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Gas Explosion Venting: Comparison of Square and Circular Vents

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In vent design guides there is no reference to the shape of the vent, only to its geometrical area. This work was carried out on the commonly used circular and square vent shapes for the same geometrical area, in order to investigate whether vent shape was a significant parameter in vent design. The work was carried out in a 0.01 m^3 cylindrical explosion vessel with an L/D of 2.8 with end wall ignition opposite the vent, which is close to the limit of applicability of US and European vent design guides for compact vessels. The vents were located on the centreline of the vessel and were compared under free venting conditions. The work was carried out for the most reactive gas mixtures of methane/air and ethylene/air. The impact of the vent shape was mainly on the external explosion and was significant at low $K_v = V^{2/3}/A_v$, with a reduced overpressure for square vents of about 30%. The effect of the vent shape was greater for ethylene/air and occurred at all K_v tested from 3.6 to 10.9. There were two contributory factors to the effect, the change in the discharge coefficient of the vent with vent shape and the greater entrainment of external air into square jets, which caused the jet to spread faster and have lower flame speeds and lower external overpressures.

1. Introduction

Explosion venting is designed to reduce the explosion overpressure, thereby reducing the impact of damage to structures or containment and people. The vent area, A_v, is a key factor in determining the maximum reduced pressure, P_{red}, in explosion venting (European Standard, 2007; NFPA , 2013). Venting of explosions involves the expanding flame pushing unburned gas through the vent, which behaves as an orifice in a pipe flow. In venting theory and in some standards, the classic orifice plate flow equation is used and this has an effective area that is a discharge coefficient, C_d, multiplied by the geometrical area, A_v. The discharge coefficient, C_d, for a small vent or large K_v ($V^{2/3}/A_v$) is normally 0.61, which is due to the contraction of the jet flow through a circular vent and can be predicted from ideal fluid flow. C_d increases as K_v decreases, as detailed by Kasmani et al. (2010) and is 0.7 for a K_v of about 2. In NFPA 68 (2013) the C_d was taken as a fixed value of 0.7, even though the methodology they used was based on the work of Swift (1980) who used a C_d of 0.61. NFPA 68 (2013) venting design standard uses the constants from Swift's work adjusted for the Cd difference. NFPA 68 (2013) also says that if A_v occupies an entire wall of the enclosure, then a C_d of 0.8 shall be permitted to be used. The European Venting Standard (2007) does not specifically include C_d in the design methodology, as it is based on the work of Bartknecht (1993) who used circular vents and so C_d was incorporated into the empirical coefficients in the design equation. Both vent design standards thus have no procedure to take into account any influence of the vent shape on the vent design. However, the European Standard (2007) in section 6.2 states that 'rectangular vents are as effective as square or circular vents'. This work was undertaken to determine if this statement and the assumption of a constant C_d for all vent shapes in NFPA 68 (2013) are justified.

Fakandu et al. (2013) have shown that the assumption in the venting standards that the number of vents does not influence the vent design is not justified, where the overpressure is controlled by the external explosion. An increase in the number of vents reduces the length scale of turbulence in the external turbulent jet flame which reduces the turbulent burning velocity and the overpressure. The use of several vents is encouraged in the vent design standards for large vented vessels, but not because they reduce the overpressure. The European standard (2007) in Section 6.2 states that 'the location of multiple vents to achieve uniform coverage of the enclosure surface to the greatest extent practicable is necessary', but no reason for this is given. As the pressure inside an enclosure is uniform across the surface, the number of vents should not matter for the same vent area, unless the number influences the vent process, as found by Fakandu et al. (2013).

For free venting the pressure loss of the flow of unburned gas through the vent is one cause of the vent overpressure, P_{fv}, (Fakandu et. al., 2011, 2012, 2013; Kasmani et al., 2011). and the other is the external explosion, P_{ext} (Cubbage and Simonds, 1955, Cooper et al 1986 and Bauwen 2010). Both of these causes of the overpressure are potentially influenced by the shape of the vent. The flow through the vent is influenced by any change in C_d with the shape of the vent. The shape of the vent may also influence the shape and area of the flame upstream of the vent, which influences the flame speed and flow through the vent. The pressure loss in pipe flow is related to the flow area base on the hydraulic diameter and this requires a square duct to have 28% greater flow area than a circular duct for the same pressure loss. The implication of this is that for the same flow area the pressure loss would be higher for the square duct for the same mass flow rate.

If the same considerations applied to flow through circular and square orifices then the implication would be that C_d would be lower for square orifice. Andrews and Ahmad (1994) have shown that non-circular orifices do have lower C_d than circular orifices and rectangular orifices had the greatest difference. If a vented explosion overpressure was controlled by the pressure loss of unburned gas through the vent, then it would be expected that a square vent would have a higher overpressure than a circular vent. However, this would only occur if the shape of the vent did not reduce the upstream flame speed and hence reduce the mass flow of unburned gas through the vent.

The external explosion is also influenced by changes in C_d through changes in the pressure loss and the turbulence in the external jet flow and this influences the external flame speed. Thus a lower C_d for square vents would be expected to increase the external jet turbulence through the increase in pressure loss. This would lead to higher flame speeds in the external jet and potentially higher overpressures. However, jets that are not round were shown by Koshigoe et al.(1989) and Gutmark et al. (1985) to influence the rate of spread of the jet and non-circular jets were shown to spread faster than circular jets. This would mean that a non-circular vent would have a greater entrainment of air and the jet would slow down more quickly and have lower flame speeds and overpressures as a consequence. This was the effect of the vent shape found in this work which shows that square vents had a lower overpressure than circular vents.

The only previous work we have found on the effect of the vent shape in relation to vent design is in the work of Nagy (1983). He describes an extensive series of tests using compressed air and measured the pressure as it flowed through the orifice type vents. Different vessel volumes and sizes of vents were used with three different vent shapes: circular, square and rectangular. He concluded that the shapes of the vent (circular, square and rectangular) did not significantly influence the orifice C_d and a mean value of 0.9 was recommended for all vent areas and all volumes. This is probably the origin of the neglect of vent shape in the vent design standards. Nettleton (1975) also found that the pressure generation in vented vessels with different vent shapes had little or no effect on the explosion over pressure. However, there were three issues with the experiments of Nagy (1983): firstly, no vented explosions were carried out with vents of different shape; secondly, the tests were carried out for very small vents relative to the volume and the lowest K_v was 19; thirdly, the values of C_d were too high and some were >1 which is impossible. When the Nagy (1983) data is examined there was a difference in C_d for circular and square or rectangular vents for the lowest vent areas in small vessels. This was 0.72 for circular vents and 0.82 for square or rectangular vents. The effect of this difference would, for the same vent area, give a lower overpressure for square vents compared with circular vents, which is exactly the finding of the present work. However, in the work of Andrews and Ahmad (1994) the C_d for a thick circular hole was 0.9 and for a rectangular hole of similar thickness it was 0.74 and in their work no C_d greater than 1 was measured. The higher C_d for a circular hole was due to using a thick plate, which allowed flow re-attachment within the hole.

2. Experimental methods

A small cylindrical vessel of 10 litres volume (L=0.460m, D=0.162m and L/D 2.8) was used for vented gas explosion with free venting, as shown in Fig. 1. This small vessel has been shown (Fakandu et al., 2011) to give reasonable agreement with vented explosion data from larger vessels (Cooper et al., 1988; Bauwens et al., 2010). The European vent design standard (EU, 2007) has no influence of vessel volume other than that contained in the K_v vent coefficient and hence the size of the vessel used in experimental explosion venting research should not influence the results. However, Kasmani et al. (2006) showed that there was a non-linear influence of the vented vessel volume, V, in the literature. The present small 10L

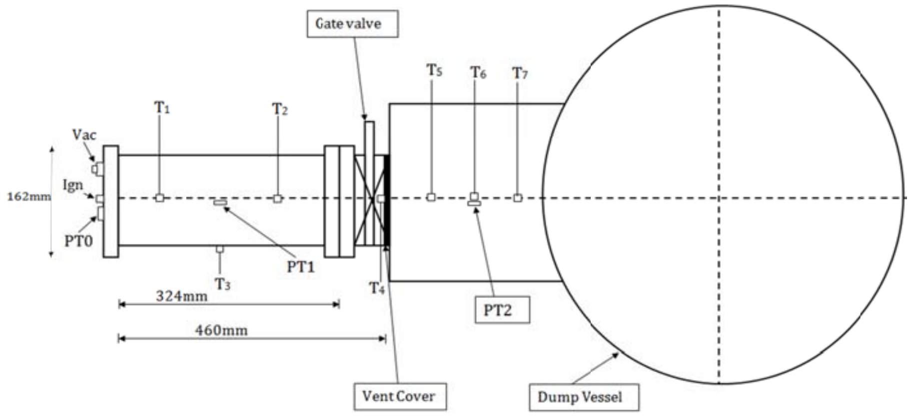

Figure 1: Sketch of the 10 L vented vessel and connected vessels

vessel enabled venting with laminar flame propagation upstream of the vent to be investigated, so that self acceleration of the flame, that occurs in larger vessel, could be avoided.

The 2.8 L/D of the 10L vessel was close to the L/D of 2 for a compact vessel, as recommended by Bartknecht (1993) and also the maximum compact vessel L/D of 3 applied by the EU (2007). NFPA 68 (2013) has no influence of L/D on vent design until L/D> 2.5. The test vessel was connected to a 0.5m diameter cylindrical vessel which was also connected to a 50m^3 dump vessel to safely capture the vented flames, as shown in Fig. 1. The flammable mixture was made up using partial pressures, starting with a vacuum in the explosion vessel. A vacuum gate valve was used to isolate the test vessel during mixture formation. This vacuum gate valve was opened prior to ignition, leaving an open vent with no static burst pressure vent cover. The ignition position was on the centreline of the end wall opposite the vent, as this has the worst case overpressure (Kasmani et al, 2010). Most of the experimental explosion venting data, on which vent design standards are based, is for central ignition (Bartknecht, 1993). The European ATEX Directive as implemented in UK legislation (Statutory Instruments, 1996) in section 3.1.1 requires the maximum possible overpressure to be designed for, that may be expected under extreme operating conditions and this does not occur for central ignition.

Three different vent coefficients, K_v, of 3.6, 5.4 and 10.9 were investigated with both the circular and square vents located at the centre of the vented cylindrical vessel end wall. Two gaseous reacting mixtures were investigated: 10% methane-air and 7.5% ethylene-air mixtures. These mixtures were the most reactive concentration for the fuel gases.

The flame speeds upstream and downstream the vent were measured using the time of arrival of the flame at two exposed junction thermocouples, T_1 and T_2, arranged axially along the centre line of the test vessel, one close to the spark and one close to the vent, as shown in Fig. 1. Thermocouple T_4 was located in the plane of the vent on the centre line and thus located the time of flame arrival at the vent, if the peak pressure occurred after this then it was caused by an external explosion. Thermocouples T_5, T_6 and T_7 were on the centre of the vented jet outside the vent and were used to determine the flame speed of the vented explosion. There was also a thermocouple, T_3, close to the wall on the centreline of the vessel to record the time of flame arrived at the wall.

Three pressure transducers were used to measure the static pressure with the test vessel and the external explosion in the connecting vessel. Piezoresistive pressure transducers were mounted in the end flange (PT0) on which the spark plug was mounted and a second pressure transducer (PT1) was mounted on the centreline of the vessel cylindrical wall, as shown in Fig. 1. A third transducer PT2 was attached to the wall of the 0.5m diameter connecting vessel and used to determine when the external explosion occurred. A 32 channel 100 kHz per channel data logging system was used to record the data.

3. Effect of the change from square to circular vents on the explosion overpressure, P_{red}.

Fig. 2 shows the ethylene pressure v. time results for K_v = 3 with a circular vent for pressure transducer end wall and external discharge vessel pressures. The latter pressure, PT2, does not change until the flame exits the vent and thus determines the time that the external explosion occurred. Fig. 2 shows that this aligns with the peak overpressure, P_{ext}, thus showing that it was the external overpressure that

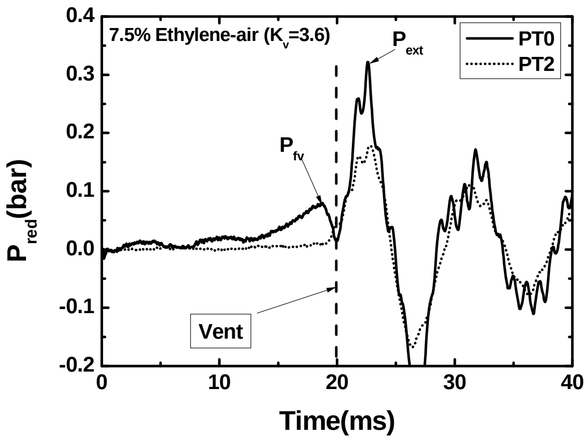

Figure 2 Pressure time records for P0 and P2 for 7.5% ethylene-air with circular vent.

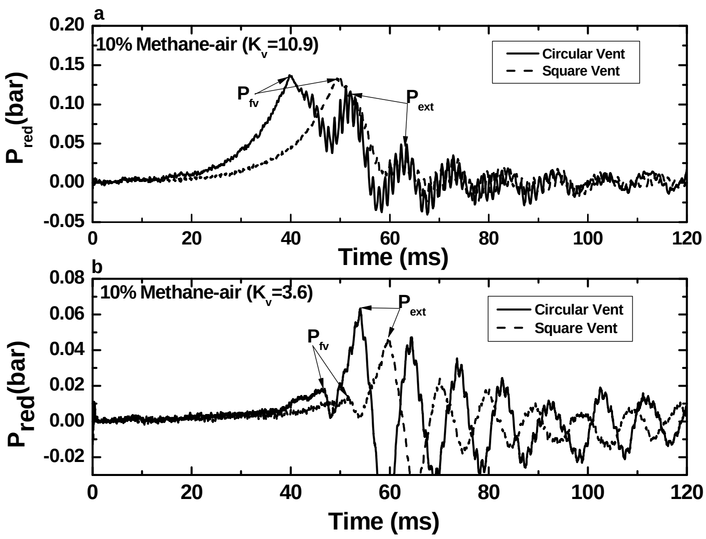

Figure 3: Square and circular vents compared for 10% methane-air (a) K_v=10.9 (b) K_v=3.6

controlled the peak overpressure in this case. The time of arrival of the flame at the vent is marked as Vent in Fig. 2, which also shows that the flame was external to the vent at the peak overpressure. The pressure peak for the flow through the vent, P_{fv}, was much lower than P_{ext} and occurred before the flame reached the vent, as it was due to unburned gas flow through the vent.

Fig. 3 compares the pressure time records for circular and square vents for 10% methane-air for K_v of 10.9 and 3.6. The overpressure due to the flow through the vent, P_{fv}, was the dominant overpressure for both circular and square vents for K_v=10.9 and the overpressures were very close in magnitude for the two vent shapes. Kasmani et al. (2010) has previously shown that for high K_v the dominant overpressure was P_{fv}.

For the larger vent area, K_v = 3.6, the results in Fig. 3b shows that P_{ext} was the dominant overpressure for both circular and square vents. The influence of vent shape was small for P_{fv} similar to Fig. 3a, but a significant influence of vent shape was found in the dominant external overpressure, P_{ext}. The circular vent had more than 30% higher external explosion overpressure than that of the circular vent. This significant change was a result of the greater rate of jet spreading for non-circular jets, as reviewed above, which resulted in faster entrainment of air into the jets and hence reduced the external flame speeds which reduced the external overpressure for the square vent. For K_v=10.9 Fig. 3b shows a major reduction in P_{ext} for the square vent, but in this case P_{ext} was not the dominant overpressure.

Table1 shows the summary of all the experiments conducted for both circular and square vents by varying the vents for three K_v, with three repeat tests for each K_v. Table 1 also shows whether the peak overpressure was due to P_{fv} or P_{ext}. Also shown is the average percentage decrease from the overpressure obtained with the circular vent, when compared to the square vent for the two gas mixtures. Table 1 shows that for methane and ethylene at all K_v the square vents always had a lower overpressure than the circular vents. The difference varied but was typically 30% lower. For methane with K_v = 10.9 the two vent shapes had practically the same overpressure, as also shown in Fig. 3a. For ethylene the results were very consistent with >30% lower overpressures with square vents at all K_v. These results clearly show that for most venting conditions a square vent will give a significantly lower overpressure than a round jet and hence give better protection.

Table 1: Summary of maximum reduced pressure for different gas mixtures and vent shapes

Kv	10% Methane-air (P_{red}-bar)			7.5% Ethylene-air (P_{red}-bar)		
	Circular	Square	Increase (%)	Circular	Square	Increase (%)
3.6	0.062 P_{ext}	0.046 P_{ext}		0.30 P_{ext}	0.23 P_{ext}	
3.6	0.076 P_{ext}	0.051 P_{ext}	35	0.29 P_{ext}	0.24 P_{ext}	30
3.6	0.064 P_{ext}	0.049 P_{ext}		0.32 P_{ext}	0.23 P_{ext}	
5.4	0.069 P_{ext}	0.056 P_{ext}		0.35 P_{ext}	0.23 P_{ext}	
5.4	0.063 P_{ext}	0.055 P_{ext}	17	0.31 P_{ext}	0.23 P_{ext}	46
5.4	0.059 P_{ext}	0.052 P_{ext}		0.31 P_{ext}	0.21 P_{ext}	
10.9	0.133 P_{fv}	0.129 P_{fv}		0.74 P_{ext}	0.57 P_{fv}	
10.9	0.137 P_{fv}	0.133 P_{fv}	3	0.72 P_{ext}	0.56 P_{fv}	31
10.9	0.137 P_{fv}	0.132 P_{fv}		0.78 P_{ext}	0.59 P_{fv}	

4. Flame speeds

The flame speeds for Kv = 5.4 are shown in Fig. 4 as a function of the distance from the end flange, where the spark was located. The maximum or peak flame speed with the circular vent for 10% methane-air downstream of the vent was 30m/s and 85m/s for 7.5% ethylene-air. However, when the square vent was used the peak flame speed was reduced to 21m/s and 75m/s for the 10% methane-air and 7.5% ethylene-air respectively. This was caused by the faster entrainment of air for the square vent thereby reducing the speed of the propagating flame as shown in Figure 4.

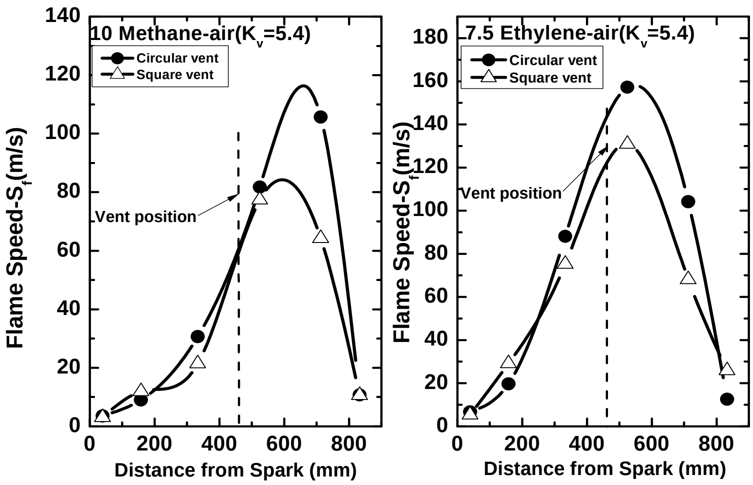

Figure 4: Comparison of the flame speeds for square and circular vents for K_v=5.4

The flame speed upstream of the vent is also shown in Fig. 4 to be lower for square vents than circular vents. This effect was greater as K_v increased. This lower flame speed would produce a lower mass flow of unburned gas through the vent and hence reduce the overpressure for square vents. However, square vents have a lower C_d than circular vents and this would increase the overpressure for square vents. The combined effects nearly cancel out. For methane with K_v of 10.9 the change in overpressure between circular and square vents was very small and this is the only condition where the overpressure was caused by the flow through the vent and not the external overpressure. For ethylene with K_v = 10.9 Table 1 shows that square vents had the highest overpressure due to flow through the vent, but the two overpressures P_{fv} and P_{ext} were nearly the same at this condition

5. Conclusions

The use of square vents is preferable to circular vents, which give at least 30% higher overpressure than square vents. The circular vents gave higher external overpressure (P_{ext}) when compared with the square vents, while small differences were found for the internal pressure (P_{fv}). This effect was concluded from literature work on non-circular jets, to be due to the faster entrainment of air by the square vent jet flow as compared to the circular vent jet flow. This resulted in slower external flames. For methane with a K_v of 10.9, P_{fv} was the higher overpressure and in this case there was very little difference in the overpressures for circular and square vents. Where the peak overpressure was due to the external explosion the square vent always had a lower overpressure than for circular vents. The more reactive ethylene/air mixtures showed more than 30% increase in overpressure at all K_v for round vents compared with square vents.

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