EXPLOSION PROTECTION METHODS BY RELIEFS

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Of all methods for protecting the process plant against the damaging effects of internal gas vapour or dust explosion, explosion relief is the simplest and most robust method of protection. This paper presents experimentally tested empirical relationships for the design of vent openings and appropriate covers for gaseous and dust explosions.

A brief description is given of explosion relief systems.

INTRODUCTION

Many chemical process plants handling flammable gases and dusts present hazards of internal explosions, which could destroy or damage plants. There are many methods available which aim either to prevent or minimise possible explosion damage.

These include:

a) Provision of openings with covers which in the event of an explosion will rupture or be displaced and discharge a large proportion of the explosive mixture and combustion products to a safe area

b) Incorporation of devices which bring about the extinction of the flame front by releasing an extinguishing agent during the initial stages of an explosion

c) Isolating the source of an explosion from the vulnerable parts of the plant, by the use of quick acting valves or barriers of an inert or combustion inhibiting gas, or flame arresters which are systems of narrow passages or cells which cool and extinguish the flame front. All such devices will extinguish the explosion flame front in an early stage of an explosion before disruptive pressures are attained.

This paper discusses briefly the parameters essential for the design of the explosion relief systems and presents empirical relationships derived from the major series of tests as a means of defining various venting requirements.

Sizing of the Openings for the Explosion Reliefs for Flammable Gases

It is essential that any openings provided for the discharge of expanding gases do not allow the explosion pressure to exceed the design limits of the protected plant; therefore design data for relief openings is essential. It is perhaps not appreciated that available test data indicate that different criteria must be applied to containers of different sizes and geometries. There are several correlations available and each of these covers a limited range of volumes. There are also many other investigations which were carried out to achieve relief protection for a specific apparatus. Some of these will be considered in this paper.

A series of explosion tests were carried out in cubical vessels of volumes 8, 28 and 85 l using 4 per cent propane/air and 6.5 per cent ethylene/air flammable mixtures by Palmer and Rogowski (1). These results provided a simple relationship between the maximum pressure and the area of the vent which was expressed as a fraction of the cross-sectional area of the explosion vessel. This correlation agreed closely with the measured values and could be represented by an equation.

$$p = 0.0386\ K^2\ kN/m^2 \qquad (p = 0.0056\ K^2\ lbf/in^2) \qquad (1)$$

where p – maximum explosion pressure

$$K - \frac{\text{cross-sectional area of the vessel}}{\text{area of the vent}}$$

Equation (1) is represented by a dashed line in Figure 1 in which the experimental values are plotted as points. There is a good agreement with the experimental results which were obtained with three different explosion vessels and a wide range of relief openings. In all these experiments the vents were located in the top cover of the explosion vessel, and remained uncovered throughout the event of an explosion. The explosion pressures within the investigated range varied with K and v in accordance with the theoretical equation:

$$p = \frac{v^2 K^2 \rho}{2 C^2} \qquad (2)$$

where C – discharge coefficient
ρ – density of gas at atmospheric pressure
v – gas velocity in an explosion vessel.

These authors repeated some of the experiments with vents covered by the flame arrester using propane/air and ethylene/air flammable gases Rogowski (2). When these results were compared, the maximum explosion pressure varied with the square of the fundamental burning velocity, S_o, of the explosive mixture used. Further tests were made in which the reliefs were covered by covers of various weights. Figure 2 shows the relationship between the maximum explosion pressure and the weight of either loose covers or covers held by permanent magnets.

The performance of reliefs fitted to cubical or rectangular chambers with volumes ranging from 0.23 m^3 (8 ft^3) – 14 m^3 (500 ft^3) have also been examined by Cubbage (3). The areas of relief vents were varied again being expressed as dimensionless K with values from 4 to 1.

The vents were covered in all explosion tests, which were carried out using a town gas/air flammable mixture. Some pressure records showed two pressure peaks. The authors concluded that the first peak was caused by the inertia of the vent cover and the second peak was caused by the frictional resistance of the vent orifice. The maximum values of the first peak agreed well with the empirical equation:

$$p V^{\frac{1}{3}} = a K w + c \qquad (3)$$

where a and c are constants
w – weight of relief per unit area – Kg/m^2
V – oven volume – m^3

which was also expressed in the following form:

$$p_1 V^{\frac{1}{3}} = S_o (0.43\ Kw + 2.78) \qquad (4)$$

when A1 – area of relief
p1 – first peak pressure kN/m^2
S_o – maximum fundamental burning velocity in m/s.

The second peak pressure, p_2, was independent of the oven volume and with town gas/air mixture, its magnitude could be expressed by:

$$p_2 = 7K \qquad (5)$$

Tests with other flammable gas have shown that the value of p_2 varied in direct proportion to the fundamental burning velocity S_o.

The equations quoted so far except equation (2) are entirely empirical and therefore this data should be applied to vessels of volumes similar to those tested. There was however the tendency to extrapolate this data to volumes much larger than those which were tested. There was little justification for doing this, and work carried out in Sweden (4) showed that the explosion in a room of 200 m^3 (7000 ft^3) volume with one side open and covered with light panels, produced a maximum explosion pressure of 5 kN/m^2 (0.75 lbf/in^2) with a 5 per cent propane/air mixture, which was a much higher value than that predicted from equation (5).

Further experimental data was obtained using low inertia reliefs with an explosion chamber 1.7 m^3 (60 ft^3) volume with larger K factors, Harris and Briscoe (5) and Burgoyne and Wilson (6). When the peak pressures are compared with the extrapolated values found by Cubbage (3) they are also much higher.

More recently a series of venting experiments were carried out in a rectangular chamber 29 m^3 (1000 ft^3) volume using layers of varying thickness of methane/air explosive mixture with low inertia vent covers by Butlin and Tonkin (7). These results were extrapolated to a depth equal the chamber height (ie with the chamber full of gas). Table 1 lists these pressures against three values of K. These values are again higher than those from extrapolation of Figure 1.

TABLE 1 - Maximum Explosion Pressures in 28 m^3 Chamber with Methane/Air Mixture

K	Maximum explosion pressure	
	kN/m^2	lbf/in^2
2	7	1.0
4	10	1.5
8	15	2.2

A series of explosions were carried out in reinforced concrete explosion chambers with windows having dimensions 3.5 m wide, 4.0 m long and approximately 3 m high, Dzagosaric (8). The precise values of K factors were not given but the smallest K factor was estimated to be approximately 1.5.

In more recent years a great deal of experimental work was carried out in West Germany on venting of gaseous and dust explosions, see Anthony (9). The explosion tests were carried out in vessels having volumes of 1, 10, 30 and 60 m^3 (35, 353, 1059 and 218 ft^3) using vent openings covered by bursting discs opening at 9.7, 19.3 and 49.6 kN/m^2 (1.4, 2.8 and 7.2 lbf/in^2). Using the results thus obtained it was proposed that the 'cubic law', previously considered applicable to unvented vessels only, could also be applied to vessels incorporating reliefs thus:

$$\left(\frac{dp}{dt}\right)_{max} \quad x \quad V^{\frac{1}{3}} = \text{constant} \quad \ldots\ldots (6)$$

where $\left(\frac{dp}{dt}\right)_{max}$ = maximum rate of pressure rise in a vessel during an explosion.

Although the data supplied may not entirely support the adoption of the 'cubic law' it does however prove (Tables 2a and b) that the maximum explosion pressures in vented gaseous explosions are dependent on $(dp/dt)_{max}$ and indirectly on the volume of the vessel. Tables 2a and 2b show the vent areas required not to exceed a given design pressure, see Anthony (9) and Donat (10). The weakest bursting disc used failed at a pressure of 10 kN/m^2 (1.45 lbf/in^2), a lower bursting pressure than this could be adopted in many instances for an industrial plant.

Table 3 lists the maximum explosion pressures determined (1), (3) and (4) for vents having K factors of 1, 2 and 3, either open or closed by low inertia covers using various flammable mixtures. Evidently the maximum explosion pressures with a given value of K increase with the increase of the volume of an explosion vessel.

TABLE 2a - Vent Areas, m^2, Required for Venting of Combustion of Propane/Air Mixture Inside Vessels of L/D approximately 1 C. Donat. (10)

Max press during venting kN/m^2	30	50	100	150	200	250
Vessel Vol m^3						
	Vent burst pressure = 10 kN/m^2					
1	0.31	0.25	0.15	0.09	0.045	-
10	2.1	1.5	0.80	0.55	0.4	0.3
30	3.0	2.25	1.5	0.9	0.6	0.45
60	4.8	3.0	1.2	-	-	-
	Vent burst pressure = 20 kN/m^2					
1	0.355	0.3	0.21	0.145	0.095	0.07
10	2.18	1.70	1.07	0.74	0.47	0.37
30	2.70	2.03	1.35	0.97	0.72	0.53
60	-	3.76	-	-	-	-
	Vent burst pressure = 50 kN/m^2					
1	-	-	0.195	0.12	0.085	0.065
10	-	-	1.21	0.79	0.56	0.42
30	-	3.48	1.88	1.35	0.97	0.72
60	-	5.22	2.22	-	-	-

TABLE 2b - Vent Areas, ft^2, Required for Venting of Combustion of Propane/Air Mixture Inside Vessels of L/D approximately 1 C. Donat. (10) (Note: Numbers are in Imperial Units.)

Max press during venting, psig						
Vessel Vol ft^3						
	Vent burst pressure = 1.45 psig					
35.3	3.34	2.69	1.61	0.97	0.48	-
353	22.6	16.1	8.6	5.9	4.30	3.23
1059	32.3	24.2	16.1	9.7	6.5	4.84
2118	51.6	32.3	12.9	-	-	-
	Vent burst pressure - 2.9 psig					
35.3	3.82	3.23	2.26	1.56	1.02	0.75
353	23.5	18.3	11.5	8.0	5.1	3.98
1059	29.1	21.8	14.5	10.4	7.8	5.7
2118	-	40.5	-	-	-	-
	Vent burst pressure - 7.3 psig					
35.3	-	-	2.10	1.29	0.92	0.70
353	-	-	13.0	8.5	6.0	4.52
1059	-	37.5	20.2	14.5	10.4	7.8
2118	-	56	23.9	-	-	-

TABLE 3 - Comparison of Maximum Explosion Pressures, in Palmer (1), Cubbage (3) and (4).

K factor	Maximum explosion pressure kN/m^2 (lbf/m^2)		
	Propane (1)	Propane (3)	Butane (4)
1	0.7 (0.1)	2.3 (0.3)	5.2 (0.8)
2	2.1 (0.3)	4.5 (0.7)	
3		7.0 (1.0)	

TABLE 4 - Comparison of the Maximum Explosion Pressures Obtained by Various Workers

	Maximum explosion pressures kN/m^2 (lbf/in^2)				
K factor	Propane (3)	Propane (4)	Pentane (5)	Pentane (6)	Methane (7)
75.8			558 (81)	669 (97)	
20.2			476 (69)	400 (58)	
9.0			193 (28)	207 (30)	
8					15 (2.2)
5.1	11.7 (1.7)		14 (2)		
4					10 (1.5)
3	7.0 (1.0)				
2	4.5 (0.7)				
1	2.3 (0.3)	5.2 (0.75)			

Table 4 lists the maximum explosion pressures indicated (3) to (7) where the experimental data covers a wide range of vessel volumes. Some data (3) and (4) overlap; other data - for methane (8) is of somewhat limited accuracy and was carried out using natural gas/air mixture and is not included in Table 4. Further data (5) and (6)are in reasonable agreement but much greater than other values. Extrapolated values quoted from Butlin and Tonkin (7), in spite of being obtained with natural gas/air flammable mixture, give values similar to those obtained by other workers, using propane/air or pentane/air flammable mixture.

It is not known what degree of repeatability may be obtained in these experiments. However, even under rigorously controlled conditions considerable departure must be expected where different vent covers are used and when the peak pressure controlled by the vent cover determines the maximum explosion pressure. The shape of the vessel and geometry of the vent and vessel would also be expected to influence the results, because of these factors the results give satisfactory agreement.

All results discussed apply to empty enclosures initially at atmospheric pressure. If the enclosures contain obstacles these maximum explosion pressures may be greatly exceeded. If more complex enclosures are involved, again design data is not adequate. There is much evidence from accidental explosions in buildings, that if an explosion propagates through a series of interconnected chambers, much higher maximum explosion pressures will result, see Mainstone (11).

TABLE 5 – K Factors Required for Venting of Stoichiometric Propane/Air Flammable Mixture

Vessel Volume		Maximum pressure during venting kN/m^2 (lbf/in^2)					
		30 (4.35)	50 (7.25)	100 (14.5)	150 (21.8)	200 (29.0)	250 (36.3)
m^3	ft^3	K Values					
1	35.3	3.3	4.0	6.7	11.2	11.0	15.5
10	353	2.2	3.2	5.8	8.5	11.8	21.5
30	1059	3.1	4.3	6.5	11.0	16.0	–
60	2118	3.3	5.0	13.0	–	–	–

Table 5 lists results shown in Tables 2a and b, recalculated to correlate the maximum explosion pressure with K factor (10) and (12). Figure 3 shows the plot of results from Tables 4 and 5. The maximum explosion pressures obtained with small K factors exceed greatly the corresponding values shown in Table 4 whereas the values obtained with large K are somewhat smaller than corresponding values shown in Table 4. Perhaps it is significant that values obtained with small K factor shown in Table 3 where from tests using only loose vent covers. The results presented in Tables 3, 4 and 5, however, present important practical implications for the vent designer who has to arrive at the appropriate vent areas for various enclosures. Vents of large area are likely to be applied to building structures, where window openings may be utilised as vents. In such instances some of the results quoted from Donat (11) may not apply, since the structure of the building is unlikely to withstand such pressures. All are appropriate for industrial applications where vents having large K factors are mostly used.

Ideally the vent designer should have one working formula to cover all possible design requirements. At present such a formula is not available. The designer has to select results which are most appropriate to the case in hand and proceed from these, making an allowance for the flammable gas or dust and the chamber in question, and for the pressure enhancing effects caused by factors such as turbulence or more complex geometry.

If no allowance is given for the complexity of the structure the resultant maximum explosion pressures may greatly exceed values predicted from the data presented above.

The origin and the generation of such pressure pulses is not properly understood. Turbulence, precompression, and pressure and rarefaction waves are often put forward as causes of greatly increased rates of combustion and hence increases in pressure, however. Therefore until further data becomes available no precise allowance can be made for such factors. Some rule of tumb methods are available and should be used in practical situations. A detailed survey of empirical and theoretical formulae for the design of explosion venting has been produced by Anthony (10).

Sizing of Openings for the Explosion Reliefs for Flammable Dust/Air Mixtures

There is a wealth of information on explosion reliefs for dust explosions. However, much of this data is of early origin and many contradictions are to be found in literature. Until two decades ago much of the work was carried out in the USA, but more recently, most work has been carried out in the UK and West Germany. Each of these three countries has produced well defined guide lines for sizing of reliefs for industrial plants. UK recommendations define specific vent areas for three ranges of the maximum rates of pressure rise measured in a small standard apparatus, see Palmer (13). Table 6 lists vent areas as a ratio to the compartment volume.

TABLE 6 - Vent Areas from Dzagosaric (8)

$(dp/dt)_{max}$		Vent ratio	
$MN/m^2/s$	$lbf/in^2/s$	m^2/m^3	ft^2/ft^3
34.5	5000	1/6.0	1/20
34.5–69.0	5000–10 000	1/4.5	1/15
69.0	10 000	1/3.0	1/10

A similar approach was taken formerly in the USA. However, the 1974 revised edition of the same guide (12) advocates vent areas in accordance with the West Germany practice (14). Their recommendations are based on experiments carried out with vessels of various sizes using vents covered by bursting discs. Vessels having volumes of 1 m^3 (35 ft^3), 10 m^3 (353 ft^3), 30 m^3 (1059 ft^3) and 60 m^3 (2120 ft^3) were tested and the results were presented in forms of graphs showing vent areas versus maximum explosion pressure for three grades of bursting discs opening at 9.7 kN/m^2 (1.4 lbf/in^2), 19.3 kN/m^2 (2.8 kbf/in^2) and 70.3 kN/m^2 (10.1 lbf/in^2).

Dusts were divided in three classes in accordance with the rate of pressure rise determined in an experimental apparatus. They are shown in Table 7.

TABLE 7 - Classification of Dusts

Class	dp/dt Rate of pressure rise	
	$MN/m^2/s$	$lbf/in^2/s$
1	$\leqslant$ 50.3	$\leqslant$ 7300
2	50.3–151.7	7300–22 000
3	151.7	> 22 000

The data may be applied to turbulent dusts at atmospheric pressure. The results in tabulated form are also presented by Donat (10).

Vent Closures

Vents usually require some cover eg for the protection and retention of the contents of the protected space and must be installed so that the flammable materials can be discharged safely from the vent. In vent systems designed for buildings some of the non structural elements such as windows may be used as relief panels if their strength is known or can be ascertained. On industrial equipment covers will be specifically designed and mounted and quite often they are required to reseal after an explosion. A variety of closures are available. Bursting discs are widely applied in situations, where a self-sealing relief is not required. A great deal of development has been carried out on bursting discs and a wide variety of commercial products is available. The traditional version is a plain disc made from metal foil with good creep resistance under working loads of long duration but freedom from metal fatigue may be required when exposed to pulsating pressures. Most plain bursting discs are designed to fail under tensile stresses and in order to secure good repeatability high purity metals may be needed. In recent years the performance of bursting discs has been improved by various preformance tests and also by the introduction of materials which fail by brittle fracture or are displaced from the holder after a certain amount of deformation. Most of such innovation concentrated on improvements in repeatability of performance and on design of discs with low bursting pressure and yet with good resistance to accidental mechanical damage and to pulsating pressures. For large non-resealable vents various blow-off panels are advocated, which can be held down by a variety of devices. The simplest self-sealing vent closure for medium and large reliefs is the hinged door. Self-sealing can be achieved by gravity forces with possible assistance from weights in order to obtain a good seal, in addition the door may be held by pretensioned shear pins, springs, catches and metal links which fail under tensile forces. The other common form of closure is in the spring-loaded vent cover. With this type of relief cover helical springs are used, as a rule the advantage offered is slower opening and thus a lower rate of combustion occurs.

Performance of all reliefs depends very much on the rate of pressure rise and the results obtained with static or semistatic tests for bursting discs may underestimate the maximum explosion pressure. Most available methods have been described, see Donat (10) and (12).

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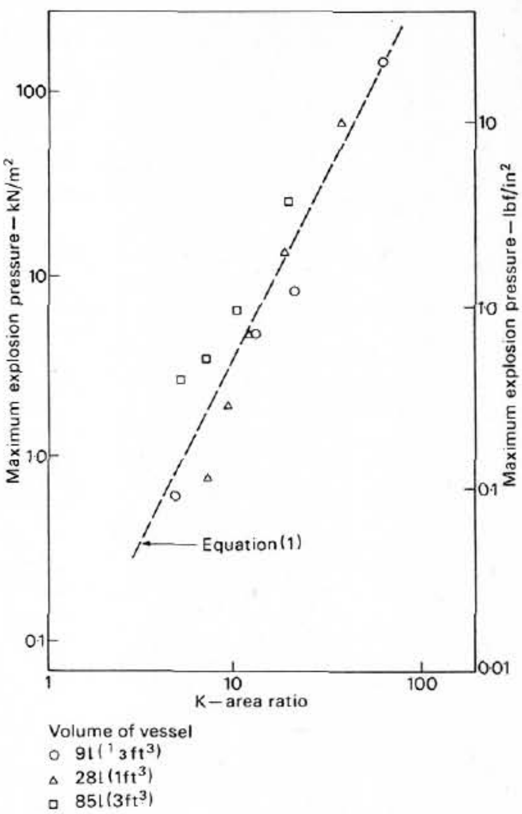

Figure 1 Relationship between vent area and the maximum explosion pressure — 4 per cent propane/air

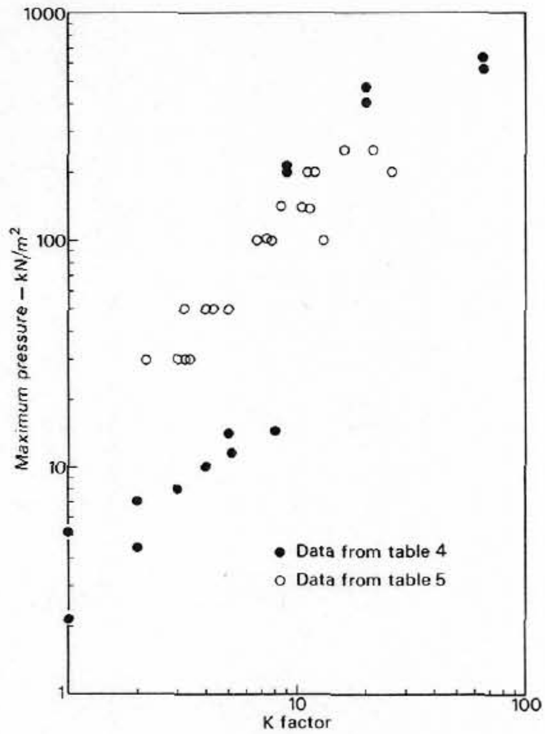

Figure 3 Relation between maximum explosion pressure and K factor

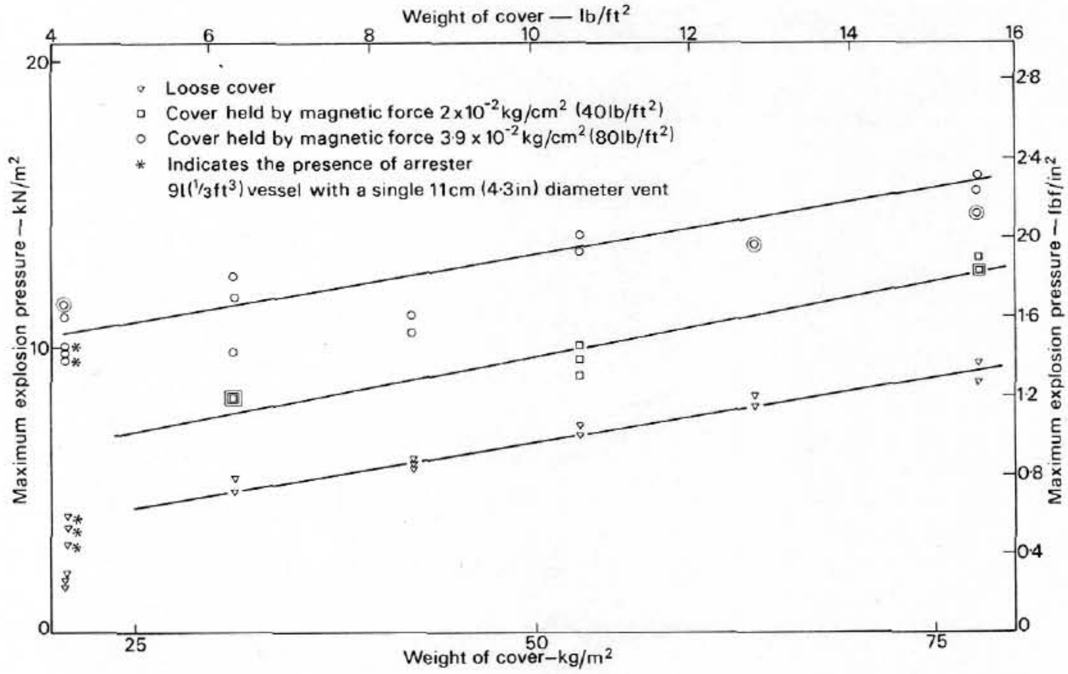

Figure 2 Relation between maximum pressure and the weight of vent cover or the weight of the vent cover plus force of the magnets