

Gas Explosion Venting: External Explosion Turbulent Flame Speeds that Control the Overpressure

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In most vented explosions the peak overpressure is controlled by turbulent flame propagation external to the vent. This has been known for many years, but a method to predict the overpressure from the external flame speed has not been developed. Current vent modelling is based on the assumption that the unburned gas flow through the vent controls the overpressure and does not address the issue of the external explosion. This work shows that the external flame speeds in a small vented explosion test facility can be predicted from Taylors's acoustic theory (1946). Vented explosion data is presented for vent coefficients from 3 – 22 for the most reactive mixtures of methane, propane and ethylene in terms of the overpressure and the external flame speed. The overpressure from Taylors's acoustic theory give a good prediction of the measured overpressure.

1. Introduction

One of the most efficient and cost effective ways of explosion protection is venting. The USA (NFPA 68, 2013) and European (EN14994:2007) vent design standards are incompatible. Figure 1 shows that the agreement is poor between the two design standards and experimental results, other than those on which the European standards are based. Figure 1 has experimental data with free venting or venting with very low static burst pressures. Bartknecht's [1993] data on which the European gas venting standard is based had a 0.1bar static burst pressure, but this does not account for the high overpressures that were measured, relative to other data using similar or larger volumes. The new NFPA 68 [2013] standard uses a laminar burning velocity approach for the mixture reactivity, rather than the deflagration parameter, $K_G = dP/dt_{max}V^{1/3}$, used in the European standard and in earlier editions of NFPA 68. Figure 1 shows that the new NFPA method gives better agreement with experimental results. However, there is still a wide variation in overpressures measured in experimental results and some results that are higher than the new NFPA 68 predictions. There is clearly a need for a better understanding of the combustion aerodynamics of the venting process.

2. Experimental Methods

A 0.1 m³ cylindrical vented vessel was used, as shown in Figure 2. It had an L/D of 2.8 which is close to the L/D of 2 for compact vessels, as recommended by Bartknecht [1993]. All the explosions were for free venting. Different vent areas were used giving a range of K_v from 3.1-21.8. The vents were circular holes in the centre of the end flange of the vessel directly opposite the ignition point on the centre of the rear wall. This end ignition position has been shown to have the worst case overpressure and higher than for central ignition [7, 9]. Most of the experimental explosion venting data is for central ignition, as recommended by Bartknecht [1993] but the ATEX Directive [1994] in Europe requires the worst case to be considered and this is normally end ignition for vessels that are at the limit of the compact vessel definition, which the standards define as L/D 2.5 [NFPA68, 2013] or 3 [EN14994:2007]. Square vents rather than the present circular vents have also been shown to reduce P_{red} [Fakandu et al., 2014].

The vented vessel was connected to a 0.5m diameter vessel with an L/D of 1 and this was used to support the thermocouples for the measurement of the flame speed in the vent discharge jet flame. This 0.5m diameter vessel had no influence on the venting process as it was much larger than any of the vent diameters

investigated. The explosion finally vented into a 50m³ dump vessel. The flame travel time was recorded by mineral insulated, exposed junction type-K thermocouples, arranged axially at the centre line of both the main test and the 0.5m dia. vessel, as shown in Fig. 1. Thermocouples T₁, T₂ and T₄ were located on the centreline of the main test vessel, while thermocouples T₅, T₆ and T₇ 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, T₃, located on the wall of the main test vessel to measure the time of flame arrival at the wall of the vessel.

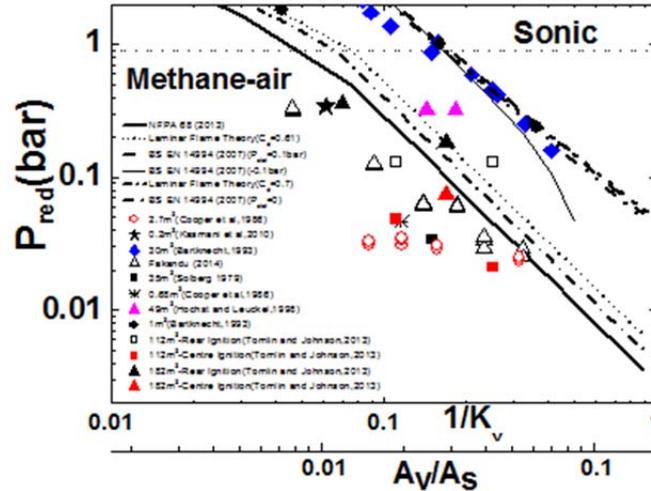


Figure 1: Experimental data on vented explosion P_{red} for 10% methane-air compared with design standards and laminar flame venting theory.

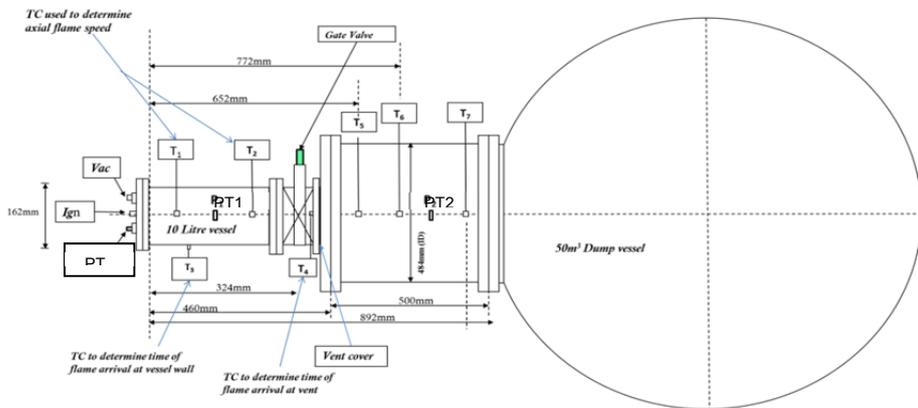


Figure 2: Experimental 0.01 m³ Vented Vessel with External Vented Flame Speed Measurements

Two piezo electric pressures transducers PT0 and PT1 were located at the end flange (PT0) opposite the vent and mid-way along the vessel (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 [Solberg et al., 1980; Bauwens et al., 2010]. A third transducer PT2 was located in the 0.5m dia. connecting vessel which measured the external explosion overpressure and its time of occurrence. This was of great assistance in determining when the external explosion occurred.

3. Characteristic of the Pressure Peaks in Free Vented Explosions

There are six possible causes of the peak overpressure in vented explosions and which one is the maximum, 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

[Kasmani et al, 2010; Fakandu et al., 2011, 2012, 2014], but have been given a more descriptive nomenclature 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 (f_v) 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. It will be shown in the results section that in most vented explosions in the present work either P_{fv} or P_{ext} is the peak overpressure, depending on K_v , K_G and ignition position.

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. This peak is significant as the laminar flame theory assumes that P_{fv} and P_{mfa} occur at the same time, as discussed below, but the present experiments show that they often occur at different times and that in most cases P_{fv} occurs before the time of maximum flame area and has a higher overpressure than P_{mfa} .

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. The high frequency acoustic pressure oscillations referred to by Cooper et al [1986] are referred to as P_{ac} , but were not significant in the present work. The present vented vessel was instrumented with flame position detectors and external pressure transducers to determine where the flame was at the time of the peak pressure.

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

Peak pressure events	This work	Fakandu et al. [2012]	Cooper et al [1986]	Harrison and Eyre [1987]	Cates and Samuels [1991]	Bauwens et al. [2010]
Peak due to vent opening, 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. burn rate	P_3
Peak due to the reverse flow into the vented vessel	P_{rev}	P_5				
Peak due to high frequency pressure oscillations.	P_{ac}	P_6	P_4			P_2

4. Laminar Flame Venting Theory

Most theories of venting assume that flow through the vent dominates the overpressure and that P_{fv} is the dominant overpressure [Cates and Samuels, 1991; Bauwens et al., 2010; Bradley and Mitcheson, 1978] and it will be shown in this section that NFPA 68 [2013] has adopted this approach to gas explosion vent design. Andrews and Phylaktou [2010] have reviewed laminar flame venting where it is assumed that the unburned mixture ahead of the flame is expelled through the vent and the maximum overpressure is the vent orifice flow pressure loss at the maximum unburned gas vent mass flow rate [Molkov et al., 2000]. The unburned gas mass flow rate is the product of the flame surface area, A_f , the unburned gas velocity ahead of the flame, $U_L(E_p-1)$ and the unburned gas density, ρ_u . A further assumption is made, that the maximum possible mass burning rate is used with the flame area is the surface area of the vessel walls, A_s [Runes, 1972].

The laminar flame venting model with the above assumptions, leaves the prediction of P_{red} a function of A_v/A_s , as shown in Eq. 1. [Andrews and Phylaktou, 2010]. This formulation of the laminar flame venting theory has been adopted in NFPA 68 [2013] using the original Swift [1988] formulation of Eq. 1 with the turbulence factor of 5 used by Swift [1988] replaced with λ and a procedure given in NFPA 68 [2013] to calculate this.

$$A_v/A_s = C_1 \varepsilon^{-1} \lambda U_L (E_p-1) P_{red}^{-0.5} \quad \text{with } P_{red} \text{ in Pascals} \quad (1)$$

where $C_1 = \rho_u^{0.5}/(C_d 2^{0.5}) = 1.27$ for $\rho_u = 1.2 \text{ kg/m}^3$ for a vent discharge coefficient $C_d = 0.61$. ε is the expansibility factor that takes into account compressible flow effects for sharp edged orifices. Other laminar flame venting theories treat the vent as a theoretical nozzle and use compressible flow nozzle equations which

do not apply to vents [Bradley and Mitcheson, 1978; Molkov et al., 2000]. Values of ϵ are given in orifice plate flow metering standards and are usually between 0.9 and 1, depending on K_v (lower for high K_v). With P_{red} in Eq. 1 converted to bar and the above value for C_1 inserted and an E_p of 8.05 used, which is the adiabatic value for propane, Eq. 1 becomes Eq. 2 for P_{red} in bar.

$$A_v/A_s = 0.0283 \epsilon^{-1} \lambda U_L P_{red}^{-0.5} \quad (2)$$

The constant in Eq. 2 becomes 0.0247 if a C_d of 0.7 is used, as in the work of Swift [1988] which is the C_d value adopted in NFPA 68 [2013] as Eq. 3. This predicted value of the constant in Eq. 2 is only 11% higher than in NFPA 68 and so the laminar flame venting theories have very similar results. Fig. 1 shows that these differences in the assumed vent C_d result in significant differences in the predicted P_{red} .

$$A_v/A_s = C P_{red}^{-0.5} = 0.0223 \lambda U_L P_{red}^{-0.5} \text{ for } P_{red} < 0.5 \text{ bar} \quad (3)$$

There is no reason for limiting this equation to a P_{red} of 0.5 bar [2013], as all compressibility effects are contained in the expansibility factor, ϵ , in Eqs. 1 and 2.

It may also be shown that the laminar flame theory of Bradley and Mitcheson [1978] for free venting can be expressed in the above format as in Eq. 4 [Andrews and Phylaktou, 2010].

$$A_v/A_s = 0.831[\lambda U_L(E_p - 1)] / [C_d a_v P_{red}^{0.5}] = 0.0284 \lambda U_L P_{red}^{-0.5} \quad (4)$$

where a_v is the velocity of sound at the vent, taken as 343 m/s for air. E_p has been taken as the adiabatic value for propane of 8.05. Eq. 4 is identical to Eq. 2. There was a difference in C_d of 0.6 instead of 0.61 used in Eq. 4, but this only changes the constant in Eq. 4 to 0.0280. Bradley and Mitcheson [1978] went on to use a value for the turbulence factor λ of 4.19 to produce a prediction that would encompass data from vented explosions with a static burst pressure at the vent, with a 1.19 constant in Eq. 4 replacing 0.0284 λ .

The A_v/A_s formulation of the laminar flame venting equation can be converted into a form using the vent coefficient K_v as $A_s = C_2 K_v$, where C_2 is 4.84 for a sphere, 6 for a cube and 5.54 for a cylinder with $L/D=1$ and 5.86 for the present cylinder with an L/D of 2.8. This then converts Eq. 1 into Eq. 5 and this has the same form as in the European vent design guidance [EN14994:2007].

$$1/K_v = A_v/V^{2/3} = C_1 C_2 \epsilon^{-1} \lambda U_L (E_p - 1) P_{red}^{-0.5} \quad (5)$$

If Eq. 5 is used for a cube and P_{red} is converted from Pa to bar then with $E_p = 8.05$ Eq. 5 becomes Eq. 6.

$$1/K_v = 0.170 \epsilon^{-1} \lambda U_L P_{red}^{-0.5} \quad (6)$$

For propane with $U_L=0.46$ m/s [2] and taking $\epsilon = 1$ and $\lambda = 1$ Eq. 6 becomes Eq. 7. For 10% methane –air with U_L taken as 0.42 m/s [Satter et al., 2014] and E_p as 7.54 the constant in Eq. 7 becomes 0.062.

$$1/K_v = 0.078 P_{red}^{-0.5} = a P_{red}^{0.5} \quad (7)$$

Eqs. 1 -7 are based on incompressible flow through the vent with a compressible orifice plate flow correction in the expansibility coefficient, ϵ . This is the approach used in orifice plate flow metering for the influence of compressible flow and the correlation given [BS1042] is Eq. 8.

$$\epsilon = 1 - [0.41 + 0.35(1/K_v)^2] P_{red}/[\gamma (P_i + P_{red})] \quad (8)$$

For $K_v > 5$ the K_v term in Eq. 8 is negligible. For a P_{red} of 0.5 bar, $K_v > 5$ and the ratio of specific heats $\gamma=1.4$ Eq. 8 gives $\epsilon = 0.90$.

Current EU [2007] design guidance for gas explosion protection using venting are based on the experimental data of Bartknecht [1993]. The vent design Equation 9 [Bartknecht, 1993] is for a vent static burst pressure, P_{stat} , of 0.1 bar. Equation 9 uses the deflagration index, K_G , as the gas reactivity parameter.

$$1/K_v = (0.1265 \log K_G - 0.0567) P_{red}^{-0.5817} \quad (9)$$

Eq. 9 has an unusual log relationship with the gas reactivity K_G . It may be shown [Andrews and Phylaktou, 2010] that K_G is linearly related to U_L and Eq. 6 shows that $1/K_v$ should be linearly related to U_L . This lack of agreement of the Bartknecht approach with the above theory was probably the reason for NFPA68 [2013] to move from using Eq 9 to using Eq. 6 in 2013. Both approaches are compared with experimental data in Fig. 1 and the Bartknecht approach is in poor agreement with experimental data apart from his own, whereas Eq. 6 is in good agreement with a wide range of data although there is significant data scatter around Eq. 6.

5. Pressure Peaks in Vented Explosions

Fig. 3 shows a typical vented explosion pressure record for PT0 and PT2. The time of arrival of the flame at the vent is marked and this shows that the maximum overpressure was due to the external explosion. The

pressure peak P_{iv} occurred just before the flame left the vent. The external pressure transducer P2 showed no response until the flame left the vent and had a peak pressure rise in line with that of the maximum pressure inside the vessel. This is clear evidence that the external explosion controlled the maximum vented pressure. After the external explosion there was a reverse flow into the vessel and the flame was then detected at the internal vessel wall by thermocouple T_3 , indicating the time of maximum flame area, but this was not P_{max} .

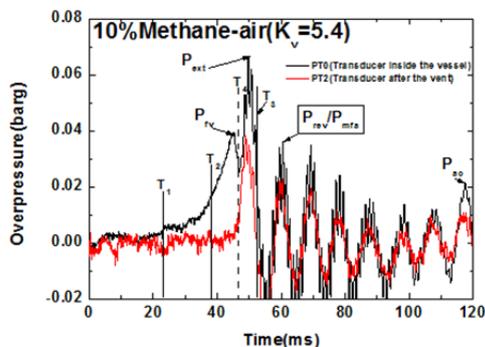


Figure 3 Pressure records for PT0 and PT2

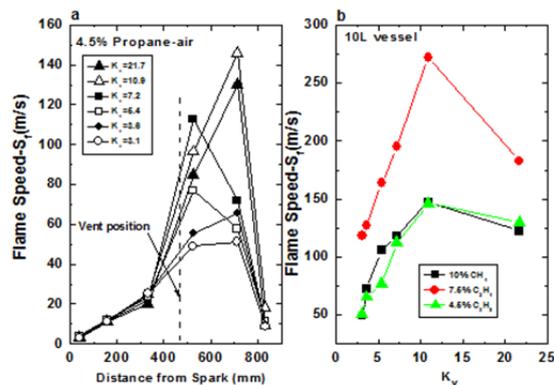


Figure 4 Flame speed as a function of distance and K_v

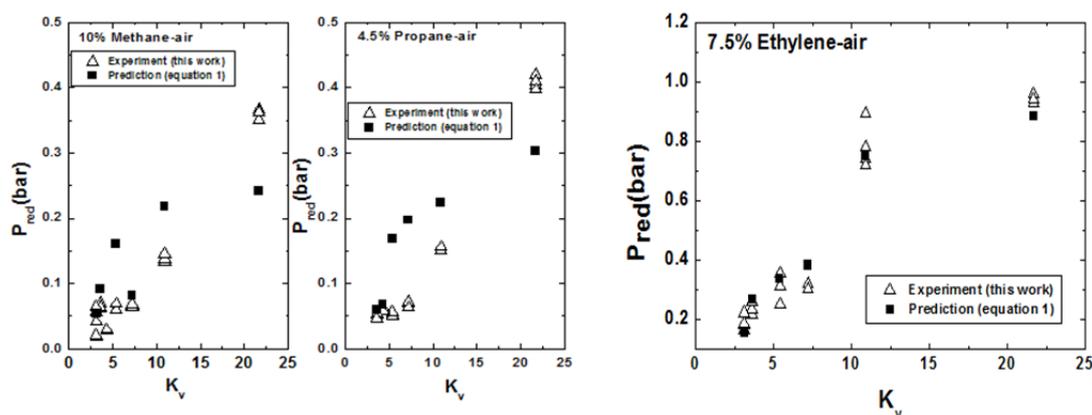


Figure 5 Comparison of the measured overpressures and those predicted from Eq. 10 for methane, propane and ethylene air maximum reactivity vented explosions.

6. Flame Speeds in the Internal and External Explosions

Fig. 4 shows the flame speeds measured for a range of K_v on the axis of the vent from the spark to the external flame. The vent position is also shown. Fig. 4 also shows the peak external flame speed as a function of K_v for methane, propane and ethylene vented explosions. It is clear that the peak flame speed was outside the vent. These fast external flames cause high static pressures behind the flame front. Taylor [1946] showed for spherical waves the static pressure behind the expanding wave was related to the Mach number by Eq. 10.

$$\frac{P_+}{P_o} = \frac{2\gamma M^2}{1+M} \quad (10)$$

where P_+ = peak overpressure, P_a = ambient pressure (absolute), γ = the specific-heat ratio, and M = Flame Mach number. Harrison and Eyre [1987] showed that this could be used to predict the static pressure behind the flame front in vapour cloud explosions in the presence of obstacles.

Eq. 10 has been applied to the present peak external flame speed measurements and compared with the peak pressure due to the external explosion in Fig. 5, for methane, propane and ethylene explosions. A reasonable prediction of the peak overpressure from the external flame speed using Eq. 10 is shown, with excellent agreement for ethylene. This indicates that Eq. 10 can be used to predict the external explosion overpressure. To use Eq. 10 in vent design a procedure to predict the external flame speed based on the internal mass burn rate is required and the laminar flame theory is a good basis to do this.

7. Conclusions

1. Current European vent design procedures based on Bartknecht's [1993] equation has poor agreement with independent experimental data and grossly over predict the vent area required.
2. The laminar flame vent theory has been shown to be the basis of both the Bartknecht and NFPA68 [2013] approach to vent design. The theory predicts a turbulence factor of 2.6 is needed for Bartknecht's data, but no assumed turbulence is needed for agreement with other large volume vented explosion data.
3. Vented explosions have a peak pressure that is in many cases controlled by the external flame. Very high external jet flame speeds were measured and shown to predict the external overpressure using Taylor's equation. This should be included in vent design procedures.

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