds inside the vessel and sudden increase of associated gas velocities ahead of the flame create sonic flow unburnt gas at the duct entrance and this condition gives rise to choked flow. This leads to the ‘hesitant’ outflow of the gases from the explosion for a short period.

Fuel concentration and ignition position play important roles in determining the development of pressure inside the main vessel. Rich fuel mixtures remarkably give a significant contribution in high $P_{\max}$ corresponding to P_v inside the vessel in comparison to stoichiometric fuel concentration. Even though there is no major difference of $P_{\max}$ for initially open vent fuel-air explosion either at rear or central ignition, maximum pressures exhibit a sensitivity to ignition position where rear ignition mostly resulted in higher $P_{\max}$ compared to central ignition at different P_v, in particular at higher P_v i.e. $P_v = 424$ mbar.

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