# EXPLOSION VENTING AND MIXTURE REACTIVITY INFLUENCES IN A SMALL VESSEL

Fakandu, B.M., Kasmani, R.M., Andrews, G.E. and Phylaktou, H.N.

Energy and Resources Research Institute
University of Leeds, Leeds LS2 9JT
Leeds, United Kingdom

## Introduction

Explosion venting is influenced by the reactivity of the gas mixture. This is normally correlated using either the laminar burning velocity, $U_L$, or the deflagration index, $K_G = (dp/dt)_{max}V^{1/3}$. This work used a small 9 litre vessel that was considered to give a laminar flame explosion and enabled laminar flame venting theory to predict the influence of reactivity through the $U_L$ term. It was shown that $U_L$ is directly related to $K_G$ and hence that laminar flame venting theory can be expressed in terms of $K_G$, which is used in the experimental presentation of venting data and in venting design standards. It is shown that the treatment of hydrogen in the standards, significantly underestimates the overpressure for vented hydrogen explosions.

## Experimental Methods

A small cylindrical vessel of 9 litres volume ($0.00948m^3$, L=0.460m, D=0.162m and L/D 2.8) was used for vented gas explosion with free venting. Different vent areas were investigated with $K_v$ ($V^{2/3}/A_v$) from 2.4-19.03. The L/D of this vessel is close to the L/D of compact vessel as recommended by Bartknecht [1] and also applied in the NFPA 68. The EU vent design guidance for explosion venting of compact vessels defines this as L/D<3. The vessel was designed with an L/D of 2, but when a gate valve was added and a removable vent orifice support added, the length to the orifice face increased the L/D to 2.8. The ignition position was on the centreline of the end wall opposite the vent as this has the worst case overpressure [2, 3]. Most of the experimental explosion venting data is for central ignition as recommended by Bartknecht [1] but the ATEX Directive [4] in Europe requires the worst case to be considered.

The flammable mixture was made up using partial pressures, starting with a vacuum in the explosion vessel. The flame speed upstream of the vent was measured using the time of arrival of the flame at two thermocouples on the centreline, one close to the spark and one close to the vent. There was also a thermocouple close to the wall on the centreline to record the time the flame arrived at the wall. The arrival time of the flame at the vent was determined using the thermocouple just upstream of the vent. Piezo resistive pressure transducers were mounted in the

end flange on which the spark plug was mounted and a second pressure transducer was mounted on the centreline of the vessel cylindrical wall. A 32 channel 100kHz per channel data logging system was used to record the data.

## Laminar Flame Venting Theory

Andrews and Phylaktou [5] have reviewed laminar flame venting theory and showed that the vent area can be predicted from the equation:

$$1/K_v = C_1C_2\ U_L\ (E_p\text{-}1)\ P_{red}^{-0.5} \quad (1)$$

where $C_1 = [\rho_u^{0.5} / (C_d\ 2^{0.5})] = 1.270$ for $\rho_u$=1.2 kg/m$^3$, $C_d$= 0.61

$C_2 = A_s/V^{2/3} = 4.84$ for a sphere, 6 for a cube, 5.54 for a cylinder with L/D=1 (2)

$E_p$ = Ratio of unburned gas to burned gas density ratio at constant pressure

Equation 1 can also be shown to be of the same form of the Swift [6] equation and of the Bradley and Mitcheson [7] vent theory. Andrews and Phylaktou [5] have also shown that $U_L$ and $K_G$ can be approximately related by Eq. 3.

$$K_G = 3.16(P_m/P_i - 1)U_L\ E_v \quad m/s \quad (3)$$

where $P_m$ = the maximum explosion overpressure in a closed sphere, bar

$P_i$ = the initial pressure, bar

$E_v$ = the ratio of unburned gas density to burned gas density at constant volume

This form of $K_G$ can be applied to any initial pressure and is clearly a velocity term. The more usually expressed for $K_G$ does not normalize the pressure or the pressure rise to the initial pressure and is given in units of m/(sbar), but this cannot be applied to higher initial pressures where the form of Eq. 3 is the only practical approach.

Equation 3 may be used with Eq. 1 to covert the reactivity term from $U_L$ to $K_G$ and Eq. 4 results:

$$1/K_v = C_1C_2\ \{K_G/[3.16\ (P_m/P_i - 1)\ E_v]\}\ (E_p - 1)\ P_{Red}^{-0.5} \quad (4)$$

For a given gas Eq. 4 can be expressed as Eq. 5

$$1/K_v = C\ K_G\ P_{red}^{0.5} \quad (5)$$

Equation 5 is the form of the equation that Bartknecht used to correlate this venting data from experiments in a 10 m$^3$ cubic vessel. The $CK_G$ term was 0.167 for methane, 0.200 for propane and 0.290 for hydrogen for a 100mb vent burst pressure. Bartknecht correlated the $K_G$ terms to give a venting design equation for 100 mb vent burst pressure as in Eq. 6.

$$1/K_v = (.1265 \log K_G - 0.0567)\ P_{red}^{-0.5817} \quad (6)$$

The problem with the Bartknecht data is that the value of the reactivity constant for hydrogen is too low if the ratio of the constant is to be the ratio of their laminar burning velocities. The hydrogen to methane ratio should be about 7.7 and it is 1.7 in the work of Bartknecht. The problem is that Bartknecht [1] used a 10 m$^3$ vessel for methane and propane vented explosions and a 1 m$^3$ vessel for hydrogen. Gas flames self accelerate through cellular flames [9] and the distance to self accelerate was different for the two sizes of vessels. It is considered that the design equation for hydrogen explosion venting that is used in the European and NFPA 68 [10] explosion venting guidance is unreliable and this work was undertaken to show that it could be predicted from the burning velocity of $K_G$ for hydrogen using either Eq. 1 or 6.

## Experimental Results

Methane, propane, ethylene and hydrogen – air vented explosions were investigated for the most reactive mixture. The pressure time history for the stoichiometric concentration for the four gases is shown in Fig. 1 for a $K_v$ of 19.3. The peak overpressure increases markedly from methane to propane then to ethylene and finally hydrogen for the same vent area. The venting process was so fast for hydrogen that a detonation pressure spike occurred as the flame reached the vent, as shown in Fig. 1. There was also the onset of detonation at the vent for the ethylene explosion.

Figure 2 shows the time of arrival of the flame at the two centreline thermocouples, T1 and T2, and the time of arrival at the vessel wall on the centreline of the vessel, T3. For all the gases the peak overpressure occurred after the flame had left the vent, after T2. However, the peak overpressure occurred before the flame had reached the wall. This shows that the peak pressure was not due to the external explosion peak pressure, but was caused by the burning of the trapped unburned gases between the central flame moving rapidly to the vent and the outer unburned gas mixture. For the hydrogen-air, the trapped unburned gas flame touched the wall of the vessels well after the flame had exited the vent.

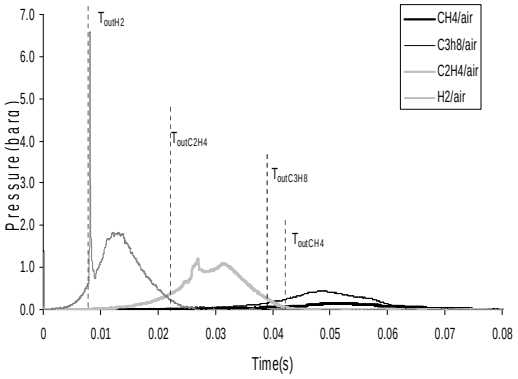


Fig .1 Pressure-time history for different fuels with $K_v$=19.3

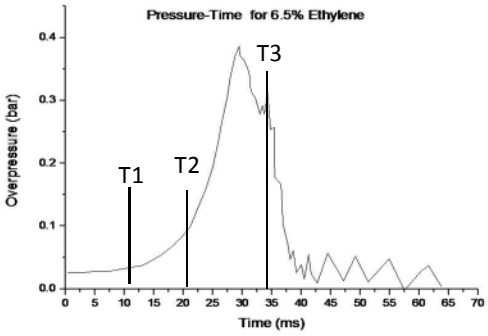


Fig .2 Time of arrival T3 of the flame at the outer wall at 34ms for $K_v$=19.3.

## Flame Speed Analysis

The time of arrival at the two bare bead thermocouples on the vessel centreline were used to determine two flame speeds: the initial flame speed from the time of the flame to travel from the spark to the first thermocouple and the time to travel from the first thermocouple to the second one near the vent outlet. The two flames speeds are referred to as the initial and later flames speeds in Figs. 3-6. For 10% methane –air, a range of initial flame of 2.5-6m/s was obtained for the small vessel with the average flame speed of 4m/s from the time of ignition to the first thermocouple at a distance of 0.078m from the ignition position. There was no significant influence of $K_v$ on this initial flame speed which was close to the expected 3m/s spherical flame speed that has been measured in laminar flames in spherical vessels [8, 9]. The flame speed increased in the later stage of the explosion reaching up to twice the initial flame speed as shown in Fig 3. The later flame speed was not significantly affected by the vent coefficient. This was not expected as the unburned gas velocity at the vent throat increases as $K_v$ increases and this was expected to result in an increase in the flame speed approached the vent as the vent area was reduced (higher $K_v$).

However, the last thermocouple was located 1.3 D upstream of the vent and it may be that this was sufficiently far from the vent for the flame acceleration by the vent flow to have little influence on the velocity more than 1.3D upstream.

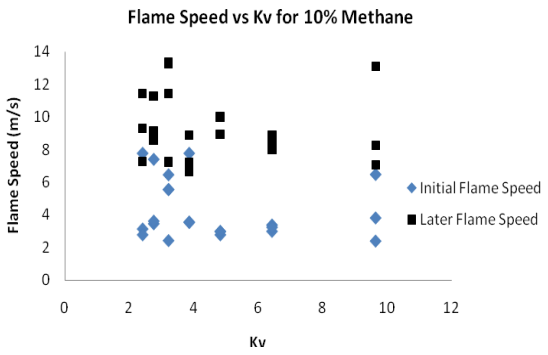


Fig .3 Flame speeds at different stages of flame propagation for 10% methane

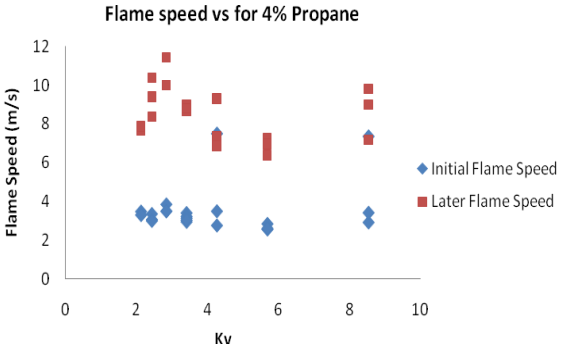


Fig .4 Flames Speed for 4% propane for different Kv.

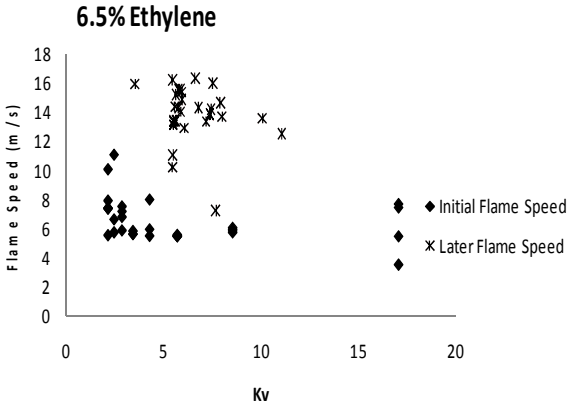


Fig .5 Flame speeds at different stages of flame propagation for 6.5% ethylene

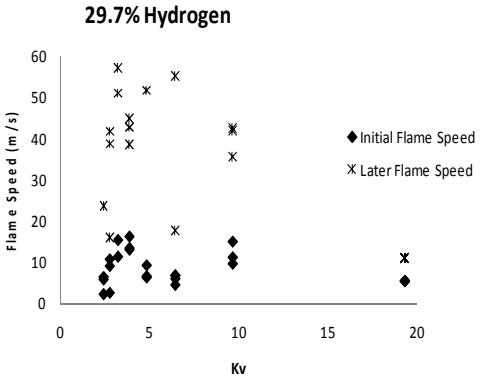


Fig .6 Flame speeds at different stages of flame propagation for 29.7% hydrogen

Propane also showed a steady initial flame speed of 3.5m/s for all the vent sizes as shown in Fig 4. This is close to the spherical flame speed for propane. The later flame speed was about 10 m/s and relatively independent of $K_v$. For ethylene there was an initial flame speed of about 6 m/s. The later flame speed was highest at low $K_v$ at about 15 m/s and then decreased as $K_v$ was increased. For hydrogen the initial flame speed was about 10 m/s which is close to the spherical flame speed for 30% hydrogen in air (14m/s), in a closed constant volume explosion vessel [8]. The later flame speeds increased to 50 m/s at low $K_v$ and decreased to 10 m/s at high $K_v$. This was unexpected as the unburned gas velocity through the vent was increasing with increase in $K_v$. However, as $K_v$ increases the vessel end wall becomes increasingly closed and the mean velocity in the vessel decreases due to the flame essentially propagating towards a flat wall with a small hole in it.

The ratio of later and initial flame speeds was about 3 for methane, propane and ethylene. This ratio increases to about 5 for hydrogen-air. This indicates an acceleration of the flame which may not be linked to the increase in unburned gas velocity at the vent. There may be further acceleration of the flame between the last thermocouple and the vent outflow and this is currently being investigated. The flame acceleration by the development of cellular flames could still be

significant [9] but was not expected in a vessel length of 0.46m. If the distance is large enough, self acceleration of laminar flames into cellular flames can increase the flame speed by about a factor of 3 [9], which is close to that measured in this work. It can be concluded that the high instability of the flame front is the major cause of the increased flame speed close to the vent. This is also in agreement with the work carried out in large spherical vessel by Kumar et al, [11] and later work which suggested high flame front instability for higher concentrations of hydrogen [12]. The literature has shown that the stage of self acceleration and cellularity of a laminar flame starts at 0.1m based on the data obtained from experimental work of large spherical balloons [9]. The length of this small cylindrical (0.48m) does allow for some self acceleration of the flames.

The ratio of the hydrogen later flame speed to that for methane is about a factor of 5 and this would create much higher venting overpressures in hydrogen explosions. This ratio is a little lower that the ratio of laminar burning velocities but is sufficiently high to suggest a large overpressure difference with hydrogen. The average flame speed for different gases is shown, for a $K_v$ of 19.3, as a function of equivalence ratio in Fig. 7 in a small vessel of 0.0067$m^3$. The flame speed increased very rapidly in hydrogen/air up to $\Phi = 1.18$ before decreasing gradually at the very rich concentration. The hydrogen/air flame speed was 53.8 m/s at $\Phi = 1.18$. This was about 28 times higher than 2.1 m/s at $\Phi = 0.34$. For ethylene/air, the peak flame speed was 13.6 m/s at $\Phi = 1.0$.

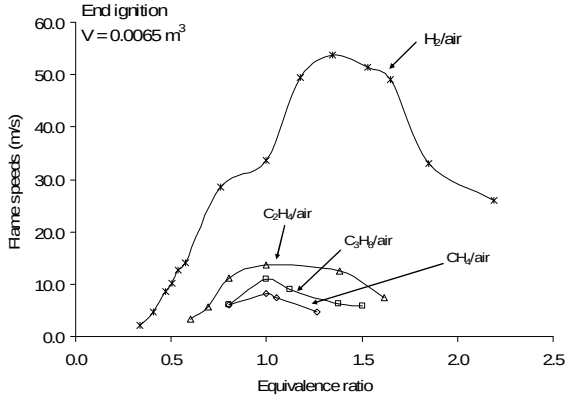


Fig. 7. Flame speeds for the studied gas/air as a function of equivalence ratio.

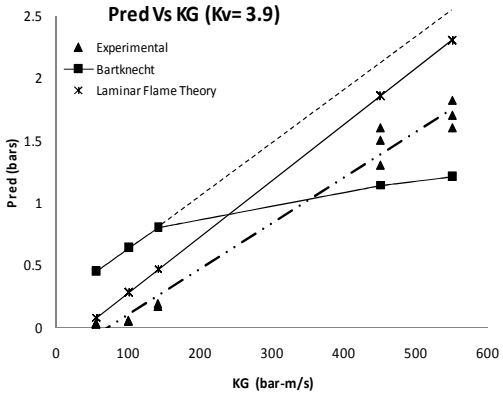


Fig. 8 Influence of $K_G$ on the vented explosion Overpressure for a constant $K_v$.

Harris and Wickens [12] in 6.2m radius spherical balloons showed maximum flame speed of 7, 8 and 15m/s for methane, propane and ethylene-air respectively. These values are lower than the later stage flame speeds in the present work for methane and propane. However, for ethylene the spherical flame speed of 15 m/s is reasonably close to that in Figs.5 and 7. Andrews and Bradley [8] showed that hydrogen flame becomes cellular very easily at a flame radius of the order of 50mm. In the present 9 litre vessel with less than 0.5m of travel distance an average flame speed for stoichiometric hydrogen-air (30%) of 56m/s was measured, which is considerably higher than the 17 m/s measured by Andrews and Bradley [8] for the maximum reactivity hydrogen-air mixture (40%). Acceleration of the hydrogen flames towards the vent is clearly occurring in these small explosions. Although the vent flow would be expected to increase this velocity inversely with $K_v$, no dependence on the measured velocity well upstream of the vent on $K_v$ was detected and hence it is concluded that self acceleration was significant.

Fig. 8 shows the dependence of the overpressure on $K_G$ (using Bartknecht's values) for a fixed $K_v$ of 3.9, with comparison with the above laminar flame theory and Bartknecht's vent design

equation. The results show that the laminar flame theory overpredicts the measured overpressure, which indicates that the flame area at the peak overpressure is less that $A_3$ and no turbulence is generated. Bartknecht's vent overpressure equation greatly overpredicts the results for methane, propane and ethylene but underpredicts for hydrogen. The expected prediction for hydrogen is indicated by the dashed line. It is concluded that Bartknecht's prediction for vented hydrogen explosions, as used in US and EU vent design standards is unsafe and should be revised.

## Conclusions

Vented explosions in a small 9L vessel with an L/D of 2.8 was investigated, as it was considered that this size would produce a laminar flame explosion and enable laminar flame venting theory to be validated without empirical turbulence factors. The results showed that after an initial period of flame propagation from the spark at the laminar spherical flame speed there was a fast central flame accelerating towards the vent, which left a trapped unburned gas volume in the vessel. This fast flame speed was not influence by $K_v$ and was measured well upstream of the vent and not influence by the acceleration of the flow into the vent, which was dependent on $K_v$. It was concluded that self acceleration of the flames was significant in this small vessel over the total length of 0.46m. The vent design procedures based on Bartknecht equations lead to underprediction of the present experimental results for hydrogen and these procedures for hydrogen explosion venting need revision.

## References

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