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Vent static burst pressure influences on explosion venting

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Abstract

The overpressure generated in a 10L cylindrical vented vessel with an L/D of 2.8 was investigated, with end ignition opposite the vent, as a function of the vent static burst pressure, P_{stat}, from 35 to 450mb. Three different K_v ($V^{2/3}/A_v$) of 3.6, 7.2 and 21.7 were investigated for 10% methane-air and 7.5% ethylene-air. It was shown that the dynamic burst pressure, P_{burst}, was higher than P_{stat} with a proportionality constant of 1.37. For 10% methane-air P_{burst} was the controlling peak pressure for K <~8. This was contrary to the assumption that P_{red} > P_{burst} in the literature and in EU and US standards. For higher K_v the overpressure due to flow through the vent, $P_{fv,}$ was the dominant overpressure and the static burst pressure was not additive to the external overpressure. Literature measurements of the influence of P_{stat} at low K_v was shown to support the present finding and it is recommended that the influence of P_{stat} in gas venting standards is revised.

Keywords: explosion venting, vent static burst pressure, turbulent combustion.

1. Introduction

The prediction of the maximum overpressure, P_{red}, required for the design of explosion vents (Bradley and Micheson, 1978a and 1978b, Razus and Krause, 2001) does not have a specific methodology for predicting the effect of the vent static burst pressure, $P_{stat.}$. The explosion venting theories also have empirical constants, often referred to as turbulence factors, to make the predictions be higher than experimental data with a vent static burst pressure. It is usually assumed that the effect of P_{stat} is included in these empirical turbulence factors. The US NFPA 68 (2013) gas vent design standards for P_{red} <0.5 bar has no procedure to account for the influence of P_{stat}, but does require for P_{red} <0.1 bar that P_{stat} > P_{red} – 0.024 bar and for P_{red} >0.1 bar that P_{stat} <0.75 P_{red}. The present work shows that the literature and the present results show that these limitation cannot be complied with as the vent burst pressure, P_{burst}, is always greater than P_{stat} by a 30 – 50% due to materials being stronger under dynamic load that static load, as discussed in detail in A.6.3.2 of NFPA 68 (2013). In the European standards for gas venting (2007) Bartknecht's approach (1993) to the influence of P_{stat} is followed as discussed in more detail later. This is valid for P_{stat} > 0.1 bar and has P_{red} linearly increasing as P_{stat} increases with this applying at all K_v and all mixture reactivities. For P_{stat} <0.1bar the European standard (2007) has no design recommendations, in spite of this being an important area of vent projection. Clearly these two vent design standards are incompatible.

Vent design correlations and design standards normally predict the maximum explosion overpressure (P_{red}) without giving considerations to the individual pressures peaks associated

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 at pressure P_{stat}	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

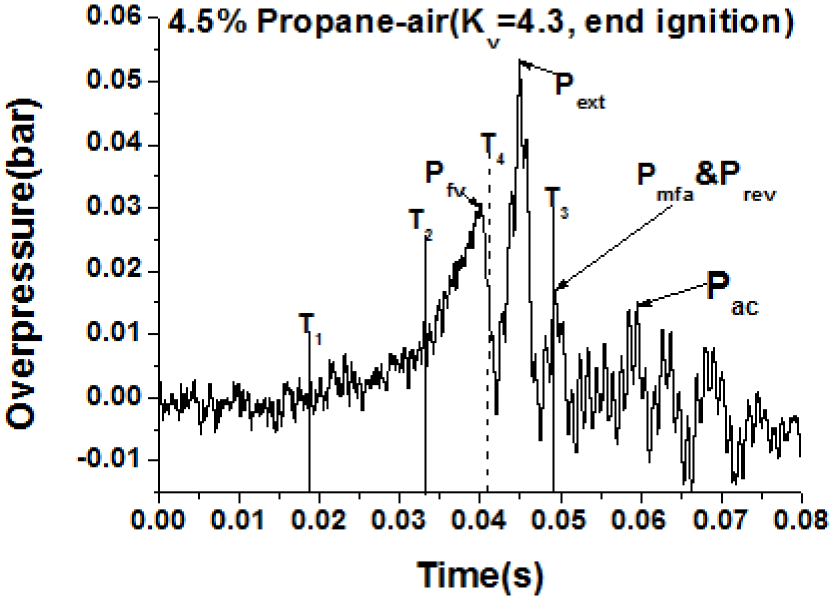

Figure 1: 4.5% vented explosion overpressure as a function of time from ignition for a 0.01 m^3 vessel with an L/D of 2.8 with K_v = 4.3 with end ignition.

with physical phenomena in explosion venting. The literature shows that there are different pressure peaks associated with different events in explosion venting (Runes, 1972; Marshall, 1977; Yao 1974; Cooper et al, 1986; Harris, 1983; Swift, 1989; Cates and Samuel, 1991; Molkov, 2001). These different events and the various nomenclatures that have been used for them are summarised in Table 1. These various peaks are shown as an example in Figure 1 for a vented 4.5% propane-air vented explosion with K_v = 4.3 in the present 0.01 m^3 explosion vessel with an L/D of 2.8 with end ignition opposite the vent. In this case there was an open vent, so no P_{burst} pressure occurred. The flame position as a function of time is shown by flame detectors $T_1 – T_4$. T_4 is at the vent plane and as the peak pressure is after this then it is definitively identified as due to the external explosion, P_{ext}. However, the other pressure peaks can be identified as shown; these can be the maximum pressure for other venting conditions.

Most theoretical models for the prediction of the reduced pressure assume that the flow through the vent dominates the overpressure, P_{fv} (Bradley and Mitcheson, 1978a; Molkov, 2001). The laminar venting theory assumes that the maximum overpressure is the vent orifice flow pressure loss at the maximum unburned gas vent mass flow rate (Andrews and Phylaktou, 2010). This theory predicts that the maximum reduced pressure is achieved when the flame touches the wall of the vessel. Fakandu et al. (2011) showed that this was not the case for the cylindrical vessel used for this work, as the flame touches the wall of the vessel well after the flame has left the vent as shown in Figure 1, at time T_3. Also, the pressure-time profiles were shown to be different depending on the vent coefficient, K_v, so that which event controlled the peak overpressure varied with K_v (Fakandu et al., 2011).

When a vent cover is used, the magnitude of the vent opening pressure depends on the type of vent material used and the vent area. The pressure associated with the bursting of the vent material is referred to as the dynamic pressure (P_{burst}) in this work, while P_{stat} is the static burst pressure from tests where compressed air pressure is slowly increased until the vent cover bursts (NFPA 68, 2013). The difference is because materials are stronger under dynamic short pressure pulse loading than they are under slow static pressure loading, as detailed in NFPA 68 A.6.3.2 (2013). In some vent design procedures (Bartknecht, 1993), the ratio of P_{burst}/P_{stat} is ignored and the influence of P_{stat} is always to increase $P_{red.}$ In spite of its importance there is little data on the influence of P_{stat} over a range of K_v and for different mixture reactivities. This work aimed to provide more data on the influence of P_{stat} with better instrumentation of the venting process, so that the physics of the action of P_{stat} could be determined.

2. Vent Design Procedures for the Influence of P_{stat}

Only the European vent design procedures (2007) have a procedure for accounting for the influence of P_{stat} on P_{red} and this used the correlation of Bartknecht (1993) given in Eq. 1, who investigated P_{stat} in a 1 m^3 vessel. Bartknecht's (1993) results are shown in Figure 2. The lowest P_{stat} investigated was 0.1 bar and often there are requirement to use lower values than this and these are explored in the present work. Figure 2a for 10% methane-air shows that the influence of P_{stat} was strongly dependent on K_v and there was only a linear relationship between P_{red} and P_{stat} at the low K_v of 3.3. In Fig. 2b the P_{stat} effect is given for a K_v of 3.3 for different mixture reactivities. However, there were no experiments at different mixture reactivity apart from at P_{stat} of 0.1 bar and the data in Fig. 2b was an assumption that the P_{stat} trend for methane would be the same for the other mixture reactivities. This assumption has been carried through into the EU gas venting standards, without informing the user of the standard that the assumption has not been verified. Also, the linear relationship between P_{red} and P_{stat} that Fig. 2a shows, only occurs at the low K_v of 3.3 but is applied in the EU standard

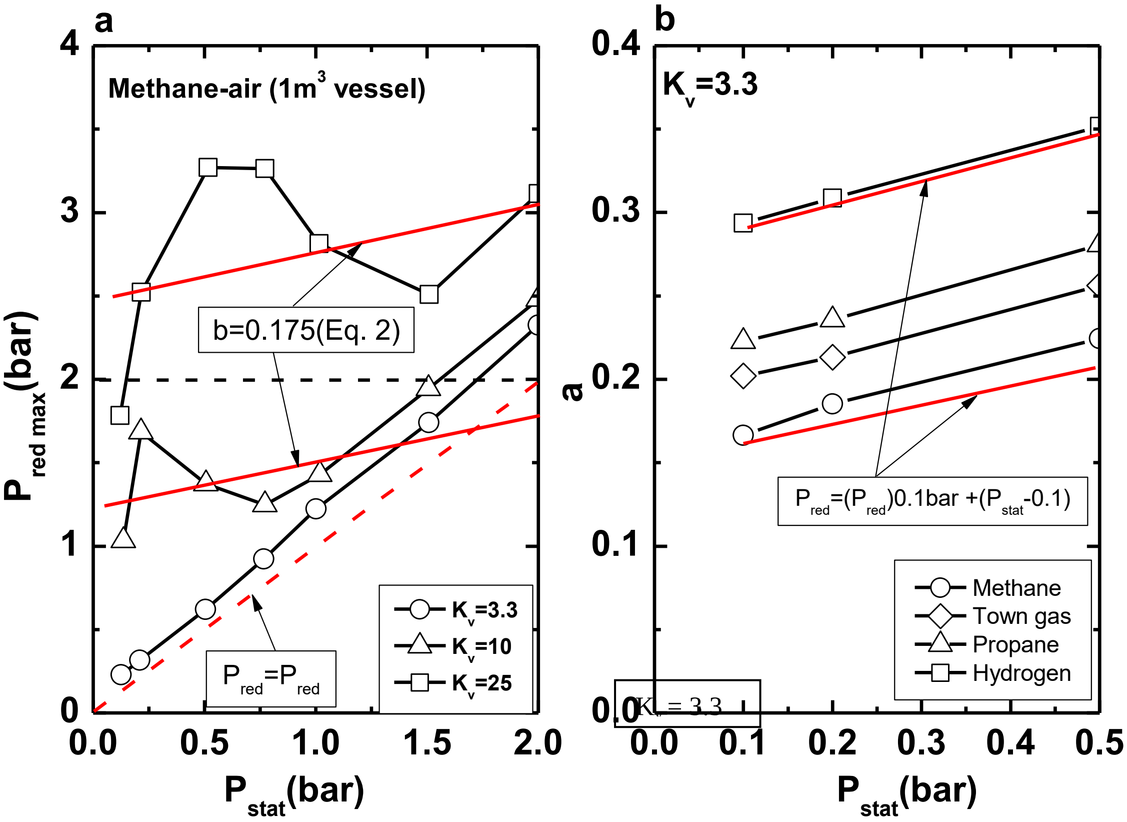

Figure 2: P_{red} as a function of P_{stat} for a 1 m^3 vessel for 10% methane-air.

$$\frac{1}{K_v} = \left[\frac{0.1265 log_{10} K_G{}^{-0.0567}}{P_{red}{}^{0.5817}} + \frac{0.175(P_{stat} - 0.1)}{P_{red}{}^{0.5717}} \right] \qquad (1)$$

for all K_v, which is invalid but there is no mention of this in the EU standard. Eq. 1 is stated by Bartknecht to be valid up to a P_{red} of 2 barg and P_{stat} of 0.5 bar, with no limit on K_v. Comparison of Eq. 1 for a K_v of 10 in Fig. 1 shows that it is valid only up to a P_{stat} of 0.2 bar and not applicable for higher values of K_v, due to the P_{red} limit of 2 Equation 1 may be simplified to Eq. 2 using two significant figures on the constant, as they are not known to the precision implied in Eq. 1.

$$P_{red}{}^{0.57}/K_v = a + b\,(P_{stat} - 0.1) \qquad (2)$$

The constant 'a' was evaluated by Bartknecht in a 10 m^3 cubic vented vessel with a P_{stat} of 0.1bar, for methane and propane as 0.164 and 0.200 respectively for a range of K_v from 2.2 to 10. For hydrogen a 1 m^3 vessel was used with 'a' evaluated as 0.290, although this value cannot be correct as it implies hydrogen is only 45% more reactive than propane, whereas the ratio of burning velocities is at least 7 (Fakandu et al., 2012). The use of a different volume for the vented vessel for hydrogen was the problem. The reactivity term in Eq. 1 is based on a correlation of these values for 'a' with Bartknecht's values for the mixture reactivity K_G measured in a 5L sphere, 55 bar m/s for methane, 100 for propane and 550 for hydrogen.

These problems with Bartknecht's correlation of the P_{stat} and his limited data set, has led to the US venting standards abandoning this approach (NFPA 68, 2013), although it is continued with in the European gas venting standard. In NFPA 68 (2013) there is no procedure to account for the influence of P_{stat} for P_{red} <0.5 bar. For 0.1 bar< P_{stat} < 0,5 bar NFPA 68 (2013) requires that P_{stat}<0.75 P_{red} or P_{red}/P_{stat} > 1.33, unfortunately this ratio is exceed by the dynamic burst pressure effect discussed in NFPA 68 (2013) in s. A.6.3.2. For 0<P_{stat}<0.1 bar NFPA 68 (2013) requires that P_{stat}< (P_{red} – 0.024bar). It will be shown in the present work that these design rules are difficult if not impossible to comply with for low K_v with relatively high P_{stat}, as P_{stat} dominates P_{red} and P_{burst} is the dynamic burst pressure which is > P_{red} and this is not allowed in NFPA 68. This shows that this new NFPA 68 approach to the P_{stat} effect on vent design present design is also not compatible with experimental data. There is clearly a need for further research and more experimental data on the influence of P_{stat} in vent design and this work was undertaken to try to provide more data with accompanying interpretation of the physics involved

3. Review of Investigations into the Impact of P_{stat} on P_{red}

Cubbage and Simmonds (1955) showed in Eq. 3 that the P_{burst} overpressure peak was linearly dependent on the inertia of the vent cover.

$$P_{burst} = cw + d \quad [3]$$

where "c" and "d" are constants and "w" is the weight of the material divided by the area. If w is in kg/m^2 then this can be converted to a static pressure as wAg Pa, where A is the area of the vent cover. Eq. 3 shows that the P_{stat} pressure was additive to the term 'd' which was related to K_v and U_L. Rasbash (1969) determined Eq. 4 for the pressure generated in cubic vented explosions using data from his studies of propane-air in small vessel. Eq. 4 implies that the influence of K_v is additive to that of P_{stat}. Another way of looking at this type of correlation is that for a free venting with P_{stat} = 0 the K_v term is that measured for free venting and P_{stat} is simply an additive pressure to that for free venting. The present results will be shown not to support such a P_{stat} effect.

$$P_{red} = 1.5\ P_{stat} + 0.5\ K_v. \quad [4]$$

Cubbage and Marshall (1972) also correlated the pressure developed in a vented explosion and took the P_{stat} term as additive to the term taking into account the influence of K_v and U_L. They had no multiplier of P_{stat}, similar to that in Eq. 4, and essentially assume that the dynamic burst pressure was the same as the static burst pressure.

The influence of P_{stat} by various investigators is shown in Fig. 3 for K_v of 1.72 and 3 and in Figure 4 for K_v of 4 and 6. On each graph the line for P_{red} = P_{stat} is shown in bold. For most of the data for K_v <4 P_{red} is close to P_{stat}, with some results below P_{stat}, probably due to an error in the measurement of P_{stat}. For K_v > 4 there is evidence of P_{red} being higher than P_{stat}. The present results will show agreement with these results, that P_{stat} determines the overpressure up to a critical value of K_v when there is an additive term that is a function of K_v and U_L.

4. Experiment Equipment

A small cylindrical vessel was used, 10 litres volume (0.00948m^3, L=0.460m, D=0.162m and L/D= 2.8), as shown in Fig.5. Bartknecht (1993) recommended that Eq. 1 was valid up to an L/D of 2. The NFPA 68 (2013) gas venting procedures for compact vessels are valid up to an L/D of 2.5. The EU vent design guidance for explosion venting of compact vessels defines the compact vessel limit as L/D<3. The present L/D of 2.8 is thus close to the limiting (worst case) conditions for compact vessels in the USA and European gas venting standards. The test vessel was designed to withstand detonation and was pressure rated at 30 bars. It had thick walls and end flanges and would have none of the vessel acoustic interactions that occur in

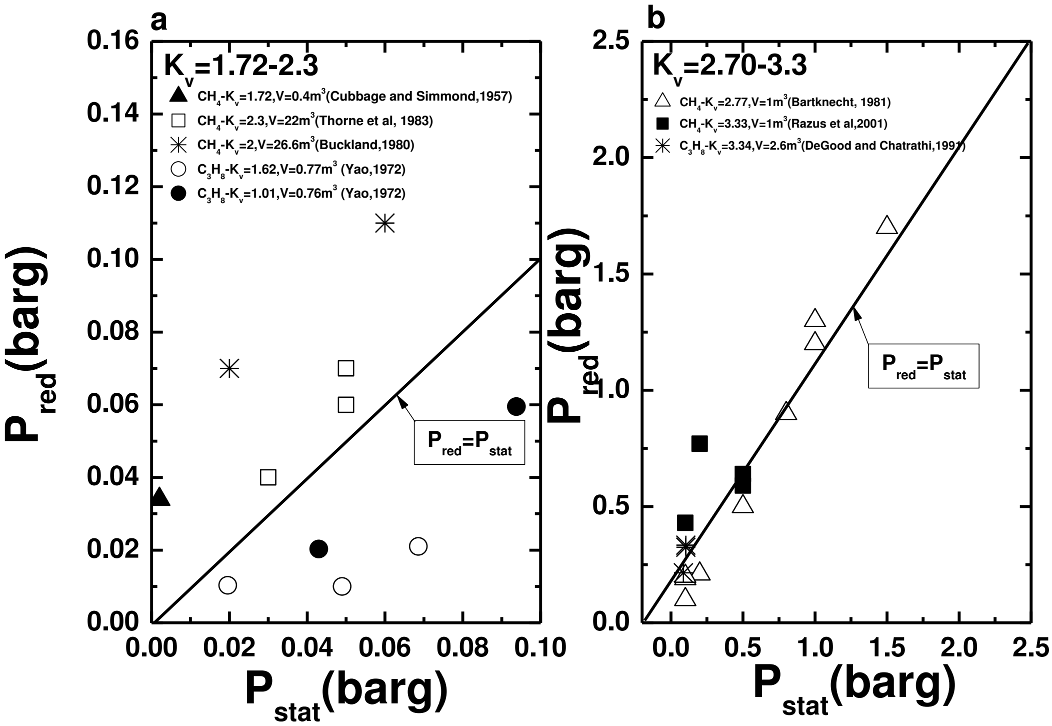

Figure 3: P_{stat} verses P_{red} for methane-air and Propane-air (a) K_v=1.72-2.3 (b) K_v=2.7-3.3.

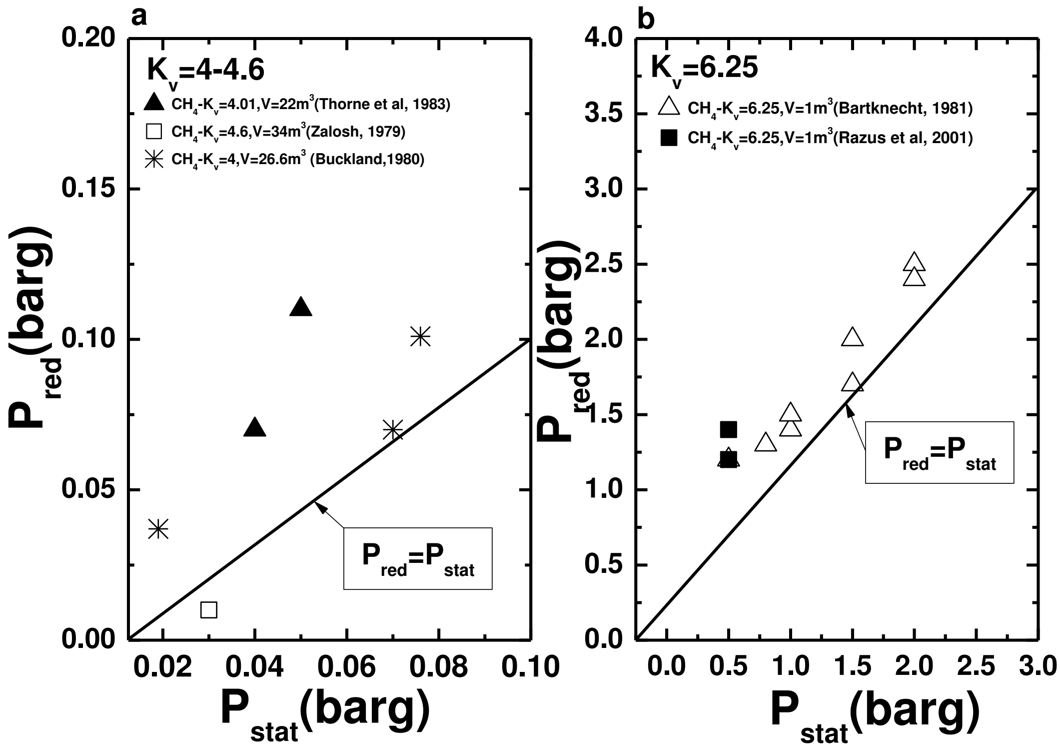

Figure 4: P_{stat} verses P_{red} for 10% methane-air (a) K_v=4-4.6 (b)K_v=6.25.

thin walled vessels and no high frequency pressure fluctuations, P_{ac}, of the type discussed by Cooper et al. (1986) and Bauwens et al. (2010) were detected.

The test vessel was deliberately of small volume to ensure that laminar flame propagation with no flame self-acceleration would occur. This was because there is no additional volume. effect in the European venting standards other than K_v. In the US NFPA 68 (2013) standards

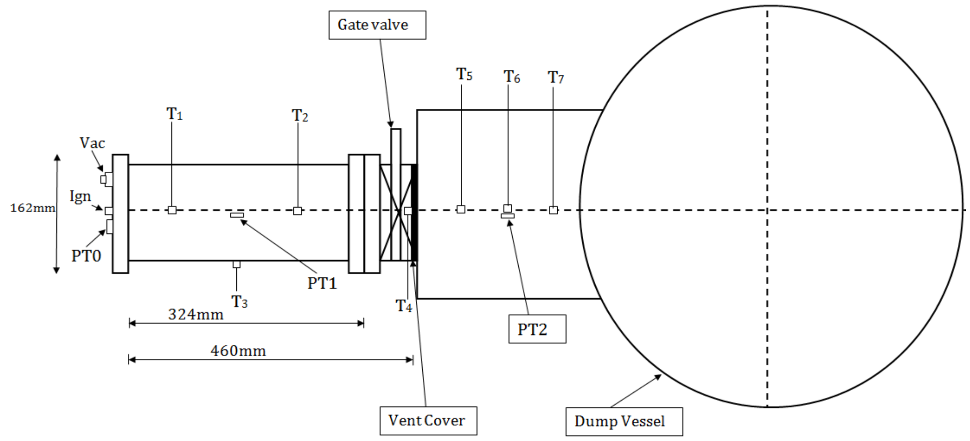

Figure 5: The 10 litre venting vessel and connecting vessels.

there is no specific volume effect in addition to K_v through the parameter λ that is a multiple of the vent area. This parameter has several components and one of these involves the Re of the vent flow. As this increases with the size of the vent, which increases as the volume increases for the same K_v then there is indirectly an additional volume effect. It may be shown that the λ term in NFPA 68 (2013) for the vent Re effect on P_{ext} is for constant K_v and propane-air is a volume effect of $V^{0.033}$. If the present results were scaled up from 0.01 m^3 to 100 m^3 then P_{red} would increase by a factor of 1.39. This correction term assumes that it is the external explosion that controls P_{red}.

The test vessel was connected to a 0.5m diameter cylindrical vessel which was connected to a 50m^3 dump vessel to safely capture the vented flames. The 0.5m diameter vessel between the vented vessel and the dump vessel was used to mount three thermocouples on the centreline of the discharge jet so that the vented jet flame velocity could be determined as a function of distance from the vent. This vessel was sufficiently larger than the vented vessel to give free venting conditions in the near vent area.

A vacuum gate valve was located downstream of the vent and this enabled, when closed, the mixture of gas and air to be accurately made by partial pressure. The gate valve separates the test vessel from the 0.5m dia. vessel and only opens prior to ignition to allow the required

mixture to be ignited before the explosion occurs. The vent cover was mounted downstream of the gate valve and different sheet material were used with different burst pressures. A 16 J ignition energy was used and the spark plug was located at the centreline of the end flange opposite the vent. End ignition was shown by Kasmani et al. (2010a) and Fakandu et al. (2014) to give significantly higher overpressures in vented explosions compared with central ignition.

The dynamic vent burst pressure (P_{burst}) was determined by slowly increasing the pressure of compressed air upstream of the vent until the pressure transducer, P0 for the different vent sheet materials which were repeated 3 times to achieve good repeatability. Furthermore, the static burst pressures (P_{stat}) for all the materials were determined using compressed air as required by the vent design standard (NFPA 68, 2013).

The flame travel time was recorded by mineral insulated, exposed junction type-K thermocouples, arranged axially at the centreline of both the vented vessel and the 0.5m dia. discharge vessel, as shown in Fig. 5. Thermocouples T_1, T_2 and T_4 were located on the centreline of the main test vessel with T_4 at the vent plane to determine when the flame exited the vent. Thermocouples T_5, T_6 and T_7 were mounted on the centreline of the 0.5m dia. connecting vessel. The time of flame arrival was detected from the thermocouples start of temperature rise 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, which was taken to be the time of maximum flame area inside 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. The time of arrival at T_3 could be taken as the maximum flame area time and this could then identify whether this corresponded with a pressure peak, P_{mfa}, as identified as an important pressure peak in the work of Cooper et al. (1986) and Bauwens et al. (2010).

Two piezo electric pressures transducers were used with one at the end flange (PT0) opposite the vent and mid-way the vessel length (PT1) respectively as shown in Fig. 5. In low flame speed explosions these pressure transducers had identical pressure time characteristics and only pressure records for PT0 are reported in this work. For hydrogen explosions there were dynamic flame events that caused these two pressure transducers to record different pressure time records. 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 occurred.

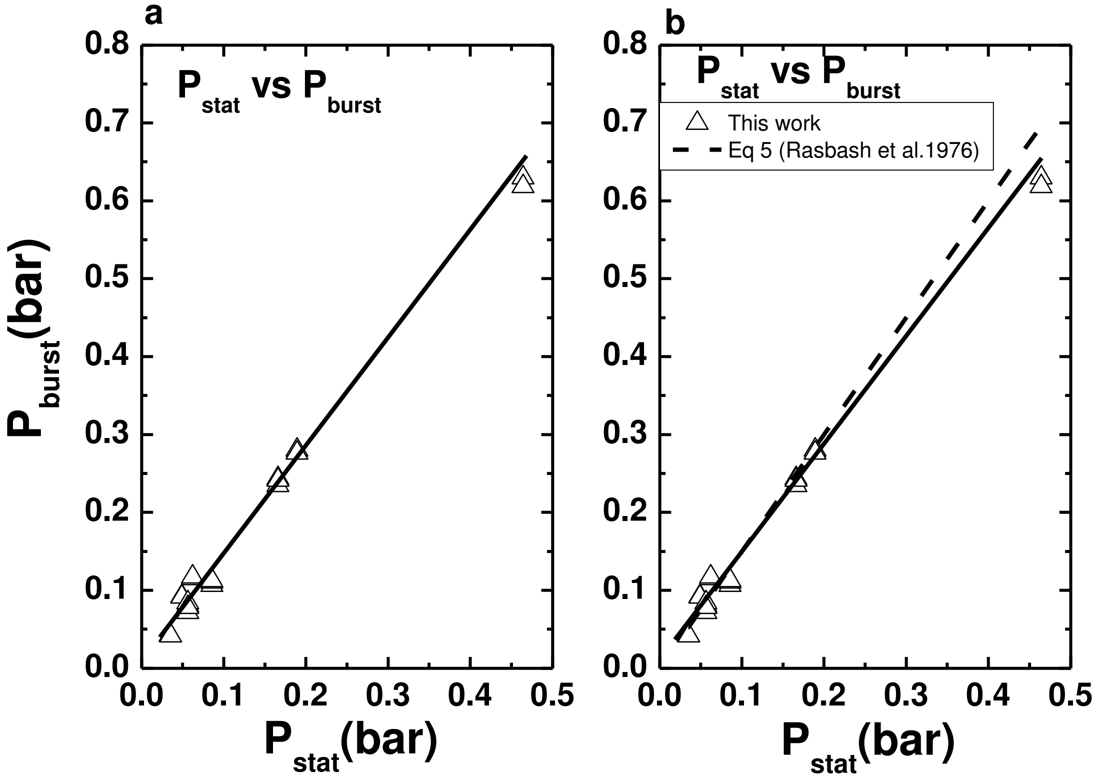

Figure 6: Relationship between P_{burst} and P_{stat} for Kv=1-21.7.

5. Results and discussion

5.1 Relationship between P_{stat} and P_{burst}

Fig. 6a compares the measured P_{burst} as a function of P_{stat}. The results show close agreement with the P_{burst}/P_{stat} constant of 1.5 in Eq. 4, as shown in Fig. 6b. The line of best fit to the present results is given in Eq. 5.

$$P_{burst} = 1.37\ P_{stat} \qquad [5]$$

Most empirical correlations, as in Eqs. 1-4, above assume that the first pressure peak in the pressure time record must be less than the maximum reduced pressure obtained during explosion venting (Cubbage and Marshall 1972, Rasbash, 1969, Rasbash et al. 1976). In

NFPA 68 P_{red} (either P_{fv} or P_{ext}) has to be always greater than P_{burst}, which is impossible for practical vent covers at low K_v.

5.2 Influence of P_{stat} on P_{red} at low, medium and high K_v

The results in Fig. 7a for P_{stat} = 0.035 bar and K_v of 3.6 show that for low K_v, P_{red} is determined by P_{stat} for 10% methane-air. For the free vent Fig. 7b shows that P_{red} was controlled by the external explosion at 0.05 bar and it was identified as an external explosions because the peak pressure occurred after the flame had passed thermocouple T_4 at the vent plane. With a P_{stat} of 0.035 bar Fig. 7a shows that the P_{burst} was 0.043 bar and the external overpressure was reduced to 0.04 bar, so that P_{burst} was the controlling factor in $P_{red.}$ Fig. 7b shows that for free venting the pressure due to the flow of unburned gas through the vent was 20mb. With the 35mb P_{stat} the flame took longer to reach the vent compared with free venting. This was because there was no flow towards the vent when it was closed and hence the initial flame spread was slower than for free venting. When the vent burst due to the closed vessel pressure rise, there was then an outflow of unburned gas through the vent and the pressure initially falls. After the vent burst the fall in pressure was so fast that it created a vacuum and this induced a reverse flow of unburned gas back into the vessel. The flame propagation inside the vessel was continuing and the flame expansion pushed unburned gas out of the vent.

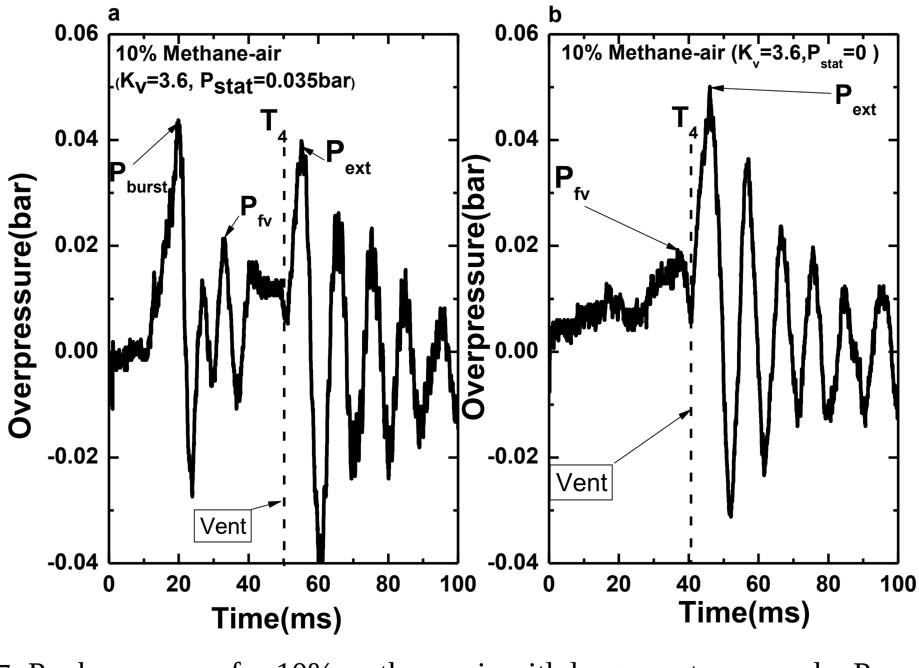

Figure 7: Peak pressures for 10% methane-air with large vent area and a P_{stat} of 0.035bar.

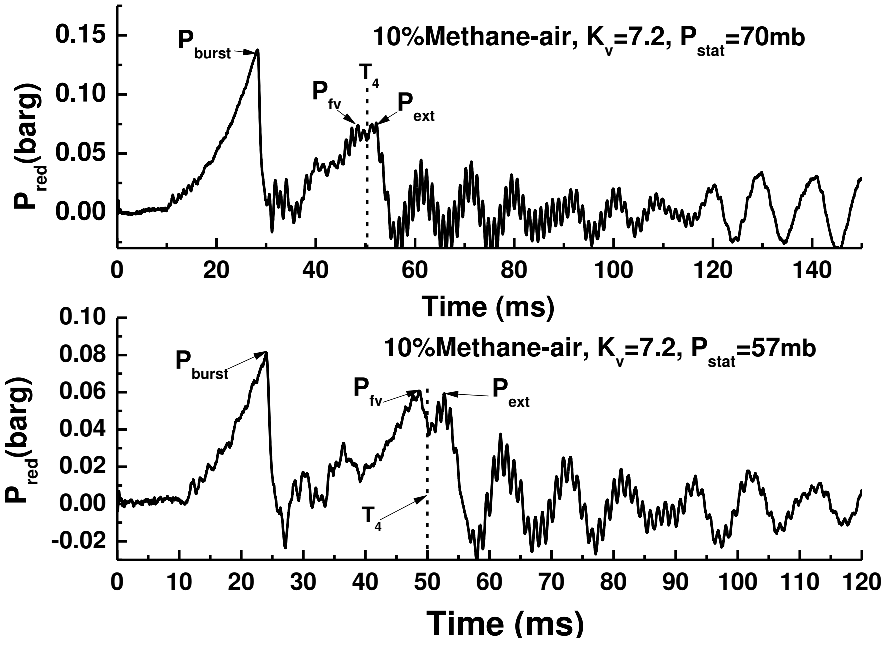

Figure 8: Peak pressures for 10% methane-air with (a) P_{stat} = 70mb (a) P_{stat} = 57mb.

The pressure loss on the vent bursting sets off a pressure and flow oscillation and this considerably slowed the progress of the flame to the vent. The P_{fv} peak occurred on an oscillation before the flame reached the vent and was lower than for free venting. This resulted in lower external jet turbulence and a lower external overpressure. The net result was that P_{red} was lower for the vent with the bursting cover than for a free vent, as shown in Fig. 7

The PT0 pressure-time record for 10% methane-air for K_v=7.2 and P_{stat}=70mbar is shown in Figure 8a and for a P_{stat} of 57 mb in Figure 8b. The results in Figure 8b are directly compared with those for free venting in Fig. 9. These results all shows that for P_{stat} of 57 and 70 mb at K_v of 7.2 P_{red} is still controlled by P_{burst}, as it was at K_v = 3.6 with P_{stat} = 35 mb in Fig. 7. Figure 8a shows that P_{burst} is 135mb and occurs 28ms after ignition, well before the flame emerges from the vent at 50ms. The P_{fv} and P_{ext} pressure peaks are very similar at 75mb, but occur just before and just after the flame emerges from the vent. Similar events occur in Figure 8b with 57mb P_{stat} where the vent bursts at 24ms with P_{burst} of 80mb. The flame arrives at the vent at 50 ms with the P_{fv} and P_{ext} pressure peaks either side of this time with P_{fv} slightly higher than P_{ext} at 61mb compared with 59mb. For free venting the flame arrives at the vent at 52ms, only 2ms later than with the vent covers. The peak overpressure is P_{fv} at 61mb the same as for the P_{stat} = 57mb P_{fv}. With a vent cover the initial flame propagation inside the closed vessel is slower than with free venting. Once the vent bursts this accelerates the flame and creates more turbulence in the external jet. The net result is that the time to reach the vent is very similar for free venting and with a vent cover. Also Figure 9 shows that once the vent bursts the subsequent events are very similar to those for free venting. Free venting overpressures increase with K_v (Fakandu et al., 2011, 2012, 2013; Bartknecht, 1993) and so there will be a value of K_v at which the P_{burst} is not the dominant overpressure. This is illustrated in this work at a K_v of 21.7 in Figure 10. For a free venting Figure 10 shows that P_{red} was 0.35 bar and was due to the flow through the vent P_{fv}, although the pressure peak occurred at the same time as the flame reached the vent. With a P_{stat} of 0.086 bar the P_{burst} was 0.1 bar and occurred after 24 ms, but P_{red} was much higher at 0.39 bar which is only 0.04 bar above that for free venting. Both pressure peaks occurred at a similar time of 50ms coincident with the flame passing through the vent.

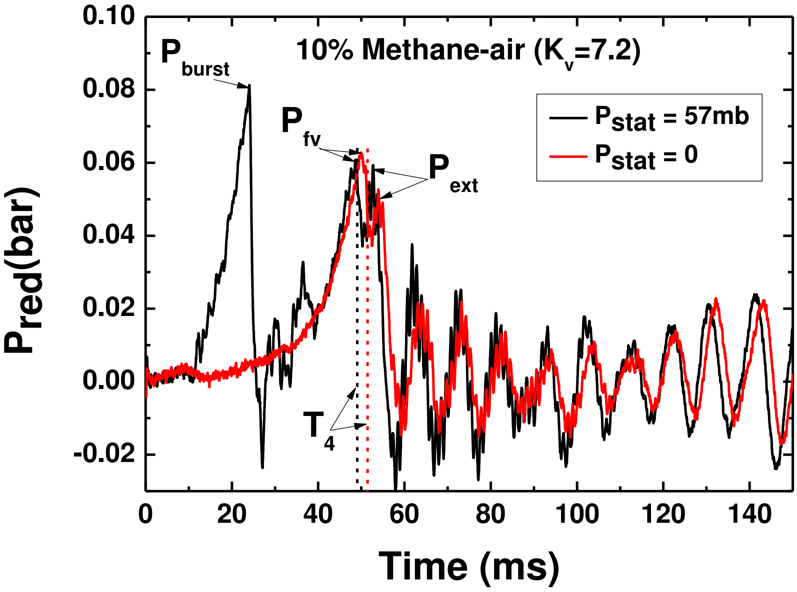

Figure 9: Comparison of the pressure time records for 10% methane-air for $K_v = 7.2$ for free venting and for P_{stat} = 57mb.

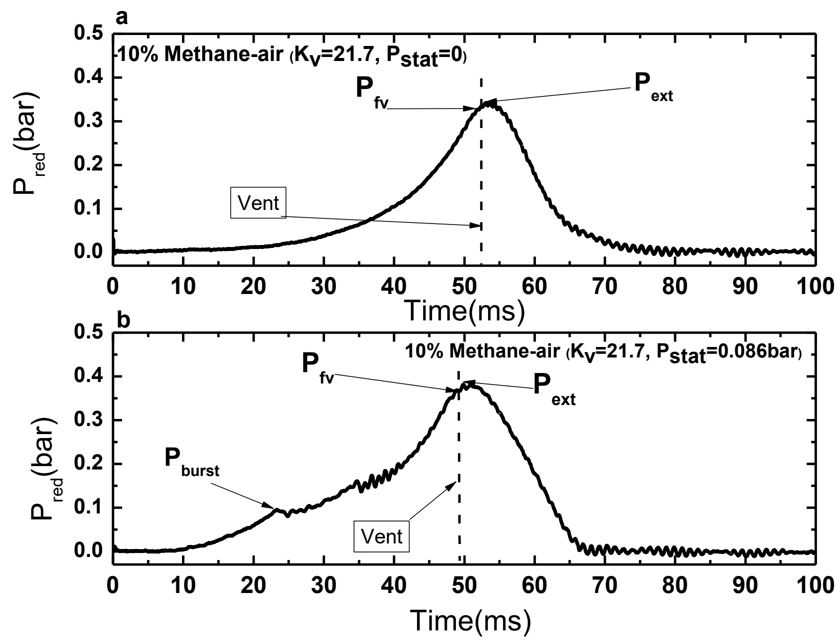

Figure 10: Pressure v. time record for 10% methane-air with a $K_v = 21.7$

(a) free venting and (b) P_{stat}= 86mb.

5.3 P_{red} as a function of P_{stat}

Figures 11 and 12 show P_{red} as a function of P_{stat} for K_v of 3.6, 7.2 and 21.7, with Fig. 11 concentrating on the present data for P_{stat} < 300mb and Fig. 12 comparing the work with the results of other workers for similar K_v. The main result from Fig. 11 is that P_{red} was controlled by P_{stat} for a K_v of 7.2 or lower, but that at a K_v of 21.7 the flow through the vent controlled P_{red} and the P_{stat} effect was lower, but still significant. Fig. 12 concentrates on the data for P_{stat} < 300mb. This shows, as discussed above, that for K_v of 3.6 the initial influence of P_{stat} up to 50 mb was to reduce P_{red} below that of free venting and at P_{stat} of about 100mb

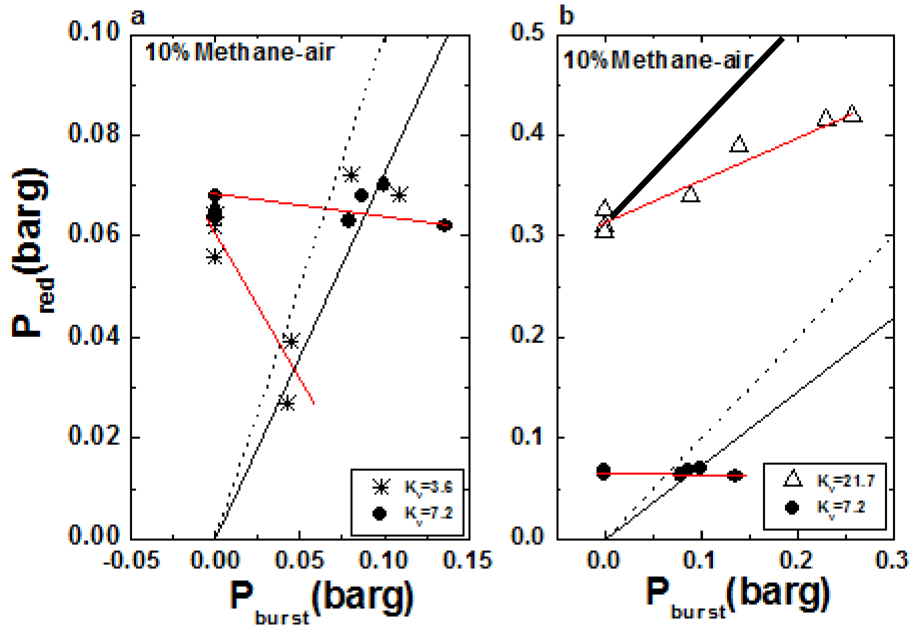

Figure 11: Peak pressures as a function of P_{burst} for K_v = 3.6, 7.2 and 21.7 for low P_{burst}

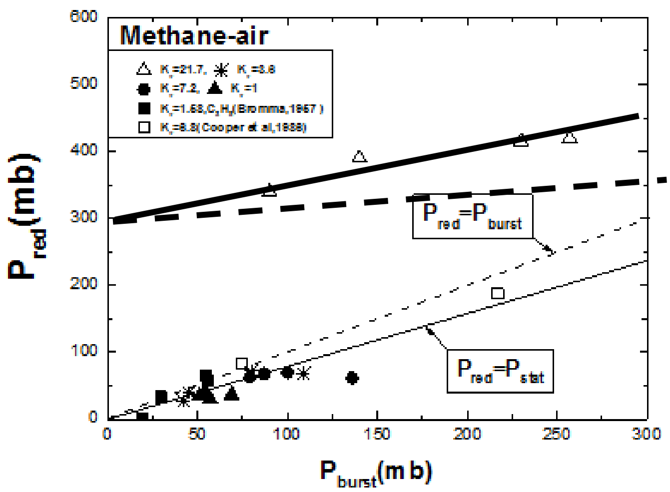

Figure 12: Peak pressures with P_{burst} for different K_vs. The dashed line is the 0.175 P_{stat} constant in Eq. 1

P_{red} was close to that of free venting. This effect was due to the reduced flame speed upstream of the vent. At a K_v of 7.2 this effect was still present, but the reduction was small and the net effect was to have very little influence of P_{stat} on P_{red} up to P_{stat} of 150mb, the limit of the values tested at this K_v.

The present results are compared in Figure 12 with others in the literature as P_{red} as a function of P_{stat} for a range of K_v. Figure 12 shows a linear relationship between P_{stat} and P_{red} for high K_v=21.7, which is below that for simple additive effect of P_{stat} similar to the result of Bartknecht (1981). The evidence of the present work and of the literature on the influence of P_{stat} is that for Kv < ~8 P_{burst} dominates P_{red} and there is no effect of K_v. For K_v > ~8 P_{red} is dominated by P_{fv}. Further work is needed to define the critical K_v more precisely and to investigate the influence of the mixture reactivity. Figure 12 shows that the data of Copper et al. (1987) for a K_v of 8.8 agrees with the present results that P_{red} is determined by P_{stat}. The results of Bromma (1967) also agree with the present work that P_{stat} determines P_{red} at low K_v.

Conclusions

1. Current vent design guidance in Europe is incompatible with the experimental data of Bartknecht and of the present work for low K_v. Bartknect's data and the present work show that for K_v < ~8 P_{stat} determines P_{red}. The US NFPA 68 (2013) guidance is impossible to comply with as P_{red} is determined by P_{stat} and their requirement that P_{red} is always greater than P_{stat} cannot occur at low $K_{v.}$ The data of Cooper et al. (1987) and Bromma (1967) in larger volume vented vessels support this conclusion.
2. The critical K_v is >.9 and <21.7 and it is recommend that at present K_v = 9 should be used as the critical $K_{v,}$ but more work is required to determine this more precisely and to investigate the influence of mixture reactivity and vessel size. Bartknecht's data for K_v = 10 shows that this is beyond the critical condition as P_{red} is significantly higher than P_{stat}., but with a non-linear dependence on P_{stat}.
3. For K_v greater than the critical value P_{fv} controls P_{red} and the influenced of P_{stat} is reduced and can be predicted from free venting correlations with an additive term for the P_{stat} effect that has a constant greater than that in Eq. 1 at 0.5.

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