
R.M. Kasmani¹, G.E. Andrews¹*, H.N. Phylaktou¹ and S.K. Willacy¹

¹ Energy and Resources Research Institute, School of Process, Environment and Materials Engineering, University of Leeds, UK

Abstract

Current guidance on the design of vent ducts usually assumes that the vent duct is the same area as the vent and predicts for most vent duct geometries a large increase in the overpressure. A vent duct with twice the diameter of the vent was investigated and compared with a vent duct of the same diameter as the vent (162mm). A 0.2 m³ explosion vessel was used with an L/D of 2, which is the limit of application of the compact vessel venting design correlations in the USA and Europe. The worst case ignition position on the rear wall centre was compared with central ignition for a vent coefficient, Kv, of 16.4 and a 1.3m long vent pipe. For central ignition, which is the basis of all experimental work on which venting guidance is based, the larger vent duct gave a lower overpressure (400mb) than the vent duct with the diameter the same as that of the vent (580mb), the free vent overpressure was 180mb for central ignition. However, for end ignition the overpressures were much higher than for central ignition and the larger diameter vent duct only had a lower overpressure for lean mixtures. For the most reactive mixture the overpressure was higher for the larger vent duct, 1.05 bar compared with 0.35 bar for free venting. This was shown to be due to the high unburnt gas velocities induced in the vent pipe by the most reactive explosion. This flow induced very high turbulence levels at the vent pipe inlet and these were higher for the larger downstream pipe due to the higher turbulence generated in the dump flow expansion. Flame speeds in the vent pipe of up to 500 m/s were measured for the most reactive mixture in the large vent duct. The overpressure results were not predicted by the current US and European vent design guidance.

Introduction

Venting of explosions offers one of the simplest and cost effective solutions to explosion protection. However, if the maximum overpressure is to be low then the flame outside the vent has to expand to a very large volume, of the order of (E-1) times the vessel volume, where E is the adiabatic flame expansion ratio at constant pressure. For hydrocarbon air explosions this is an external flame volume about 7 times the volume of the vessel. Experiments (1) show that the vented flame length is given by Eq.1.

Maximum flame length = const V^{1/3} \quad [1]

where the constant is 8 for a vertical discharge and 10 for a horizontal discharge.

This would give a 30m flame length for say a 9m³ volume with a horizontal discharge. These very large flames can only be considered acceptable if the vented vessel is located in the open with no people or equipment within 30m of the vent. In many circumstances this is not possible, particularly in industrial plant that is enclosed, with production workers in the vicinity. Under these circumstances a vent duct is required to be fitted to the vent, to discharge the vented flame to a safe place, which is often at roof level.

* Corresponding author: profgeandrews@hotmail.com

Proceedings of the European Combustion Meeting 2009

For vented explosions connected to a vent duct, NFPA 68 [2] and the European Venting standard [3] use the work of Bartknecht [4] and who carried out experiments in large volume vented vessels and recommended Eqs. 2 and 3 for the increased overpressure, P’_red, due to a vent pipe of length L.

P’_red = 1.24 P_{red}^{0.8614} \quad \text{for } L < \text{ or } = 3 \text{m (this is } L/D < 6 \text{)} \quad [2]

P’_red = 2.48 P_{red}^{0.5165} \quad \text{for } L > 3 \text{m but } <6 \text{m (6} < L/D < 12 \text{)} \quad [3]

where P_{red} is the explosion overpressure for no vent pipe attached, given from the experimental results of Bartknecht (4) that has been adopted in the US and European standards, as shown in Eq. 4 for a 100mb static vent burst pressure.

1/K_v = [0.1265\log K_G - 0.0567]/P_{red}^{0.5817} \quad [4]

K_v is the vent coefficient, V^{2/3}/A_v , where V is the vessel volume and A_v the vent area. K_G is the mixture reactivity parameter, (dP/dt)_{max} V^{1/3} bar m/s (55 for methane and 100 for propane). The maximum rate of pressure rise in the definition of K_G is that in a closed vessel explosion of volume V with central ignition.

Eqs 2 and 3 show that the addition of a vent pipe greatly increases the explosion overpressure if the pipe is longer than 3m but has a much smaller effect for vent
pipes less than 3 m in length. For example if $P_{red}$ was 0.4 barg then Eq 2 predicts that the addition of a vent pipe of the same size as the vent would increase the pressure to 0.55 barg and to 1.54 barg for Eq. 3. The effect of mixture reactivity is assumed to be taken into account in Eqs. 2 and 3 by the impact of mixture reactivity, $K_r$, on $P_{red}$ from Eq. 4. Hence, the assumption is that the flow in the vent pipe and the additional back pressure that this causes is exactly proportional to the effect of mixture reactivity on $P_{red}$.

Equations 2 and 3 were provided by Bartknecht [4] as the correlation of his experimental results carried out in a 1 m$^3$ explosion vessel with a vent burst pressure of 150 mbar and a vent and vent pipe diameter of 0.2 m or a vent coefficient, $K_v$ ($V^{0.5}/A_v$), of 33.3. His maximum vent pipe length for Eq. 2 was 3 m (L/D =15) and for Eq. 3 was 6 m (L/D =30). However, he also makes it clear that the two correlations were for vent flow velocities $<330$ m/s for Eq. 2 and $>330$ m/s for Eq. 3. These are roughly distinguishing between subsonic and sonic venting flows and in the present work it will be shown that Eq. 3 fits the data better even though the 1.3 m pipe length is $<3$ m as the vent flow velocity was sonic. The present work investigates a $K_v$ of 16.4 with a 0.162 mm gate valve and 1.3 m long vent pipe (L/D =8) for a 0.2 m$^3$ vessel. The results should agree with Eq. 2 but are shown later to give no agreement with Eq. (2), but better agreement with Eq. 3. There has been no validation of Eq. 2 and 3 for different $K_r$, or vessel volumes, even though they are the basis of the US and European standards for the use of vent pipes.

For dust explosions, Bartknecht (4) has correlated data for a 1 m$^3$ vessel with two vent and pipe sizes of 0.3 and 0.5 m diameter and 0.3 and 0.5 m diameter (K = 14.1 and 5 respectively) and for Kst of 100, 200 and 250 m/s. The correlations are shown in form to Eq. 2 and 3 for gases and are given in Eq. 5 and 6.

$$P_{red}' = 1.84 P_{red}^{0.654} \text{ for } L < or \text{ } 3m \quad \quad [5]$$

$$P_{red}' = 3.00 P_{red}^{0.4776} \text{ for } L >3m \quad \quad [6]$$

where $P_{red}$ is the overpressure for a free vented explosion and is given for a 100 mbar static vent burst pressure by Eq. 7 for a maximum closed vessel peak dust explosion pressure, $P_m$, for the dust of $<9$ bar

$$1/K_r = 6.02x10^5 P_{red}^{0.5071} P_m K_r \quad \quad [7]$$

where $K_r$ is the dust reactivity = (dP/dt)$_{max}$ $V^{1/3}$

These equations have had some independent validation in the work of Lunn et al. (5) using an 18.5 m$^3$ dust explosion vessel with vent and vent pipes of 0.9 m and 1.1 m diameter ($K_v$ = 11 and 7.4) for a range of $K_r$. The results showed significantly lower overpressures than Eqs. 5 and 6. In order to reduce the peak over pressure in an explosion with a vent duct to that of a simply vented explosion (venting without the duct pipe attached), the vent area and vent pipe diameter needs to be increased (4), but there has been no specific experimental validation of this procedure. In the presence of a vent duct, an increase of venting area and duct diameter has not been found to always result in a decrease in the peak over pressure (6-9).

The main reason for the increase in the overpressure when long vent ducts are attached to vents is due to the phase in the explosion when the flame is in the vent pipe with unburnt gas mixture ahead of it. The expansion of the burnt gases in the vent pipe greatly accelerates the unburnt gas flow and this increases the vent pipe friction, inlet and exit pressure losses [5]. These effects are a function of the dynamic pressure in the vent pipe. In principle the dynamic pressure in the vent pipe can be reduced by simply using a larger vent diameter than that for the vent, rather than increasing both the vent and vent pipe sizes. For example, if the vent pipe was twice the diameter of the vent then the vent pipe dynamic pressure would be reduced by a factor of 16, if the vent mass flow rate remained constant. Some evidence that a larger vent pipe diameter would reduce the overpressure with no change in the vent size was provided by Nagy [10], which is quoted in NFPA 68 [2]. Nagy investigated the influence of a 35% increase in the vent duct diameter (83% increase in area) for the same vent diameter and compared this with an explosion with a 35% increase in vent diameter and pipe diameter. Vent pipe lengths up to 5 m were investigated. The results for a 5 m long vent pipe showed that the overpressure where the vent pipe alone was increased in diameter was only 7% higher than that when the vent and pipe diameter were increased. From the experiments performed on dust explosions with vent pipes [5], Hey [11] has suggested that the technique of using a larger vent duct diameter than the vent diameter is effective if the duct area/vent area is about $2-2.5$ and when $P_{red}$ is less than 0.5 barg. It is considered that this approach would be a simpler method of designing for safe vent pipes and the present work investigated for gas explosions a vent pipe that was close to twice the vent diameter, as recommended by Hey [11].

**Experimental Methods**

The experimental set-up is shown in Fig. 1. A 0.2 m$^3$ steel cylindrical explosion vessel was used with a L/D of 2. This was used as this L/D is the limit of application of the Bartknecht venting correlations in Eq. 3, as used in NFPA 68 [3]. A vent diameter of 0.162 m was investigated ($K_v$, 16.4) mounted on the end flange of the explosion vessel. Downstream of the vent was a 0.162 m gate valve. This was closed when the mixture were made up by partial pressure and then opened just prior to ignition. A vent pipe 1.0 m long was attached to this duct, but with the gate valve and the dump vessel pipe attachment the total length of 0.162 m vent pipe to the discharge point was 1.3 m (L/D =8.0). If the 1 m long vent pipe was removed than the vent pipe was reduced to the 0.3 m of the gate valve and dump vessel connecting flange (L/D =1.85). This was effectively a free vented explosion discharge and this configuration was used as the baseline free venting condition.
vented gases discharged into a 50 m³ dump vessel, as shown in Fig. 1. This was 250 times larger than the explosion test volume and effectively gave free discharge conditions, but enabled the tests to be carried out under laboratory conditions. To achieve equivalent venting with a larger vent pipe, the vent pipe discharge was connected to a 0.5m flange opening in the dump vessel. To this was attached a 0.315m diameter vent pipe which was 1m long and 1.94 times the diameter of the 0.162m diameter vent. The same 0.162m diameter gate valve was attached to the vent and discharged into the large vent duct. All the ducts were pressure rated at 250bar, as detonation in the vent pipe was known to be a possibility with overpressure in the 15 bar range possible [6-9, 12,13]. The 50 m³ vent discharge dump vessel was pressure rated at 11 bar.

---

**Fig. 1** Explosion vessel geometry with location of the pressure transducers and thermocouples.

The maximum reduced pressure, \( P_{red} \) was measured at the \( P_1 \) pressure transducer close to the upstream end of the explosion vessel, as shown in Fig. 1. The \( P_2 \) pressure transducer, close to the vent inlet flange, was used for the vent duct pressure loss measurements. Flame speeds in the primary vessel and the vent duct were determined from the time of arrival of the flame at an array of thermocouples on the vessel centreline. The average flame speed between two thermocouples was determined and ascribed to the mid-point of the distance between the thermocouples.

Fuel-air mixtures were prepared using the partial pressure method, to an accuracy of 0.1 mbar (0.01% of composition). Three different methane-air mixtures with equivalence ratios, \( \Phi = 0.68, 0.84 \) and 1.05 were used and ignited with a 16J spark at the central end wall on the vessel centreline. This ignition position has been shown in previous work to have the highest overpressures in vented explosions [14,15]. The uncovered vent condition was investigated and this was achieved using the gate valve. The influence of vent static pressure on the overpressure with the 0.162m vent duct attached has been investigated previously [14].

**The Overpressure with No Vent Duct Attached to the Vent**

The overpressures for the maximum reactivity mixture of methane-air were determined with the 1m vent pipe removed. There was still a short 0.3m vent pipe to connect the explosion vessel to the dump vessel. However, this is considered to be effectively a free discharge. The measured peak overpressures for the maximum reactivity mixture of methane-air (\( \Phi = 1.05 \)) was 180mb for central ignition and 350mb for end ignition. These are much lower overpressures than are predicted by Eq.4, which gives the overpressure to be 5.45 bar and the presence of a 100mb static pressure in the data for Eq. 4 is not going to explain such a large difference. There is no limitation on Eq.4 for the value of \( K_e \) that it applies to. However, the experimental data did not include volumes below 1m³ and it may be that Eq. 4 does not apply to small vented volumes, but no limitation on the lower volume size is set in the European Standard [3]. Examination of the venting data of Barkknecht [4] shows that all of his vessel volumes had lower overpressures than for Eq. 4 and that this was the correlation for his data for a 10 m³ vessel.

**Effect of Duct Diameter on \( P_{red} \)**

The results for central ignition in Fig. 2 show strong evidence that the use of a duct diameter twice that of the vent [4 times the area] significantly reduced the overpressure compared with a duct of the same diameter as the vent, in agreement with with the results of Nagy (2, 10) and Hey (11). For a freely vented explosion with central ignition the overpressure was 180mb for the most reactive mixture. With the large vent pipe the overpressure was 400mb and this increased to 580mb with the vent pipe the same diameter as the vent.

It was expected that the use of a vent pipe with twice the diameter as the vent would reduce the dynamic pressures in the vent pipe by a factor of 16 and that the increase in overpressure would scale by this factor. The increase in the vent overpressure with a vent pipe the same diameter as the vent was 400mb and 1/16 of this is 25mb which should give a total overpressure of 205mb. The measured overpressure with the large diameter vent pipe was 400mb, an increase of 220mb on the free vent, not the 25mb increase expected. This implies a factor of 3 increase in the mean velocity in the vent pipe from that expected. However, this assumes flat velocity profiles and this is unlikely as the vent jet has to expand and the velocity profile will be high in the centre. If the velocity profile in the vent duct was parabolic then the actual dynamic pressure is twice the mean dynamic pressure. Thus the velocity profile in the large vent duct is the likely explanation of the higher than expected increase in the overpressure.

In addition there is turbulence generated in the flow expansion, which is greater than that at the pipe inlet with no flow expansion. This occurs as a result of the known higher pressure loss of flow expansion from an orifice compared with that at a sharp pipe entry. This higher pressure loss generates more turbulence and this will cause the vented flame to accelerate and hence contribute to the higher overpressure. For the vent pipe with the same diameter as the vent all the velocities in the vent pipe are higher than for the larger pipe and this gives a higher flow backpressure and hence the higher
overpressures shown in Fig. 2 for central ignition.

The peak overpressures for end ignition are shown as a function of the equivalence ratio in Fig. 2. This shows that for end ignition of lean mixtures, with the vent pipe diameter twice the vent diameter, the overpressures were well below those for the vent pipe of the same diameter as the vent and were only slightly higher than the values for central ignition. However, for the most reactive mixture at Ø=1.05 the large vent duct had a high overpressure of 1050mb compared with 850mb for the vent duct of the same diameter as the vent. This overpressure cannot be predicted from Eqs. 2 and 4, mainly due to the inability of Eq. 4 to predict the free vented overpressures, as discussed above.

If the measured free vent overpressure of 0.35 bar for end ignition is taken as $P_{\text{red}}$ for free venting in Eq. 2, then the effect of a vent duct <3m long is predicted to be an increase in the overpressure to 0.5 bar. This is well below that measured experimentally for end ignition. If the same procedure is adopted for central ignition, which is the basis for Eq. 2, then the measured 0.18 bar overpressure for a free vent is predicted to increase to 0.283 bar, well below the 0.58 bar measured.

If the correlation in Eq. 3 for ducts >3m is used then the predicted increase in the overpressure from the measured free vent value is 1.02 bar for central injection and 1.41 bar for end injection. These predictions are closer to the measured results in Fig. 2 (0.85 and 1.05 bar respectively). As discussed above, Eq. 3 applies for sonic venting conditions as well as long vent pipes and it will be shown below that the venting conditions are close to sonic with a vent pipe attached.

Ponizy et al [6,7] demonstrated that a significant increase of over pressure occurred with relatively large vent ducts. This was shown to be due to the compression wave propagating towards the vessel, which was generated at the flame front in the duct created by the highly turbulent vent discharge flame. A model of the turbulent acceleration of dust in ducts have been performed by Clark and Smoot [16] which showed that the flame accelerated more rapidly and propagated at higher velocities in larger ducts. Increasing the diameter will increase the turbulent Reynolds number. A very high pipe turbulence level leads to very high flame speeds in the vent pipe. It is considered that this phenomena was occurring in the present work with the large diameter vent pipe with end ignition.

Fig. 3 shows the pressure and flame position time records for the two vent duct diameters for the most reactive equivalence ratio of 1.08 for end ignition. The maximum $P_{\text{red}}$ occurred after the flame exited the vent pipe for both vent pipe diameters. This was not due to an external explosion overpressure, as the pressure $P_5$ measured at the vent duct exit was low. The pressure difference between the explosion vessel and the vent pipe is shown in Fig. 4 as a function of time, together with the vent duct explosion pressure. This shows that when the flame was in the duct there was a negative pressure difference, which was higher for the large vent duct. This will cause the flow to reverse and create high turbulence in the explosion vessel. Much of the unburnt gas mixture remains in the explosion vessel at the time that the flame enters the vent duct and the turbulence created by the reverse flame flow from the vent duct in the explosion vessel caused a sudden increase in the turbulent burning rate in the explosion vessel and this created a high rate of vent discharge and the observed large increase in the overpressure. This phenomena has also been found by other workers (6,7,14,15).

**Pressure loss and unburnt gas velocity**

The pressure difference between the explosion vessel and the duct in the initial stage of the explosion can be used to compute the mean velocity of unburnt gas into the duct, during the period before the flame
This high velocity in the vent pipe creates high turbulence and when the flame arrives the flow ahead of the flame accelerates and shock waves will be generated. This will result in a high back pressure and the observed reverse flow back into the explosion vessel [6,7,14,15].

The induced flow through the duct plays an important role in the final severity of the explosion. This flow in the vent pipe is driven by the flame speeds and burnt gas expansion in the main vessel. For lean fuel-air mixtures, i.e. $\Phi = 0.68$, there was negligible effect of the duct length or diameter (L/D ratio) on the both flame speeds inside the vessel and the duct. At $\Phi = 1.08$, the highest explosion vessel flame speed in the upstream vessel was 22.8 m/s for the short vent duct, which was close to a free discharge. For the large vent duct the peak upstream flame speed was 19 m/s and for the vent duct the same size as the vent it was 16.8 m/s. The flame speeds approaching the vent were much lower for lean mixtures and hence the induced flow was lower and the impact on the overpressure of the vent duct was then lower.

The flame speed in the main vessel approaching the vent were considerably higher than for spherical laminar flame speed (~3 m/s). This was due to two effects: firstly self acceleration of the flame through the cellular flame front mechanism and secondly the suction effect of the vent discharge on the flame shape which would draw the flame expansion preferentially in the direction of the vent (14,15). These effects were both higher for end ignition, as the distance to the vent was double that for central ignition and hence the two effects were enhanced. This was the main reason why the end ignition gave higher overpressures compared with central ignition.

The flame speeds inside the duct were much higher than in the upstream vessel and were similar for both duct diameters, apart from the $\Phi=1.08$ condition when the larger duct had a much higher peak flame speed of 490 m/s for L/D = 3.18. The larger vent duct created a flow expansion from the vent jet vena contraction to the duct wall. This flow expansion created a pressure loss that is the source of the turbulence that accelerates the flame. This pressure loss is larger when there is a larger flow expansion and for the present geometry the unburnt gas dynamic head pressure loss in terms of the vent area dynamic head, was 0.47 for the 0.162m vent pipe and 1.27 for the 0.315m diameter vent pipe. This produced more turbulence and a greater flame acceleration of the flame in the larger vent pipe. Also the lower mean velocities in the larger pipe enabled a flame to propagate in regions where there was local turbulent quenching in the smaller vent pipe (14,15) and this would increase the back pressure, as found experimentally. For leaner mixtures the velocities were much lower and the turbulence generation was significantly lower, as this is proportional to the square of velocity. Hence, the effects of the vent pipe was much lower for the slower burning leaner mixtures.

entered the vent duct. The dynamic head pressure loss for a pipe inlet for incompressible flow is 0.5. The pressure difference reaches a maximum of 0.2 bar, just prior to the flame entry in the vent duct, as shown in Fig. 5. This corresponds to a mean unburnt gas velocity in the vent of 258 m/s. However, the sharp edge to the vent will produce a vena contraction and the velocity at the vena contraction, using a contraction coefficient of 0.61, would be 423 m/s. This is close to the speed of sound (360 m/s) and indicates that sonic flow occurred.
Conclusions
1. A vent duct with flow area 4 times that of the vent with $K_v=16.4$ was investigated for a vessel with an L/D of 2 and volume of 0.2 m³ for methane-air explosions. For central ignition the maximum overpressure for the most reactive mixture was 180mb for a free vent. This increased to 580mb for a 1.3m long vent duct of the same diameter as the vent. However, when the vent pipe diameter was increased to twice that of the vent, with the same length, the overpressure was reduced to 400mb. This demonstrates the effectiveness of the use of a vent duct of larger area than the vent. For less reactive lean mixtures the influence of the vent duct was much lower.

2. For end ignition in the same vessel with $K_v=16.4$, the overpressure was higher than for central ignition for all mixtures tested. For lean mixtures the relative influence of the two vent ducts was the same as for central ignition, but all the values were a little higher. However, for the maximum reactivity mixture the overpressure was 350mb for a free vent and this increased to 850mb with a vent duct the same diameter as the vent and to 1050mb for the vent duct twice the diameter of the vent. This result was unexpected and the reason for this abnormal performance was investigated.

3. The cause of the large increase in overpressure for both ducts for $O=1.08$ with end ignition was the higher flame speeds upstream of the vent due to the greater distance for flame acceleration. This induced a high unburnt gas velocity into the vent duct. For the $K_v$ of 16.4 this created near sonic flow conditions at the vent vena contraction. The arrival of the flame in the vent created sonic flow in the vent duct and the consequent high back pressure created a reverse flow into the explosion vessel. This created high turbulence which accelerated the combustion of the remaining unburnt mixture in the vessel and this further accelerated the flow in the duct creating the peak overpressure.

4. The present design correlations for explosion vents and vent ducts, which are based on very limited experimental data, do not predict the present results and their reliability for small vessel volumes with high $K_v$ is in doubt. Further work is required in this area if more reliable design guidance is to be given.

Acknowledgements
We would like to thank the EPSRC, HSE and BNFL for research contracts that have developed the explosion test facility. R. M. Kasmani would like to thank the Malaysian Government for a research Scholarship. S. Willacy would like to thank the EPSRC for a research studentship. The test facility was constructed and operated by Bob Boreham.

References
3. European Gas Explosion Venting Guidance prEN 14994:2006 (E)