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Vent Burst Pressure Effects on Vented Gas Explosion Reduced Pressure

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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 450 mb. 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 on 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.*

1. Introduction

The prediction of the reduced explosion pressure, 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 pressure, P_{stat}. Explosion venting theories also have empirical constants, often referred to as turbulence factors, accounting for vent static pressure effects for theories that apply to free venting. 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 and the literature shows that these limitation cannot be complied with, as the vent burst pressure, P_{burst}, is always greater than P_{stat} by 30 – 50% due to materials being stronger under dynamic load than 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 protection in some applications, such as gas oven venting (Cubbage and Simmonds, 1955; Cubbage and

Marshall, 1972; Cooper et al., 1986). Clearly the two vent design standards, EN14797 and NFPA 68, are incompatible which is undesirable from a safety standpoint.

2. Experimental 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 Figure 1. Bartknecht (1993) recommended that his vent design procedure 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<2. 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 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, who both used relatively thin walled vented vessels.

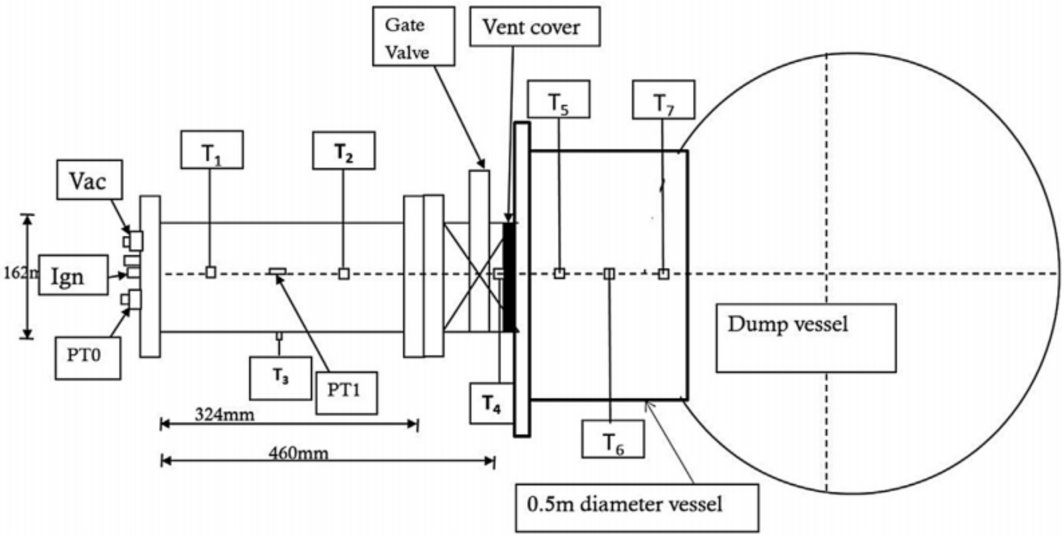

Figure 1: Schematic diagram of 10 litre venting vessel and connecting vessels.

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 on 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 static vent burst pressure (P_{stat}) was determined using the procedures in NFPS 68 (2013). The pressure of compressed air was slowly increased upstream of the vent until the pressure transducer, P0, showed a sudden reduction in pressure, indicating that the vent had burst. This procedure was carried out for the different vent sheet materials, which were repeated 3 times and demonstrated good repeatability. The dynamic burst pressure, P_{burst}, of the vent was determined from the pressure records after each explosion. There was a sudden reduction in the explosion overpressure when the vent burst and the value of the overpressure when this occurred was P_{burst}. In this work $P_{burst} > P_{stat}$, for the reasons given in NFPA 68 (2013) A6.3.2, and their relationship is discussed later.

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 Figure 1. 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 piezo-resistive pressure transducers were used with one at the end flange (PT0) opposite the vent and one mid-way along the vessel length (PT1), as shown in Fig. 1. 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 Fakandu et al. (2012) showed that 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 its occurrence. This was of great assistance in determining when the external explosion occurred.

3. The Influence of Vessel Volume on P_{red}

A very small vented vessel volume, V, was used in this work as in the European vent design guides there is no additional effect of vessel volume other than through $K_v = V^{2/3}/A_v$. In NFPA 68 (2003) the vessel surface area, A_s, is used instead of $V^{2/3}$. However, as A_s is linearly related to $V^{2/3}$ (Andrews and Phylaktou, 2010) with the constant dependent on the vessel shape (4.84 for a sphere, 6 for a cube, 5.81 for a cylinder with L/D=2) the two design equations can be expressed in the same format. K_v is the porosity of the vessel wall and is the cross sectional area of a cube of equivalent volume divided by the vent area. There is no other volume term in vent design correlations apart from that indirectly in the 2013 edition of

NFPA 68. However, as reviewed later, there is some evidence of higher overpressures in larger vessels which is not accounted for in the European guidance on gaseous explosion venting design procedures. One of the causes of overpressures being larger at higher volumes is the self-acceleration of spherical flames above a critical diameter where there is the onset of cellular flames. The acceleration continuous as the vessel dimensions and hence volume get bigger. However, as the volume of a vessel with linear size D scales with D^3 there has to be very large volume changes to determine this effect. In Bartknecht's (1993) work the volume range investigated was 1 – 60 m^3 and a volume change be at least a factor of 1000 is needed to achieve a linear scale change of 10. By using a very small $0.01 m^3$ vessel in the present work and comparing with experiments in volume >10 m^3 gives a factor of over 1000 change in volume. If the volume effect was very significant then there would be very poor agreement with the overpressures using the 0.01 m^3 vessel and for vessels >10 m^3 and it is shown later that this is not the case and the differences are relatively small but significant.

The experimental vented explosion vessel was deliberately chosen to be of small volume to ensure that laminar flame propagation with no flame self-acceleration would occur. In the US NFPA 68 (2013) standards there is no specific volume effect in addition to A_s/A_v which is a linear function of K_v. It may be shown that NFPA 68 (2013) has Equation 1 as the vent design equation.

$$1/K_v = C/P_{red}^{0.5} \qquad (1)$$

where C is a constant that is proportional to S_u, the laminar burning velocity, to the shape factor that relates A_s to $V^{2/3}$ and to a correction term λ. The parameter λ is introduced that is a multiple of the vent area and does indirectly have an additional volume term. This parameter λ has four components:

1. A flame self acceleration term φ_1
2. A vent flow term φ_2 which accounts for the turbulence in the external explosion
3. An obstacle turbulence generation term
4. A vessel L/D term for L/D 2.5 – 5.

The value of λ is a direct multiple of the vent area and is equal to the product of the above four terms. The last two terms will not be discussed here as they do not have an additional volume effect. The first two terms both involve a Re parameter, where the dimension in the Re is related to the vessel dimension and hence to the volume for the same P_{red}. However, NFPA 68 (2013) does not mention that these two terms lead to a volume effect on the design process. The self acceleration term φ_1 is 1 if the vessel is too small to have a transition to a cellular flame and this applied in the present work. For larger vessels φ_1 is given by Equation 2.

$$\varphi_1 = [Re_f/4000]^{0.39} \qquad (2)$$

where $Re_f = \rho_u S_u D_{he}/\mu_u$ and 4000 is the critical Re_f for the onset of cellular flames.

The hydraulic diameter D_{he} of the vessel in Eq. 2 is related to the vessel volume and for a sphere or cube φ_1 is proportional to $V^{0.13}$. For a factor of 1000 change in volume this will give a factor of 2.45 increase in the vent area for the same overpressure, provided both vessels are of a size to give Re_f>4000. The use of the laminar burning velocity S_u in the definition of Re_f in Eq. 2 means that for more reactive mixtures the flame diameter reduces and so φ_1 increases for more reactive mixtures.

The second φ_2 term in λ is defined by the Re of the unburnt gas vent flow as given in Equation 3. φ_2 is 1 until Equation 3 is >1

$$\varphi_2 = 1.23\,[Re_v/10^6]^{0.0487/Su} \qquad (3)$$

where $Re_v = \rho_u u_v\,(D_v/2)/\mu_u$ and u_v is the mean velocity at the vent = $(2 \times 10^5\ P_{red}/\rho_u)]^{0.5}$ for subsonic flow (P_{red}<0.9 barg). For a constant P_{red} and K_v D_v is proportional to $V^{0.33}$ and for methane with S_u = 0.4 this gives φ_2 proportional to $V^{0.040}$. For a factor of 1000 change in volume this would give a 1.32 increase in the vent area. The combined effect for a factor of 1000 increase in volume is 3.23 increase in the vent area, which for a factor of 100 increase in volume reduces to a factor of 2.19 increase in vent area and for a factor of 10 increase in vessel volume is a factor of 1.48 increase in the vent area.

None of these indirect effects of the changes in the vessel volume on the required vent area are mentioned in NFPA 68 (2013). Also, there is no information in NFPA 68 (2013) on how these λ correction terms are influenced by $P_{stat.}$ As NFPA 68 has no effect of P_{stat} for P_{red} <0.5 bar, the unstated assumption is that these corrections are not influenced by P_{stat}. However, there is no experimental evidence to verify that this is a valid assumption.

4. Characteristic Pressure Peaks in Vented Gas Explosions

Vent design correlations and design standards normally predict the maximum explosion overpressure (P_{red}) without giving considerations to the individual pressures peaks associated 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 pressure peaks are shown as an example in Figure 2 for a free 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 or mixture reactivities.

Peak pressure events	This work	Fakandu et al. (2011, 2012); Kasmani et al. (2010)	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

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

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 2, 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).

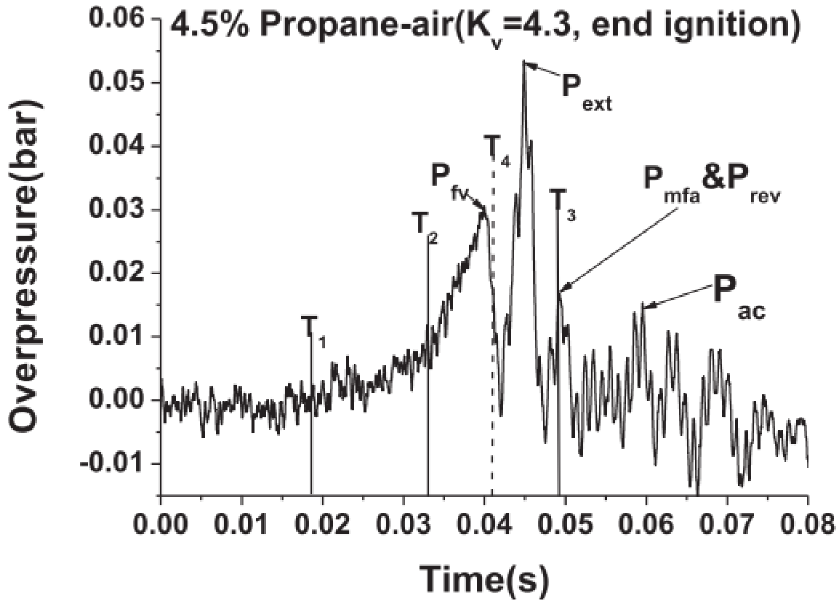

Figure 2: Pressure-time profile for a 0.01 m^3 vessel with an L/D of 2.8.

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 burst 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 in the literature on the effect of P_{stat} on P_{red} and its dependence on K_v and mixture reactivity. This work was aimed at the provision of more data on the influence of P_{stat} on P_{red} with better instrumentation of the venting process, so that the physics of the impact of P_{stat} could be determined.

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

Only EN 14994 (2007) has a procedure for accounting for the influence of P_{stat} on P_{red} and this uses the equation of Bartknecht (1993) in Equation 4.

$$\frac{1}{K_v} = \left[\frac{0.1265 log_{10} K_G{}^{-0.0567}}{P_{red}{}^{0.5817}} + \frac{0.175(P_{stat} - 0.1)}{P_{red}{}^{0.5717}}\right] \qquad (4)$$

Equation 4 may be simplified to Equation 5 as the difference in the two P_{red} exponents is not significant and there is no justification for the use of four significant figures in the constants.

$$P_{red}{}^{0.57}/K_v = a + b\,(P_{stat} - 0.1) \qquad (5)$$

The constant 'a' is the reactivity term on the LHS of Equation 4. It 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. This value for hydrogen cannot be correct relative to the other two values of 'a' for methane and propane 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 much smaller volume for the vented vessel for hydrogen was the problem, due to the vessel volume effect discussed above. The reactivity term in Equation 4 uses a log correlation of these values for 'a' with Bartknecht's values for the mixture reactivity $K_G = (dP/dt)_{max}V^{1/3}$ measured in a 5L sphere, 55 bar m/s for methane, 100 for propane and 550 for hydrogen.

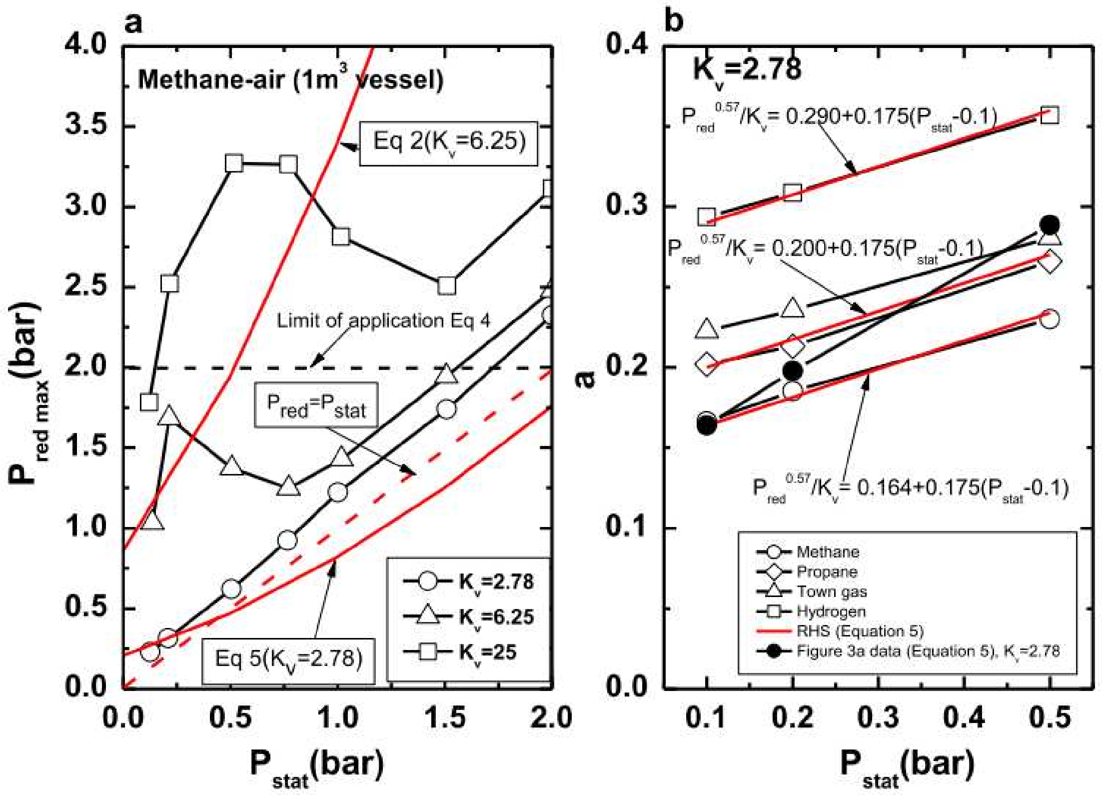

Figure 3: P_{red} as a function of P_{stat} for a 1 m^3 vessel for 10% methane-air.

Bartknecht (1993) investigated the influence of P_{stat} in a 1 m^3 vessel and his results are shown in Figure 3a. The lowest P_{stat} investigated was 0.1 bar and there are sometimes requirements to use lower values than this and these are explored in the present work. Figure 3a for 10% methane-air shows the influence of P_{stat} for three K_v of 2.78, 6.25 and 25. Comparison of the raw experimental results in Figure 3a with Equation 4 shows very poor agreement and the prediction for K_v = 25 is off the graph whereas all the data is on the graph, although all this data is outside the limits of applicability of Eq. 4 which is up to a P_{red} of 2 barg. Equation 4 is below the experimental results for K_v = 2.78 and in very poor agreement with the two higher K_vs which are above the experimental results at most P_{stat}. Also the experimental results for a K_v of 2.78 in Figure 3a show a linear relationship between P_{red} and P_{stat}, not the non-linear relationship of Equation 4. Figure 3a shows that the relationship between P_{red} and |P_{stat} is close to $P_{red} = P_{stat}$ and the constant of proportionality to fit the data is 1.1.

Figure 3a shows that for a K_v of 6.25 the vent flow was sonic with P_{red} >1barg and the relationship between P_{red} and P_{stat} was non-linear. It is considered that the venting regimes with K_v of 6.25 and especially 25 are impractical with a high P_{stat}. It would only be practical to use low P_{stat} and hence the complex dependence of P_{red} on P_{stat} for K_v of 6.25 and 25 will not be discussed further, apart from to note that they clearly do not support Eq. 4, as shown in Fig. 3a.

Figure 3b shows the P_{stat} effect up to 0.5 bar with a K_v of 2.78 for different mixture reactivities. The results for methane should be those in Fig. 3a. The 'a' axis in Fig. 3b is as per Eq. 5 with b = 0.175, as in Eq. 4. If the experimental data in Fig. 3a is plotted as $P^{0.57}/K_v$ for K_v = 2.78 then the values are well above the three data points in Fig. 3b for methane. Equation 5 is plotted in Fig. 3b and it is clear that the lines are Equations 4 and 5 for the four gas reactivities, the points are not experimental data but line identification points, as they do not agree with the methane data, which is the only experimental data for P_{stat} that Bartknecht published. Thus the validation of the P_{stat} effect in Equation 4 is only for methane at low K_v and there is no validation for other gas reactivities or for a P_{stat} effect over a range of K_v. It is concluded that the present European Guidance on gas explosion venting does not have adequate experimental verification and the results of Bartknecht for K_v = 2.78 for methane are the main basis of Equation 4, but it is not a fit to this data. The origin of the 0.175 constant in Equations 4 and 5 is difficult to find from the data in Fig. 3a. If only the data for P_{stat} = 0.2 and 0.5 barg is included for K_v = 2.78 and 6.25 for P_{red} < 2 barg then there are four data points and using Eq. 5 the average value for b would be 0.30. If all the data for K_v = 2.78 and 6.25 in Fig. 3a is included then the average for b is 0.21. To get an average for b of 0.175 would require some but not all the data from K_v = 25 to be included. Thus the value of b of 0.175 in Equation 4 is not compatible with it being based only on data below P_{red} of 2 barg and P_{stat} < 0.5 bar.

These problems with Bartknecht's correlation for the influence of P_{stat} and his limited data set, has led to the US venting standards abandoning this approach in 2013 (NFPA 68, 2013), which they had used in the 1998 – 2007 versions of NFPA 68. Their approach has been summarized above in Equations 1-3. However, Equation 4 is continued with in the European gas venting standard (EN 14994 2007). 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 exceeded by the dynamic burst pressure effect discussed in NFPA 68 (2013) in section A.6.3.2. For $0<P_{stat}<0.1$ bar NFPA 68 (2013) requires that $P_{stat}< (P_{red} – 0.024\text{bar})$. 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}. This is because 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 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

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

Cubbage and Simmonds (1955) showed in Equation 6 that the P_{burst} overpressure peak was linearly dependent on the inertia of the vent cover.

$$P_{burst} = cw + d \qquad (6)$$

where “c” and “d” are constants and “w” is the weight of the material divided by the area. ‘cw’ in Equation 6 is the P_{stat} of the vent cover. 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. Equation 6 shows that the P_{stat} pressure was additive to the term ‘d’ which was related to K_v and U_L, where U_L is the laminar burning velocity. Rasbash (1969) determined Equation 7 for the pressure generated in cubic vented explosions using data from his studies of propane-air in small vessels. Equation 7 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 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.

$$P_{red} = 1.5\ P_{stat} + 0.5\ K_v. \qquad (7)$$

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 Equation 7, and essentially assumed that the dynamic burst pressure was the same as the static burst pressure.

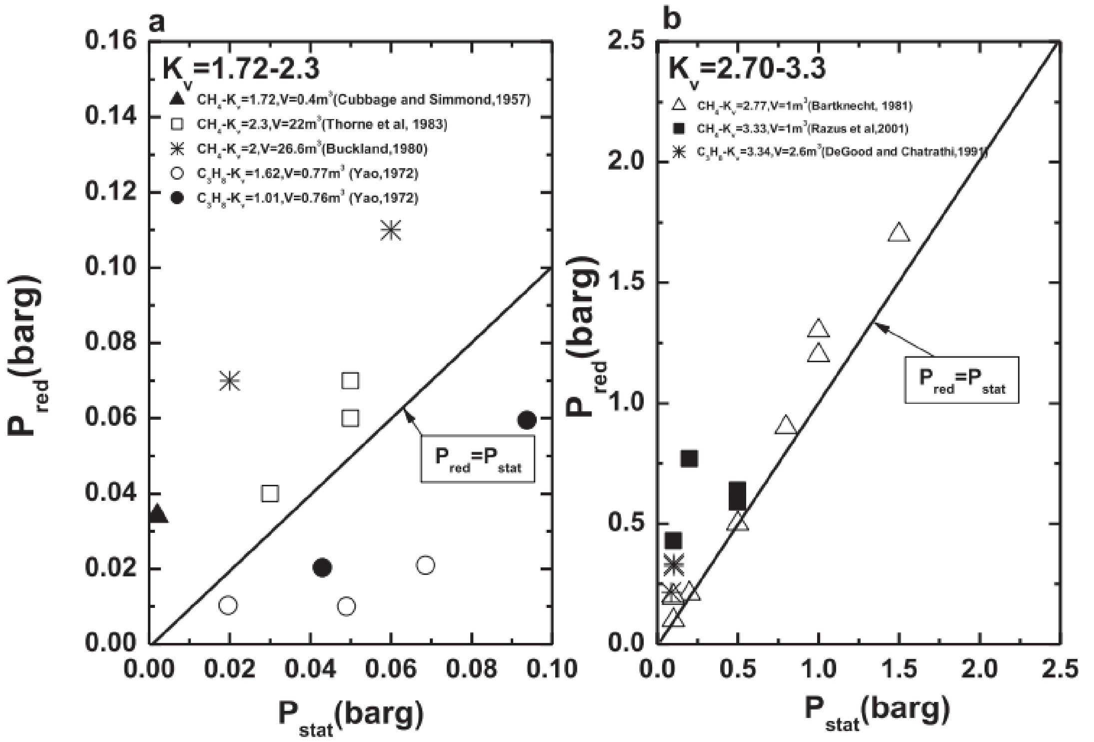

Figure 4: P_{stat} verses P_{red} for methane-air and Propane-air (a) K_v=1.72-2.3 (b) K_v=2.7-3.3.

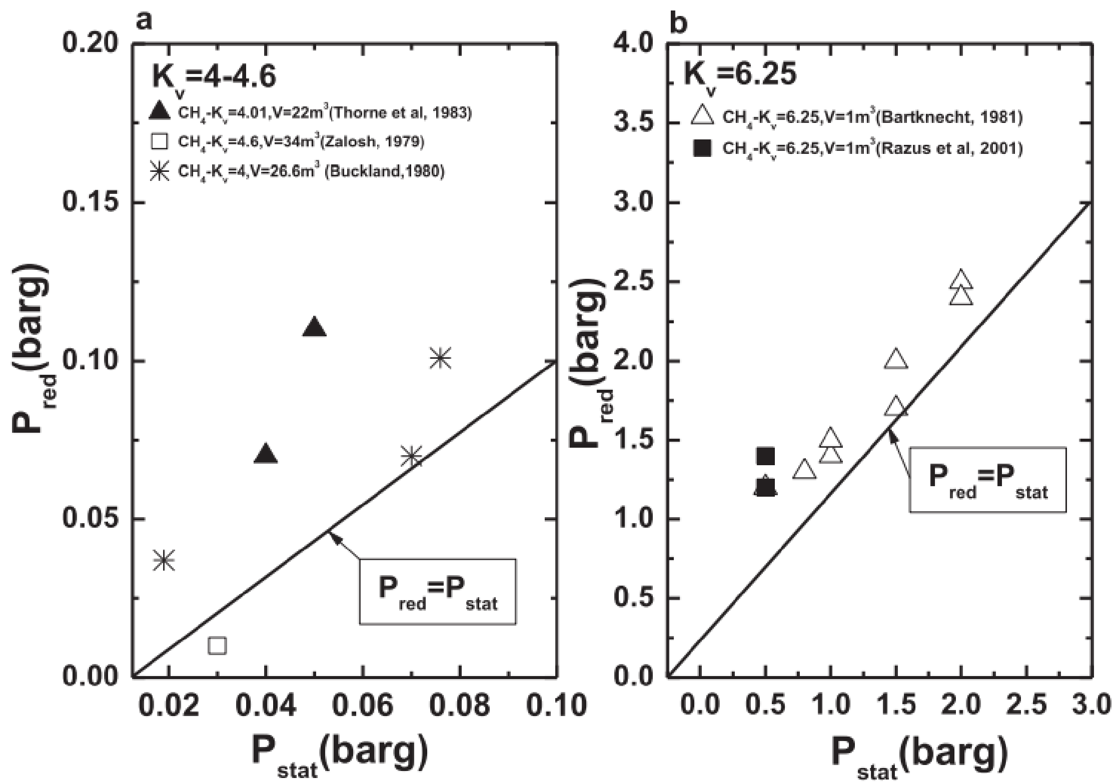

Figure 5: P_{stat} verses P_{red} for 10% methane-air (a) K_v=4-4.6 (b)K_v=6.25.

The influence of P_{stat} by various investigators is shown in Figure 4 for K_v of 1.72 and 3 and in Figure 5 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}, as Bartknecht found in Figure 3a. 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. There is considerable uncertainty in this data of the precise critical value of K_v above which P_{stat} is not the controlling factor in determining P_{red}. There also is a need to determine this critical value for different mixture reactivities, as there is insufficient data published at present.

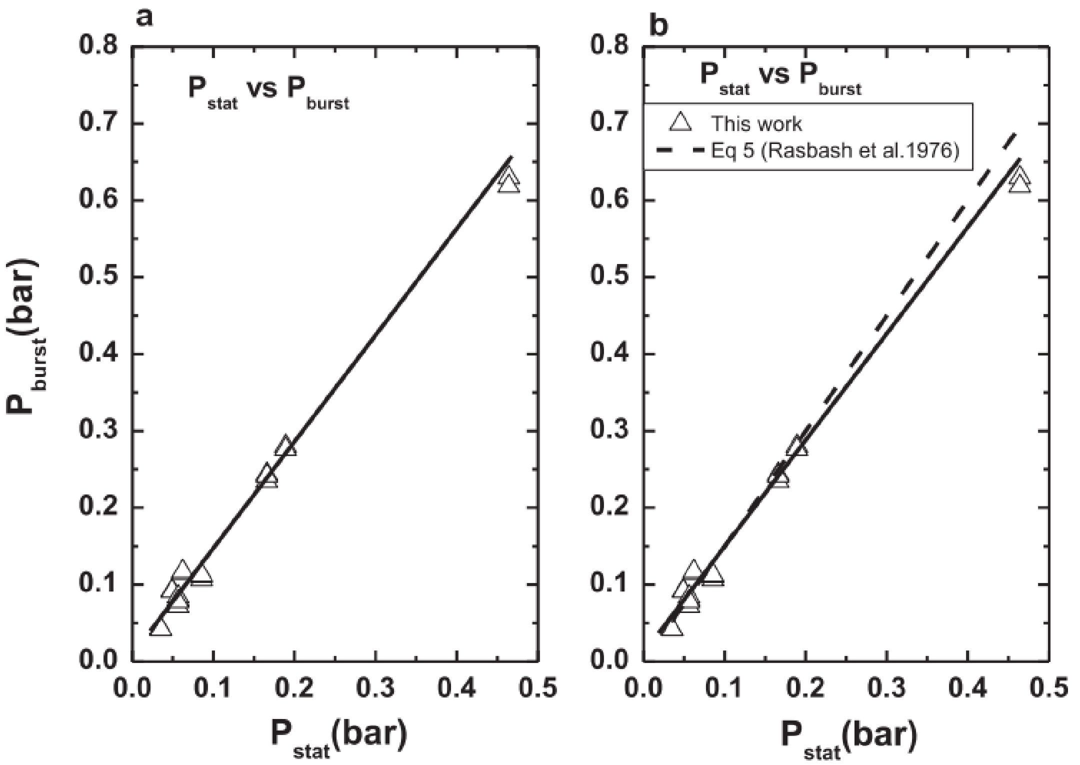

Figure 6: Relationship between P_{burst} and P_{stat} for Kv=1-21.7.

7. Results and discussion

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

Figure 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 Equation 7, as shown in Figure 6b. The line of best fit to the present results is given in Equation 8.

$$P_{burst} = 1.37\ P_{stat} \qquad [8]$$

Most empirical correlations, as in Equations 4-7, 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 (2013) 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.

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

The results in Figure 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 Figure 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 Figure 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 $P_{red.}$ Figure 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 covered and hence the initial flame speed 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 fell. After the vent burst the fall in pressure was so fast, due to heat losses from the burnt gases upstream of the vent, 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 this was made turbulent by the reverse flow through the vent. The subsequent fast burning and the flame expansion pushed more unburned gas out of the vent. This set up a low frequency oscillatory flow with oscillating pressure with decreasing cycle amplitude, this is a classic Helmholtz resonator.

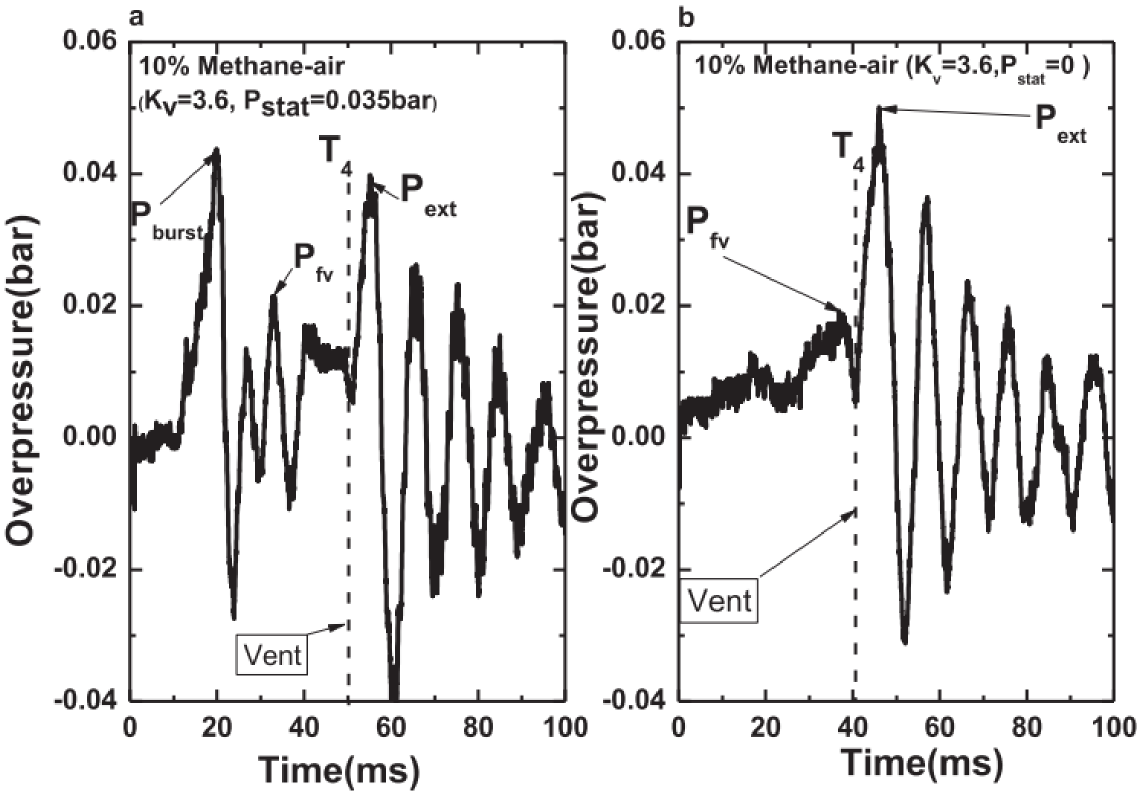

Figure 7: Peak pressures for 10% methane-air with large vent area and a P_{stat} of 0.035bar.

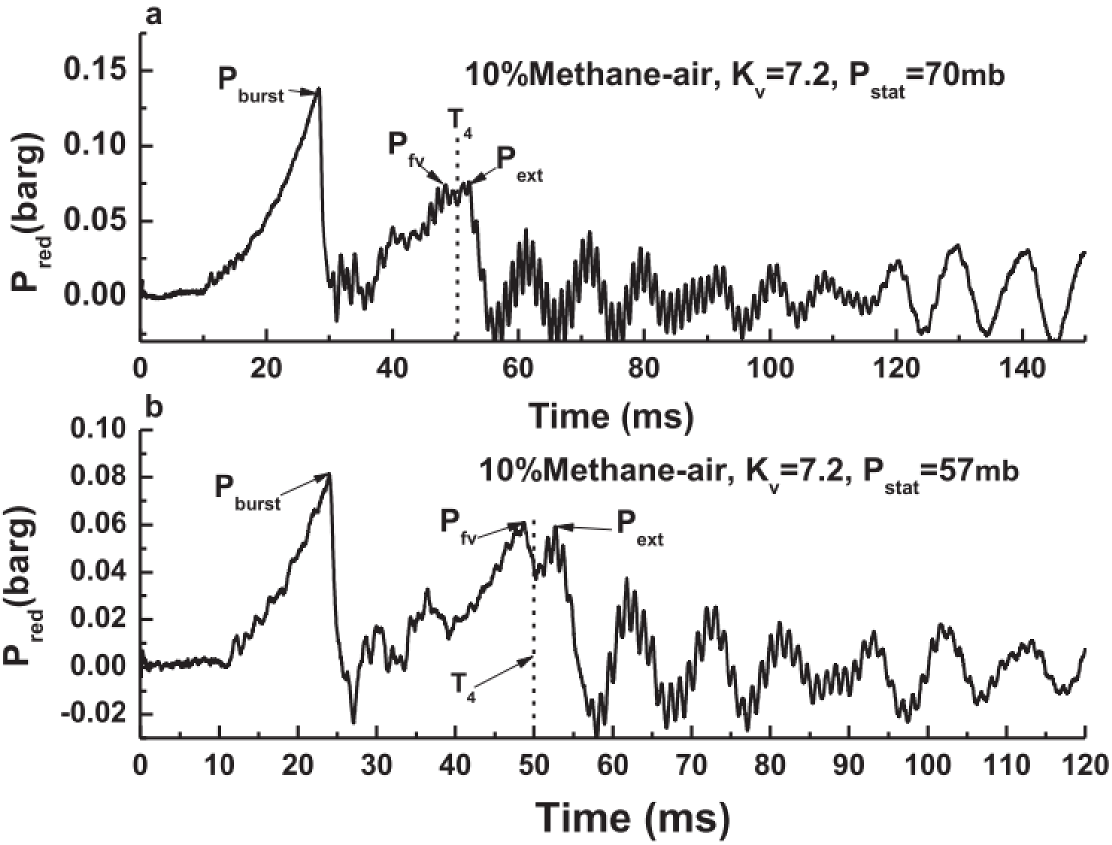

Figure 8: Peak pressures for 10% methane-air with (a) P_{stat} =70mb (a) P_{stat} =57mb.

The 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 vent covered than for a free vent, as shown in Figure 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 Figure 9. These results all show that, for P_{stat} of 57 and 70 mb at K_v of 7.2, P_{red} was still controlled by P_{burst}, as it was at K_v = 3.6 with P_{stat} = 35 mb in Figure 7. Figure 8a shows that the P_{burst} was 135mb and occurred 28ms after ignition, well before the flame emerged from the vent at 50ms. The P_{fv} and P_{ext} pressure peaks were very similar at 75mb, but occurred just before and just after the flame emerged from the vent.

Similar events are shown in Figure 8b with 57mb P_{stat} when the vent burst at 24ms with P_{burst} of 80mb. The flame arrived 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 $P_{ext.}$. For free venting the flame arrived at the vent at 52ms, only 2ms later than with the vent covered. The peak overpressure was 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 was slower than with free venting. Once the vent burst the flame was accelerated and created more turbulence in the external jet. The net result was that the time to reach the vent was very similar for free venting and with a vent cover.

Figure 9 shows that once the vent bursts the subsequent events were 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 for a K_v of 21.7 in Figure 10, which 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 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.

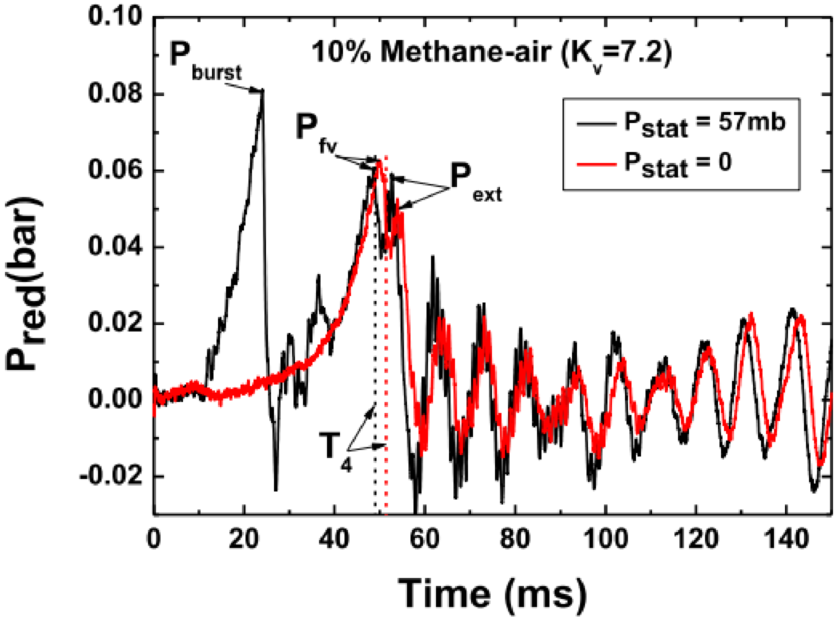

Figure 9: Comparison of the pressure time records for 10% methane-air for K_v = 7.2 for free venting and for P_{stat} = 57mb.

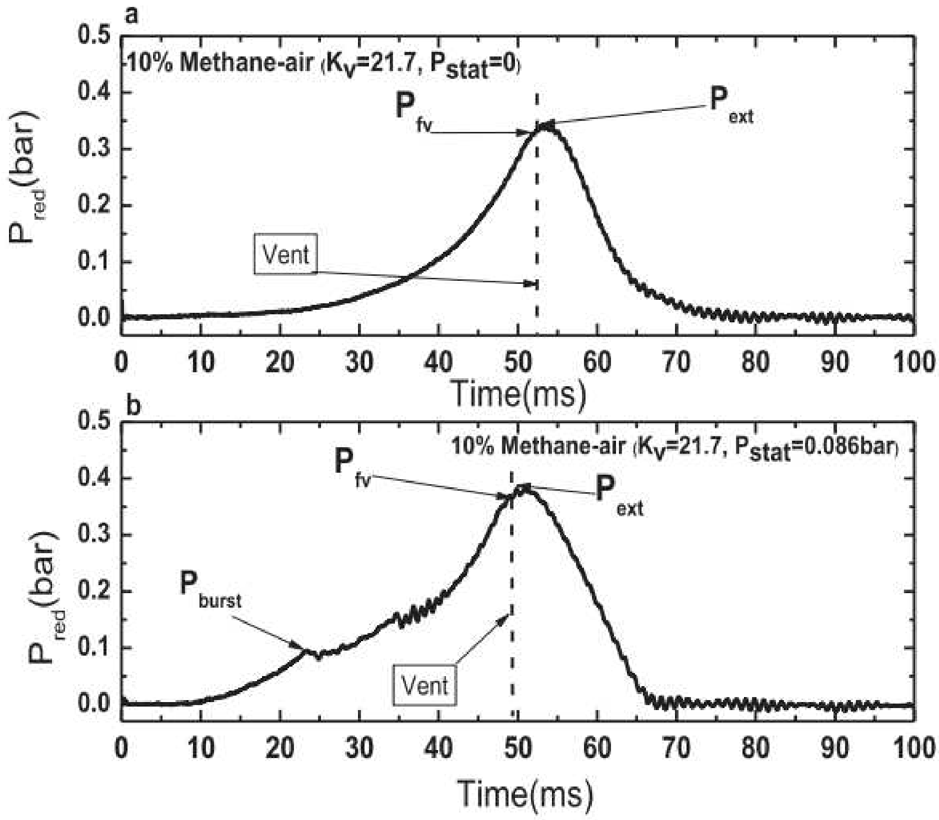

Figure 10: Pressure v. time record for 10% methane-air with a K_v = 21.7 (a) free venting and (b) P_{stat}= 86mb.

7.3 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 Figure 11 concentrating on the present data for P_{stat} < 300mb and Figure 12 comparing the work with the results of other workers for similar K_v. The main result from Figure 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. Figure 12 shows, as discussed above, that for a 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 a P_{stat} of about 100mb 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 a P_{stat} of 150mb, the limit of the values tested at this K_v.

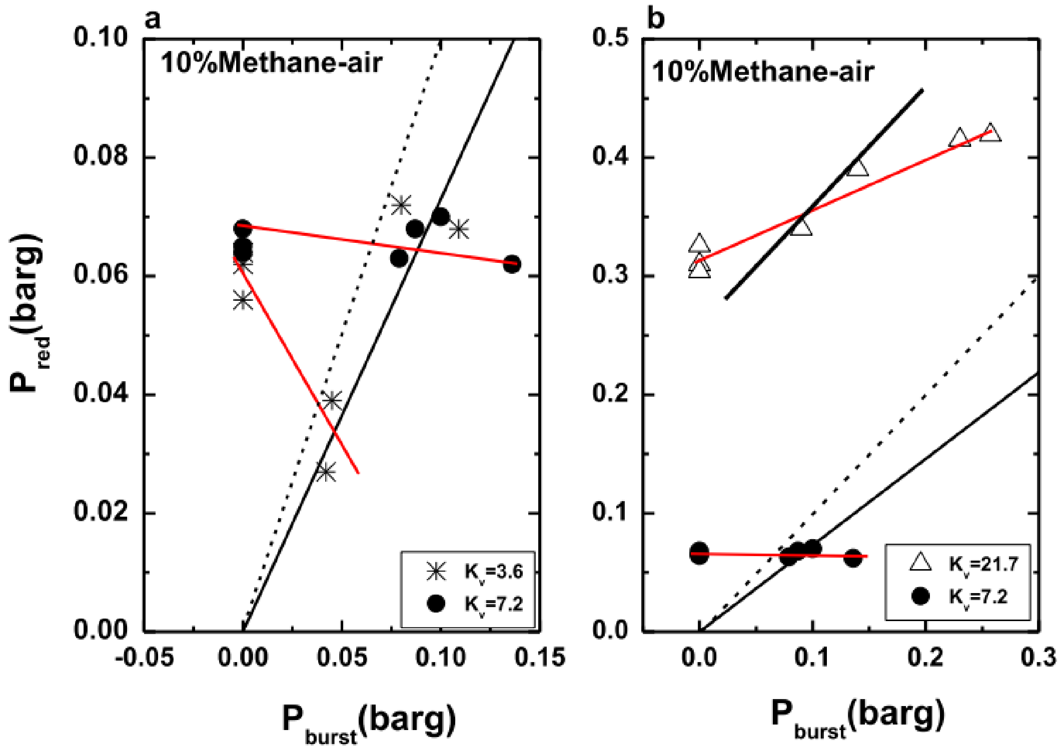

Figure 11: Peak pressures as a function of P_{burst} for K_v = 3.6, 7.2, and 21.7 for low P_{burst}. The dashed line is P_{red}=P_{burst} and the solid line is P_{red} = P_{stat}. The red line is the trend of experimental data.

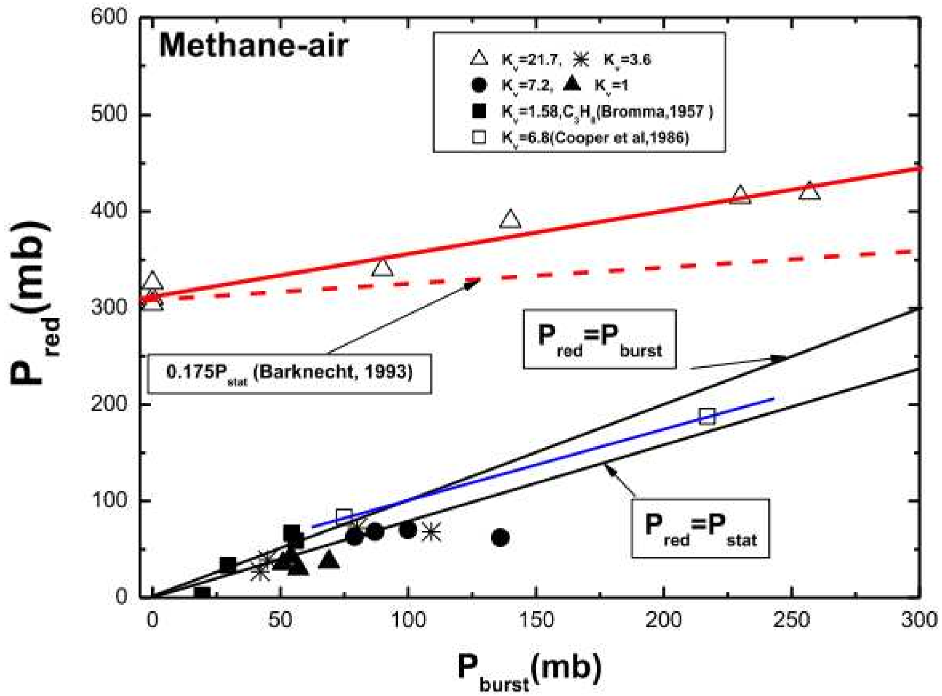

Figure 12: Peak pressures with P_{burst} for different K_vs. The dashed line is the 0.175 P_{stat} constant in Eq. 1.

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 a 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 Cooper et al. (1986) for a K_v of 8.8 agrees with the present results that P_{red} is determined by P_{stat}. The large vessel volume results of Bromma (1967) also agree with the present work that P_{stat} determines P_{red} at low K_v.

8. Flame Speeds

The centre line flame speed was measured along the flame propagation path within the test vessel and immediately after the vent. Figure 13a shows for 10% methane-air that with free venting, a maximum flame speed of 29m/s was achieved upstream of the vent as compared to that with the vent covered of 23m/s. This is similarly to the flame speed for larger vents with maximum upstream flame speeds of 29 m/s and 19 m/s for free venting and covered vents respectively. These high flame speeds upstream of the vent for free venting are responsible for higher external vent turbulence levels in the expelled unburned gas. This leads to higher downstream flame speeds when compared with the covered vents. Figure 13b shows a maximum downstream flame speed of 78m/s for free venting compared to 47 m/s for covered vents. This higher flame speed results in the higher P_{ext} observed, as shown in the pressure-time profile in Figures 7 and 9 for 10% methane-air mixtures.

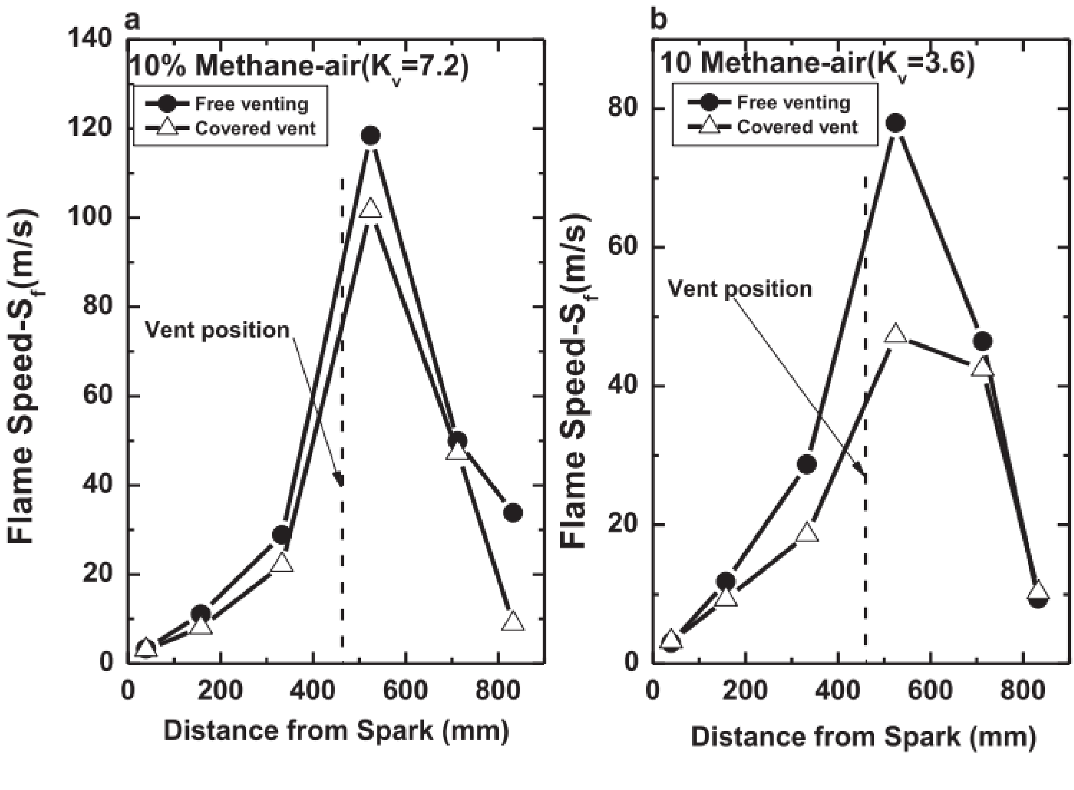

Figure 1: Flame speed as a function of distance from spark position

9. Conclusions

1. **1.** Current vent design guidance in Europe is incompatible with the experimental data of Bartknecht and of the present work for low K_v. Bartknecht's data and the present work show that for K_v < ~8 P_{stat} determines P_{red}. More experimental data is required on the P_{stat} effect and the vent design standard for gases needs revision.
2. **2.** 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.
3. **3.** The critical K_v for P_{stat} not to control P_{red} was found to be > 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 = 6.25 shows that this is beyond the critical condition as P_{red} was significantly higher than P_{stat}, but with a non-linear dependence on P_{stat}.
4. **4.** 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 of 0.5 which is greater than that of 0.175 in Equation 6.
5. **5.** The experimental results for P_{stat} of Bartknecht do not support the 0.175 value of the venting constant in the P_{stat} term. The value of this constant should be 0.30 if only data for methane at 0.2 and 0.5 P_{stat} and K_v 2.78 and 6.25 are included. The 0.175 value can only occur if data for P_{stat} > 0.5 bar and K_v of 25 is included in the average. All this extra data is outside the limits of P_{stat} and P_{red} for the applicability of the Bartknecht vent design equation.
6. **6.** There is an inadequate understanding of the effect of P_{stat} on P_{red} in explosion venting and more work to determine the critical K_v for the transition from P_{stat} controlling P_{red} to the vent flow controlling P_{red}. The influence of the mixture reactivity on this transition K_v is also not known at present.
7. **7.** There is no experimental data to support the assumption in the Bartknecht vent design equation that the P_{stat} effect is the same for all mixture reactivities.

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