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Impact of non-central vents on vented explosion overpressures

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Abstract

It is normal practice to use centrally positioned vents or single vents in most experimental work and in the application of explosion venting in industry. This work seeks to investigate the influence of non-central and multiple distributed vents on the explosion overpressure. A 10L cylindrical vessel of 460mm length and 162mm diameter (L/D=2.8) was used for vented explosion with free venting (without a vent cover). Three different vent coefficient (K_v) were investigated, Kv, 3.6, 5.4 and 10.9 for both non-central and 4 hole vents. 10% methane-air and 7.5% ethylene-air mixtures were investigated to determine the influence of the mixture reactivity. The position of the spark ignition was in the centre of the end flange opposite the vent. It was shown for the non-central vent that the flame speed upstream of the vent was lower than for a central vent and this reduced the mass flow through the vent, which reduced the overpressure and reducing the external explosion due to the lower exit velocity of the unburnt gas and hence lower external turbulence. The external flame jets downstream of the vent was influenced by the increase in characteristic length scale of the vent, which was changed by increasing the number of vents.

Keywords: Explosion venting, explosion overpressure, flame speed, turbulent length scale.

1. Introduction

Explosion venting is the most common explosion protection technique. However, there is limited data that supports supports current vent design standards and poor agreement with the design standards and experimental data (Kakandu, 2011, 2013). BS EN 14994 (2007) and NFPA 68 (2013) state that the vent location is not important and the number of vents is not important, although there is encouragement to use multiple vents. Most vent design correlations and theories are developed considering a single vent and the use of single vent was recommended for symmetrical geometry by Howard and Russell (1974) The present work was undertaken to investigate these two aspects of current vent design procedures. Also most models of explosion vented do specifically take into account the vent location or the number of vents (Bradley and Mitchenson, 1978, Andrews and Phylaktou, 2010 and Molkov, 2001.The use of unrestricted vents (when vents are left open) approximate to conditions with very low vent burst pressure. They were used in the present work so as to separate the vent location and number effects from that of vent burst pressure.

There are six possible causes of the peak overpressure pressure and in many vented explosions all six pressure peaks may be present and which one is the peak overpressure, P_{max} or P_{red} [Bartknecht, 1993] depends on K_v, K_G, P_{stat} and the ignition position. The six pressure peaks were numbered from 1-6 in the order that they normally occur in vented explosions in previous work by the authors [Fakandu et al. 2011, 2012 and Kasmani et al. 2010b] but have been given a more descriptive nomenclature in the present work as summarised in Table 1 and compared with the terminology used by other investigators.

P_{burst} is used for the pressure peak associated with the vent static pressure (P_{stat}), which was zero in the present work. The overpressure due to the pressure loss caused by the flow of unburned gas through the vent (fv) is referred to as P_{fv} in the present work and this is the overpressure predicted by laminar flame theory. Following the P_{fv} pressure peak there is usually a pressure peak, P_{ext}, due to an external explosion and this may be larger or smaller than P_{fv}, depending on the mixture reactivity and K_v. The pressure peak P_{ext} is caused by the turbulent flame propagation of the vented flame in the cloud of turbulent unburned mixture expelled from the vent

In some explosions there is an overpressure peak that occurs at the point of maximum flame area (mfa) inside the vented vessel and this will be referred to as P_{mfa} in the present work. In some vented explosions there is a pressure peak, $P_{rev,}$ that occurs after the external explosion, which is caused by the cooling of the gas mixture in the vessel which causes a reduction in the vessel pressure and a subsequent reverse flow of the external gases into the vented vessel, creating turbulence and causing a second explosion in the vessel in the unburned mixture that remained in the vessel. In some vented explosions P_{mfa} and P_{rev} occur at the same time. This occurs because the reverse flow turbulence coupled with a reactive gas mixture can lead to all the mixture inside the vessel suddenly burning.

This reverse flow explosion is followed by an oscillating mass flow out of the vent and then back into the vessel, which gives a low frequency pressure oscillation. This is quite different from the high frequency acoustic pressure oscillations referred to by Cooper et al (1986), which are referred to as P_{ac} in the present work. P_{ac} is caused by oscillatory combustion inside the vessel and unburned gas trapped in corner regions of the vessel and burning after the flame has left the vent.

Table 1 summarises the present terminology and that of other investigators for the various peaks in vented explosions. Most investigations of vented explosions do not give the pressure time diagrams and simply report P_{red} with no comment on whether this is P_{fv}, P_{ext}, P_{mfa}, P_{rev} or P_{ac}, using the present terminology. Cooper et al [1986] do not refer to a pressure peak associated with the maximum flow of unburned gas through the vent, nor do Bauwens et al. [2010]. This is surprising as the classic laminar flame venting theories are all based on predicting P_{fv} for free venting [Bradley and Mitcheson, 1978; Cates and Samuels, 1991; *-Molkov, 2000].

In most experimental work with free venting two factors govern the overpressure: the pressure loss due to flow on unburned gas through the vent, P_{fv}, and the external explosion

Table 1 Comparison of terminology for the various pressure peaks in vented gas explosions

Peak pressure events	This work	Fakandu et al. [2011,2012] Kasmani et al. [2010b]	Cooper et al [1986] Central ignition	Harrison and Eyre [1987] End ignition	Cates and Samuels [1991]	Bauwens et al. [2010] Central ignition
Peak due to vent opening pressure	P_{burst}	P_1	P_1			
Peak due unburned gas flow through the vent	P_{fv}	P_2		P_{emerg}	ΔP	
Peak due the external explosion	P_{ext}	P_3	P_2	P_{ext}	Dominant	P_1
Peak due to maximum flame area inside the vessel	P_{mfa}	P_4	P_3	P_{max}	Max. burning rate	P_3
Peak due to the reverse flow into the vented vessel after the external explosion and a subsequent internal vessel turbulent explosion. Sometimes co-incident with P_4	P_{rev}	P_5				
Peak due to high frequency pressure oscillations and acoustic resonance.	P_{ac}	P_6	P_4			P_2

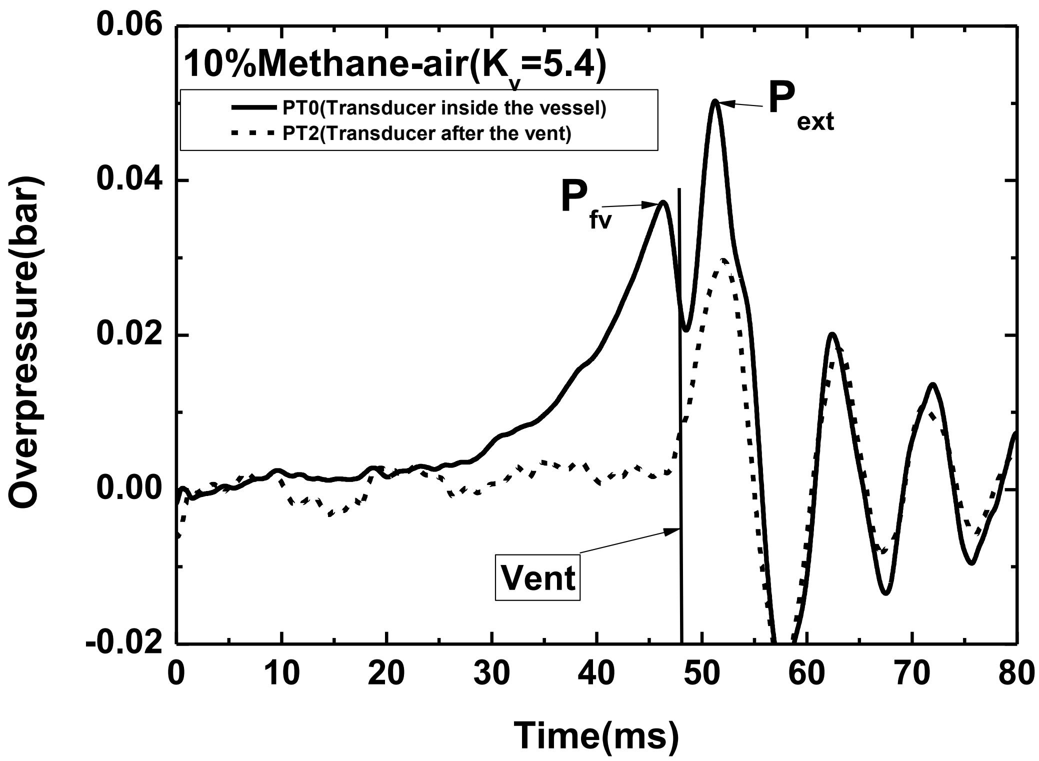

Figure 1: Pressure-time records of PT0 and PT2 for 10% methane-air.

overpressure, P_{ext}. Figure 1 shows these two pressure peaks for a vented methane-air explosion with a K_v ($V^{2/3}/A_v$) of 5.4. A pressure transducer was located outside the vent to detect the overpressure due to the external explosions. A thermocouple flame detector was located at the vent plane outlet to determine the time that the flame passed through the vent. Fig. 1 clearly shows that for this explosion the external explosion controlled the overpressure.

Most vented explosion experiments use a central position of the vent with limited data on the position of vent other than the central position. Solberg et al (1981) carried out vented explosion for initially uncovered and covered vents with the vent position non-central. This work did not discuss the influence of vent position or reasons for considering the vent at the bottom rather than central, instead the ignition position and the effect of instability was the main focus of the work. Bartknecht (1993) varied the vent area by removing the blank flanges used to block the fixed vents at different positions including central and other positions. No justification was given for this approach and the implication of departing from the traditional central position was not given. Hence, this work considers the implications of considering a different position of vents other than the central position, in order to understand how it affects overpressure and flame speed.

The displaced gases from the vented vessels result in external combustion by the emerging flame and the external explosion increases in overpressure with the vent flow velocity (Harrison and Eyre, 1987). This external explosion was shown to influence the internal pressure as well as the peak overpressure generated during explosion venting (Harrison and Eyre, 1987, Fakandu et al, 2011, 2012). The turbulent flame and the turbulent level of the external explosion is a function of the vent coefficient, Kv, and the gas velocity through the vent determines the peak turbulence and peak flame speed and this can generate sufficient overpressure to be greater than the pressure loss of the unburned gas flow through the vent. The external explosion is a turbulent flame propagation with a length scale determined by the vent blockage or K_v and by the number of vents. Increasing the number of vents decreases the length scale and this reduces the external flame overpressure (Fakandu et al., 2013). This was contrary to the assumption of the venting standards that the number of vents does not influence the vent design. The European standard (2007) states that 'the location of multiple vents to achieve uniform coverage of the enclosure surface to the greatest extent practicable is necessary', and no justification was given for this statement. Furthermore, the increase in turbulent length scale was shown to have significantly increased the flame speed downstream the vent irrespective of the K_v or the mixture reactivity (Fakandu et al, 2013).

The overpressure, flame speeds and other parameters downstream the vent was shown by Harrison and Eyre (1987) to have a close relation with the flame acceleration in the presence of obstacles ahead of the propagating flame. Extensive studies on the affect the flame interaction with a single obstacle were shown to significantly affect the overpressure and flame speed downstream of the vent as a result of the characteristic length scale (Andrews et al, 1990,Phylaktou and Andrews, 1991, Phylaktou et al, 1994 and Na'inna et al, 2012). In most of these studies, the obstacle scale was varied by simply changing the number of holes in the grid plates for a fixed K_v. Abdul-Gayed et al (1984) used the length scale (l) to analyse the intensity of turbulence and turbulence straining of premixed flames. The work and other similar works use the Reynolds number based on l as shown in equation 2 for the estimation of the turbulence when premixed flame propagate through obstacle or a vent (Abdul-Gayed et al,1984, Abdul-Gayed and Bradley, 1981, Abdul-Gayed et al, 1989).

$$R_L = {u'L}/{v} \qquad [1]$$

where R_L = is the Reynolds number, u' = the rms velocity, v =kinematic viscosity.

This work aims to investigate the effect of characteristics length scale in explosion venting by varying the length scale of the vent for a fixed vent coefficient, K_v and also estimating the level of turbulence using Reynolds number based on the length scale. As reducing the length scale of vent by using multiple distributed as replacement for single vent was shown to affect both the overpressure flame speed was shown upstream and downstream the vent (Fakandu et al, 2013). Also, the effect of non-central vent on the explosion overpressure and flame speed was also discussed. As most explosion vents as made central position and the venting standard has no requirement guiding the position of the vent.

2. Experimental Equipment

The experiments were performed in a vented vessel with a diameter of 162mm, length 460mm (L/D=2.8), and a volume of $0.01m^3$, as shown in Fig.1. Two vents with vent coefficients of the vent, K_v, of 5.4 and 10.9 (representing 60 and 80% crossectional area blockage, respectively) were investigated with the circular vents located at the bottom of the vented cylindrical vessel. Also, three different K_v of 3.6, 5.4 and 10.9 with multiple distributed vents of 4 hole vents and 16 hole vents were considered in order to compare with the single vent orifice. The experiments were carried out with free venting, with the mixture confined by a vacuum gate valve before the explosion. The test vessel was connected to 0.5m diameter cylindrical vessel which was also connected to a $50m^3$ dump vessel to safely capture the vented flames. The 0.5m diameter vessel was sufficiently larger than the vented vessel to give free venting conditions in the near vent area as shown in Figure 1. Two different gas-air mixtures were used for this experimental work including methane-air and ethylene-air at the most reactive mixture where the maximum flame temperature occurs. A 16 J ignition energy was used and the spark plug was located at the centreline of end flange opposite the vent. Each test was carried out at least three times and where possible all repeat measurements are shown.

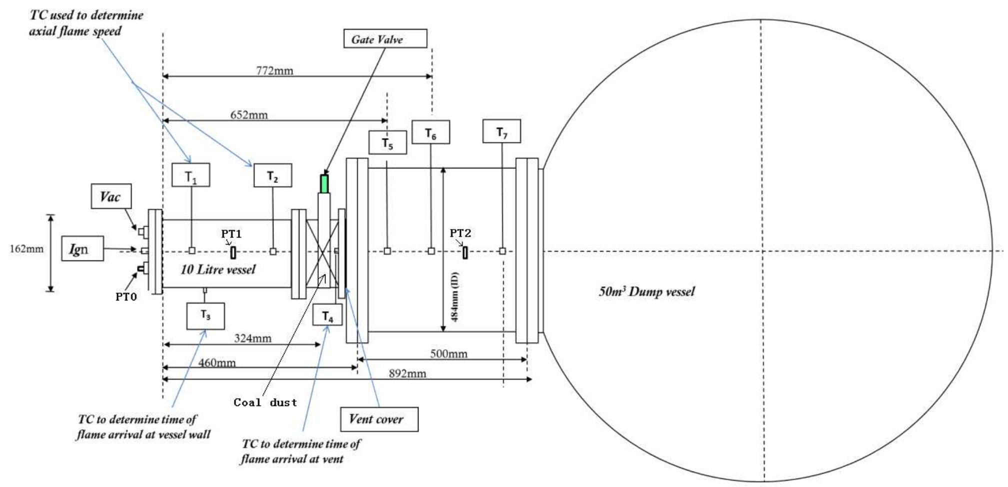

Figure 2: Experimental set-up for vented explosions.

The flame travel time was recorded by mineral insulated, exposed junction type-K thermocouples, arranged axially at the centreline of both the main test and the 0.5m dia. vessel, as shown in Fig. 1. Thermocouples T_1, T_2 and T_4 were located on the centreline of the main test vessel, while thermocouples T_5, T_6 and T_7 were on the centreline of the 0.5m dia. connecting vessel. The time of flame arrival was detected from the thermocouples and the flame speed between two thermocouples was calculated and plotted as the flame speed for the midpoint between the two thermocouples. There was also another thermocouple, T_3, located on the wall of the main test vessel to measure the time of flame arrival at the wall of the vessel. These event times are marked on the pressure time results with the thermocouple location, so that the position of the flame when a peak in the pressure time record occurs can be determined. This enabled precise determination of whether the highest overpressure was generated by an external explosion or by the internal flame displacing unburned gas through the vent.

Two piezo-electric pressures transducers PT0 and PT1 were located at the end flange (PT0) opposite the vent and mid-way the vessel length (PT1) respectively, in low flame speed explosions these pressure transducers had identical pressure time characteristics. However, for reactive gas explosions such as ethylene and hydrogen there were dynamic flame events that caused these two pressure transducers to record different pressure time records (Nagy and Portman, 1961). A third transducer PT2 was located in the 0.5m dia. connecting vessel which measured the external explosion overpressure and it time of occurrence. This was of great assistance in determining when the external explosion occurs.

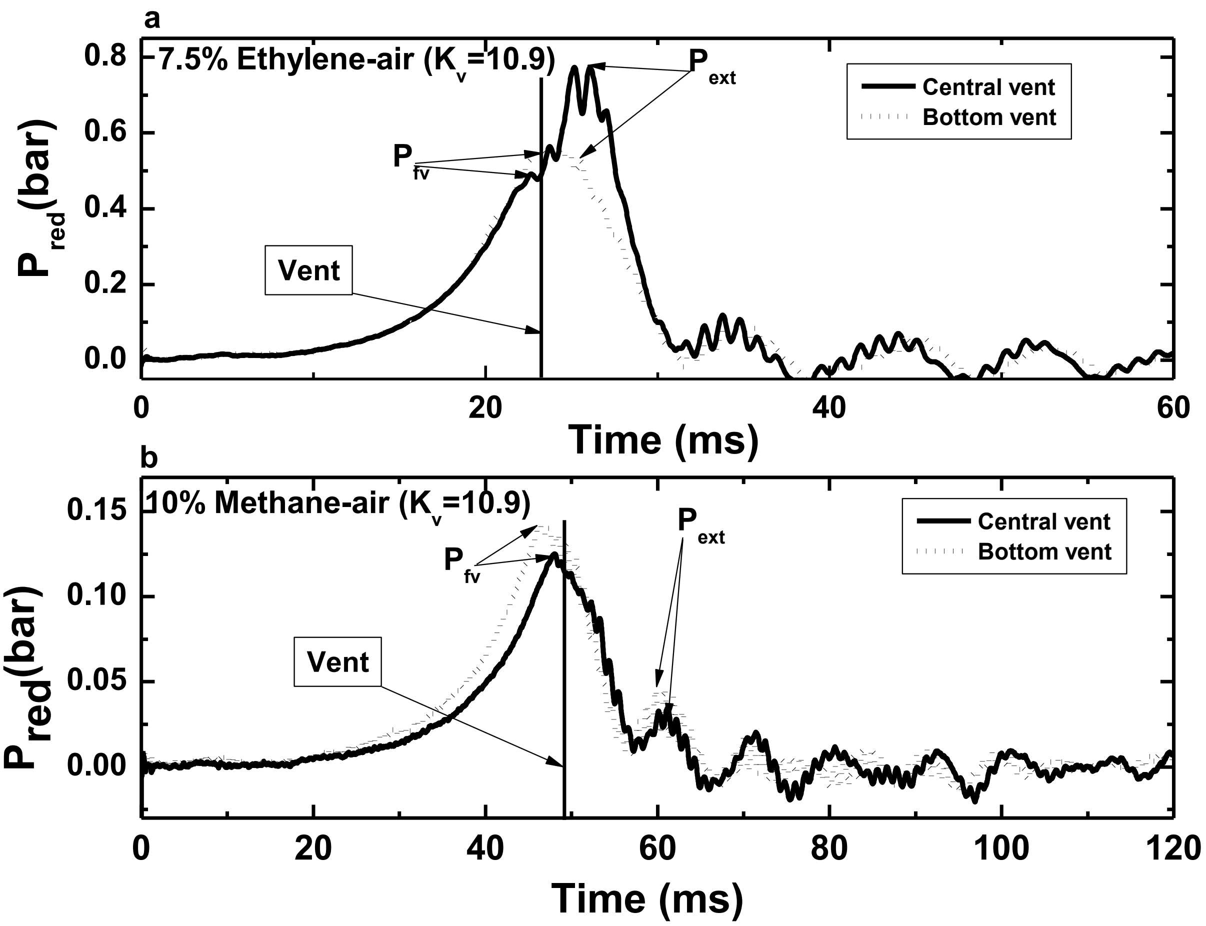

Figure 3: Pressure-time records of central and bottom vent positions for Kv=10.9.

3. Results and discussion

3.1 Influence of non-central vents on explosion overpressure and flame speed

Figure 3, shows the pressure-time records of the 10% methane-air and 7.5% Ethylene-air for a fixed K_v of 10.9, with the time of flame arrival vent located as “vent”. Fig. 3b shows that P_{fv} was higher for the more central vent when compared with the offset vent for 10% methane-air. P_{fv} was the dominant over pressure for low reactive mixtures of methane-air and propane-air (Fakandu et al, 2011). The cause of higher overpressure for the offset vent was due to the flame spreading radially rather than axially towards a central vent. This slowed the flame and increasing the burning rate through greater flame area, which also increases the flow of unburnerd gas through the vent which controls P_{fv}. The stretching of the flame surface in practice was shown by Solberg et al. (1979) to bring an early end to spherical propagation and increases burning rate.

When the more reactive mixture of 7.5% Ethylene-air was used, the offset vent showed a higher P_{fv} overpressure as compared to the central vent. However, P_{ext} was much higher for the central vent as compared to offset vent this K_v, This was due to the much lower flame speed generated by the downward movement of the flame went the vent was located offset from the centreline. This lower flame speed reduced the vent exit velocity and hence reduced the external jet turbulence.

Figure 4 show the flame speeds for 10% methane-air and 7.5% ethylene-air for K_v, 10.9, against distance from the spark position, comparing the central vent with the non-central vent. The offset vent position slowed the flame upstream of the vent as compared to the central vent and this decreased the burning rate and gave a lower overpressure for methane explosions, as shown in Fig. 3. For ethylene these trends were greater with very much higher upstream flame speeds for the central vent.

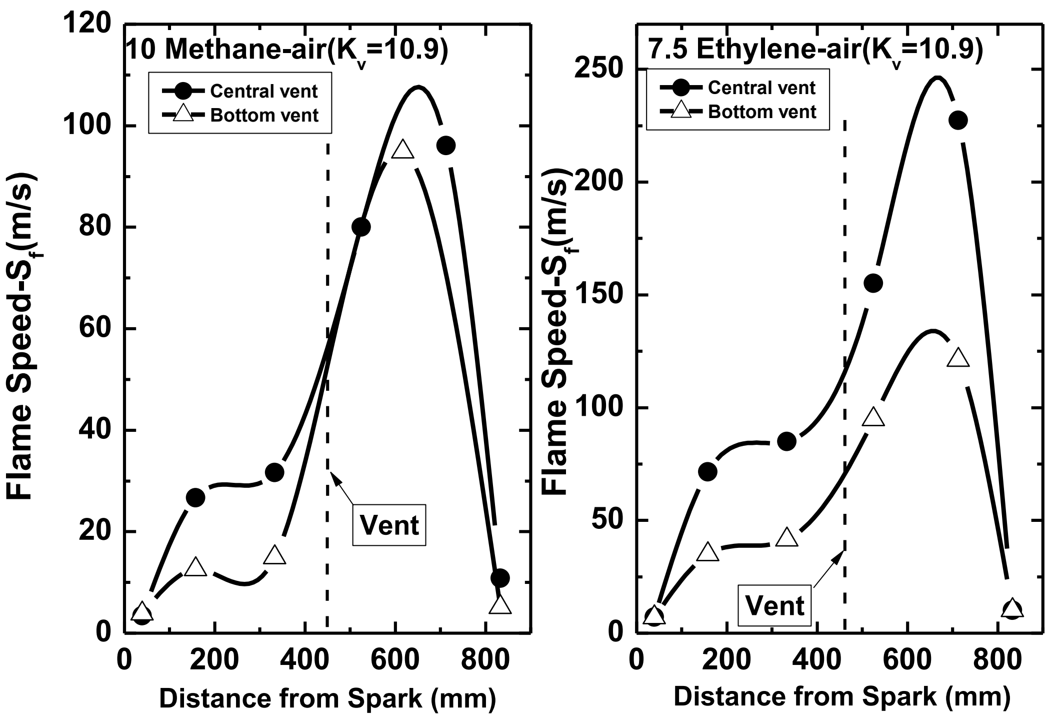

Figure 4: Flame speed vs distance from spark of central and bottom vent positions for Kv=10.9.

3.2 Effects of single vent and four vents on explosion overpressure and flame speed

Comparison of the pressure time records for single and 4 hole vented explosions for 10% Methane-air for K_v=10.9 are shown in Fig. 5a and b for a K_v of 5.4. The time of arrival at the vent thermocouple T_4 is marked as 'vent' and it is clear that P_{ext} was well after the flame passed through the vent and P_{fv} was well before this. For this small vent area, the peak pressure was P_{fv} as a result of the internal explosion pushing unburnt gas through a small orifice which gave a high flow pressure loss. Figure 5a shows that the single vent increased the peak overpressure for this vent area by more than 20%, as compared to peak pressure when the 4 holes vent was used. This was caused by the flame spreading to pass thorugh the four vents thereby increasing the flame surface area and rate of combustion.

Fig. 5b shows the opposite results for K_v = 5.4, due to the lower vent flow velocities at the large vent area. In this larger vent area explosion the vent flow pressure loss was low and the external explosion dominated the overpressure. This overpressure was reduced with four vents compared with one due to the reduced turbulence burning velocity with the smaller length scale turbulence.The benefits of using multiple distributed vent was also shown by Bjerketvedt et al, (1997).

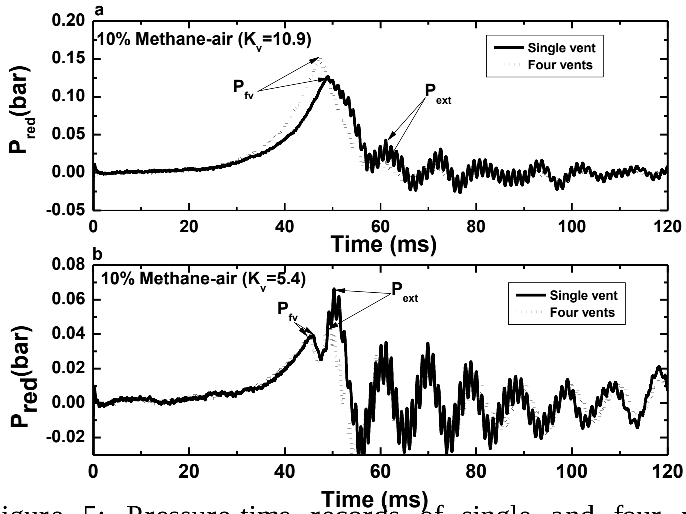

Figure 5: Pressure-time records of single and four vents for 10% Methane-air Kv=10.9 and 5.4.

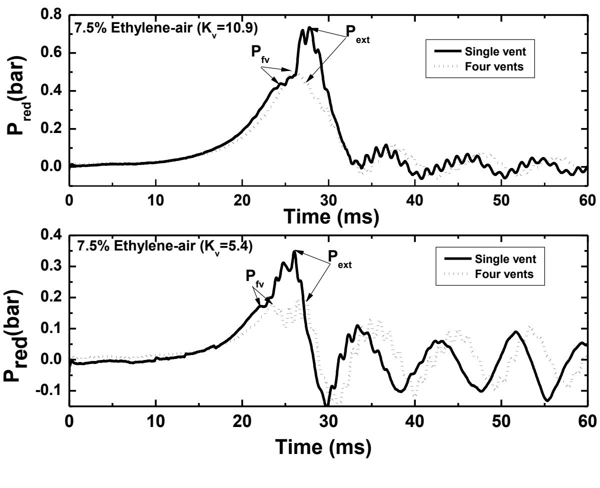

Fig. 6: Pressure-time records for single and four vents for 7.5% Ethylene-air Kv=10.9 and 5.4.

When the more reactive mixture of 7.5% Ethylene-air was used, the single vent was shown to significantly increase the peak pressure as compared to the 4 vents. This was due to increase in characteristic length scale for the single vent as compared with small scale for the multiple vents. This is in agreement earlier were the effect of length scale on explosion overpressure and flame speed when single vent was compared to 16 holes vent (Fakandu et al, 2013). Furthermore, the P_{ext} was shown to be the dominant peak overpressure irrespective of the vent area as a result of influence of reactivity. Figure 6 shows more 30% increment in flame speed when the single vent was compared with the 4 vents and this is significant for both K_v of 10.9 and 5.4. Since the single vent was considered as the worst case as mentioned above, it was necessary to consider the worst case in explosion vent design as recommended by the ATEX regulation (The European Parliament and the Council, 1994).

3.2 The effect of characteristic length scale on Turbulence downstream the vent

For less reactive mixtures of methane-air and propane-air, P_{fv} was shown to be the dominant overpressure for small vent areas or large K_v, while P_{ext} dominates for large vent areas (Harrison and Eyre, 1987, Fakandu et al, 2011). P_{fv} is controlled by the mass flow through the vent which also controls the level of turbulence downstream of the vent and the turbulent burning velocity is reduced if the number of vents increases, as the length scale is reduced and this reduces the external flame speed as shown in Fig. 7.

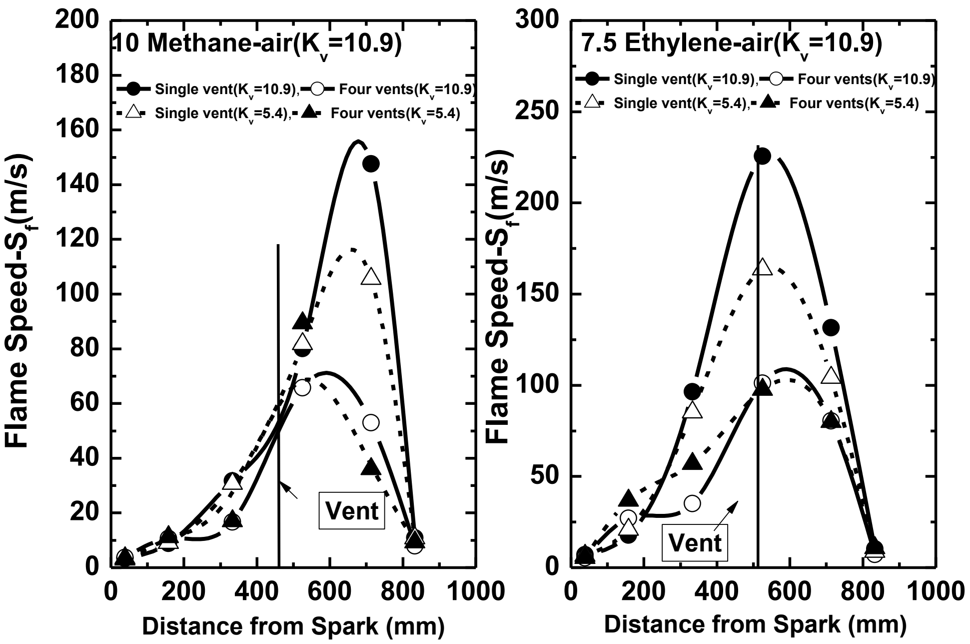

Figure 7: Flame speed vs distance from spark of single and four vents for Kv=10.9 and 5.4.

The result from the present work is in agreement with the work of Fakandu et al (2013), where the single vent orifice was compared to 16 hole vents with the same total equal length. The work also recommended the use of scaling effect as used by this approach of reducing the overpressure by reducing the scale of the vents to smaller vents of total equal size, when considering the influence of vessel volume for external vented explosions (Fakandu et al, 2013).

The degree or intensity of turbulence generally depends on various factors including the flow velocity and geometry of the confinement (Phylaktou and Andrews, 1994). Pressure loss across a single orifice is a characteristic of geometry and flow velocity of the unburnt gas ahead of the flame. This can be obtained theoretically by the pressure loss coefficient K from equation 2 (Phylaktou and Andrews, 1994).

$$K = \frac{\Delta P_T}{\frac{1}{2}\rho U^2} \qquad [2]$$

Where, ΔP_T is the pressure loss, ρ density of the gas, U is the gas flow velocity. The pressure loss coefficient ($K = \left(\frac{1}{C_d(1-BR)} - 1\right)^2$) can be used to predict the intensity of turbulence downstream which was shown to be dependent on K and the aspect ratio ($^t/_d = orifice\ thickness/orifice\ diameter$) as given in Eq 3 (Phylaktou and Andrews, 1994).

$$^{u'}/_U = 0.225\sqrt{K} \qquad (^t/_d < 0.6) \quad [3]$$

Where u' is the root-mean-square (rms) turbulence velocity and U is the mean velocity of flow. Since mean velocity of flow is a key factor in estimating the intensity of turbulence and the mean velocity shown to be 80% of the maximum flame speed upstream the obstacle (Phylaktou and Andrews, 1994), hence the turbulence downstream can be estimated using the flame speed obtained from the present work. The intensity of turbulence can also be obtained from the value Reynolds number based on length scale (l) by the turbulence scaling model using Eq.1 which is based on based on l.

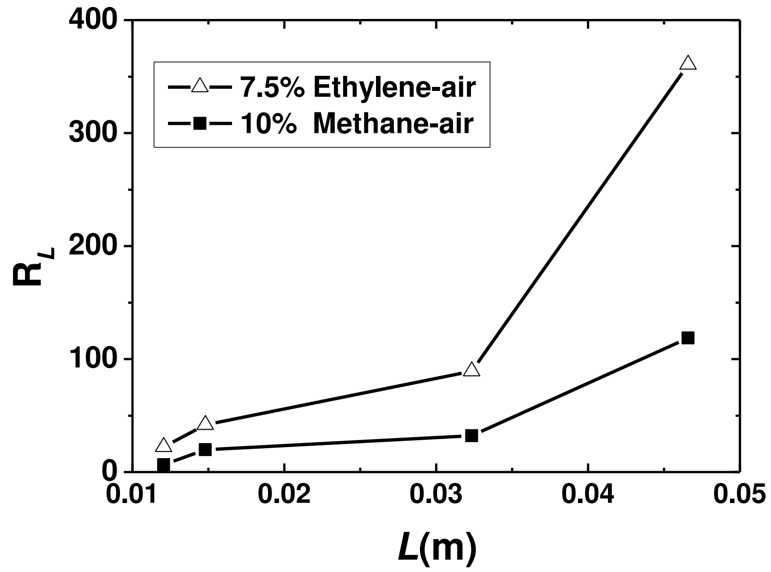

Figure 8: Obstacle length scale as a function of R_L for 10% methane-air and 7.5% ethylene-air.

Figure 8 shows the obstacle length scale as function of the Reynolds number $\mathbf{R_L}$, for the different gas mixtures. The turbulence level increased as the length scale increased. This is in agreement with the literature where the characteristic length scale was shown to influence the overpressure and flame speeds downstream the obstacle (Andrews et al, 1990, Phylaktou and Andrews, 1991, Phylaktou et al, 1994 and Na'inna et al, 2012). The use of length could be employed in the prediction of overpressure associated with external explosion and also predicting the flame speed downstream the vent.

4. Conclusions

The result from an experimental work on a 10L cylindrical vented vessel was carried out to investigate the influence of vent area distribution and non-central vent position on explosion overpressure and flame speeds. It was shown that non-central vents increased P_{fv} as compared to the centrally positioned vent. The non-central vent was shown to slow down the flame as it propagates towards the vent. This was caused by the flame diversion from the normal central propagation path as it moves to the vent position. The influence of characteristic obstacle scale was also demonstrated to have significant change on the external overpressure and flame speed downstream the vent when the length scale was reduced from single vent to four hole vents of total equal size. None of these factors are mentioned in the venting standards.

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