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DUST EXPLOSION PROTECTION — A COMPARATIVE STUDY OF SELECTED METHODS FOR SIZING EXPLOSION RELIEF VENTS

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Summary

Explosion relief vents are commonly used to discharge safely the combustion products of a dust explosion in items of powder handling plant. A problem associated with this method of explosion protection is the sizing of the vent area; this must be large enough to prevent explosion pressures from reaching damaging levels but not so large that the use of vents becomes impracticable. This report compares three common methods of estimating vent areas by applying explosibility data determined in the Hartmann bomb and the 20 litre sphere.

Introduction

It is becoming increasingly acknowledged that many materials handled in powder processing plant are potentially explosible. Dust explosions have been the subject of several comprehensive studies [1—3] in recent times. Industries handling materials such as agricultural products, foodstuffs, chemicals, pharmaceuticals, plastics, rubber, wood, confectionery, detergents, soaps, cosmetics, leather, metals, alloys, and coal products are typical of those that are faced with the risk of a dust explosion.

For a dust to explode it must be dispersed into an atmosphere containing sufficient oxygen to support combustion, the dust suspension must be subjected to a sufficiently energetic source of ignition, the dust concentration must fall within the explosible range and the particle size must be sufficiently small to promote ignition and propagation of flame through the suspension.

Explosion prevention and protection

Wherever combustible powders are handled, explosion prevention and protection measures are normally applied simultaneously since only under these circumstances can the frequency and consequences of an explosion be reduced to a tolerable level. However, there are a few situations where total exclusion of ignition sources can be achieved and under these circumstances additional explosion protection, particularly if it is not reasonably practical, need not be used. Explosion prevention measures largely involve a common sense approach to the problem and should include the control of dust suspensions by well designed dust collection systems and general "good housekeeping" throughout the plant to prevent the accumulation of dust on ledges, pipe runs and the like. The latter is extremely important since settled dust less than 1 mm thick over a wide area can provide sufficient volume of suspension for a very serious explosion when dispersed within a building. A major contribution to the prevention of a dust explosion is the avoidance of potential ignition sources such as naked flames, hot surfaces, frictional heat, welding and cutting operations, electric and electrostatic sparks, spontaneous combustion and incandescent particles. If these are to be avoided it is essential that plant is designed so that naked flames or sparks cannot come into direct contact with dust and that all plant is regularly maintained. Inerting of the atmosphere into which the dust is dispersed is an effective method of explosion prevention. However, it cannot be applied in many processes and in those for which it is appropriate it may be expensive.

Explosion protection methods are somewhat limited but may include the strengthening of plant, and in extreme cases, particularly for small volumes, the design of vessels with enough strength to contain an explosion. The most common choice of effective explosion protection is either explosion relief venting or explosion suppression. The most convenient and economical explosion protection technique is explosion relief venting and it should always be considered as the first option. It cannot be used in cases where toxic dust is involved or if the vent cannot be sited so that combustion products can be discharged in a safe and environmentally acceptable manner. Under these circumstances the second option, explosion suppression, should be considered. (There are circumstances in which both explosion relief venting and explosion suppression are used together.)

Sizing of explosion relief vents

A major and sometimes controversial problem arises when prescribing the size of an explosion relief area for a given dust in a given volume. It is essential that the vent area is large enough to prevent the explosion within the vessel from exceeding its design strength (Fig. 1). It is equally important for practical and financial reasons that the vent is not unnecessarily large. Consideration must also be given to the vent cover needed to keep process material within the vessel; it needs to be of low inertia but durable and strong enough to withstand process pressure fluctuations and has to be designed to open at a predefined pressure allowing rapid and unhindered passage of the combustion products. For vents that cannot discharge directly to a safe place it may be necessary to incorporate ducting to lead the discharged combustion products away to a safe area. In order to avoid unwanted back pressure effects, which could raise the explosion pressure within the relieved vessel above desirable levels, the ducting should be designed to withstand pressures

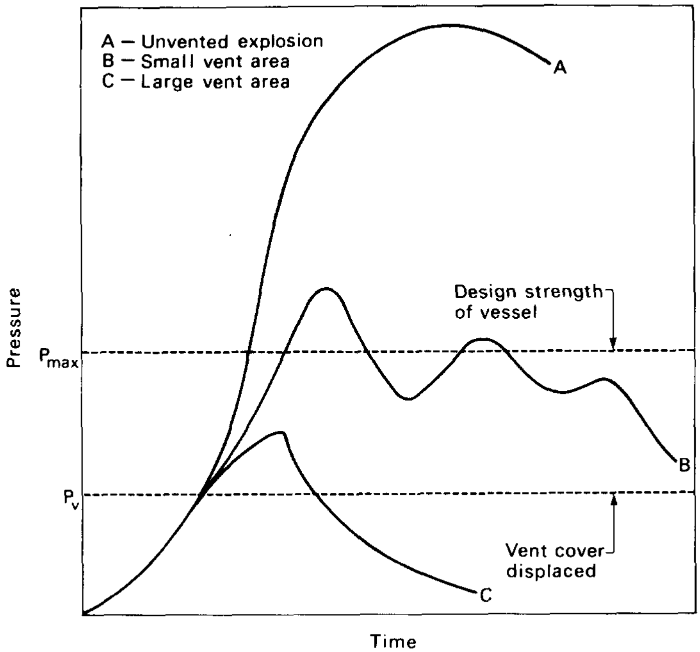


Fig. 1. Typical pressure/time history of a vented and an unvented explosion.

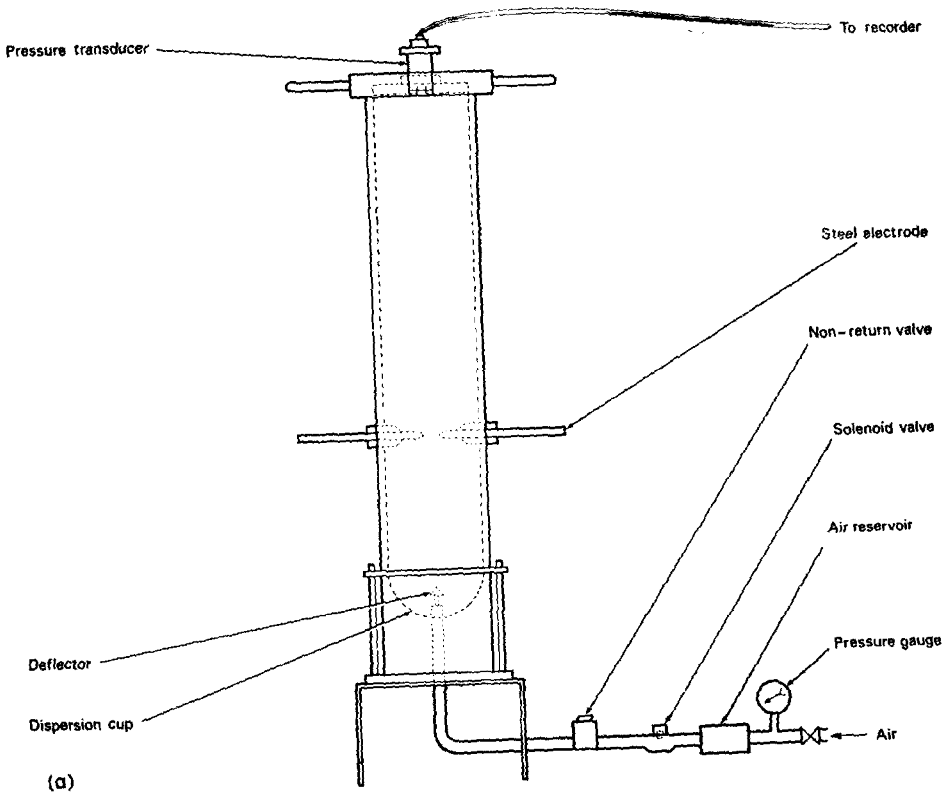
at least as great as the plant to which it is attached, have a diameter or cross-section at least as big as the relief area, should contain no bends, and should be as short as possible (not greater than 3 metres). These factors need to be considered together with the explosibility of the dust when prescribing the size of the explosion relief vent. The three methods of specifying the vent area considered in this paper are detailed below.

The vent-ratio method

For many years in the U.K. and U.S.A. the Hartmann bomb apparatus (Fig. 2), has been used to determine explosion pressure data, the maximum rate of pressure rise being related empirically to a relief area for a given vessel by what has traditionally been referred to as the vent-ratio method [1,2], since the required vent is defined in terms of the ratio of vent area to the volume of vessel being protected (Table 1).

Important fundamental features of the vent-ratio approach are that the vent areas are prescribed assuming the use of low inertia relief covers and that the maximum pressure within the vessel being protected is in the range 0.07—0.14 bar (1—2 lbf/in^2) and secondly, that discharge ducts, if incorporated, are not greater than 3 metres in length.

Since the vent ratio is a dimensional parameter, a situation frequently arises where for large vessels the prescribed vent area is impracticably large and in fact cannot be accommodated in some cases. For this reason the vent ratios given in Table 1 have been traditionally accepted for vessels having


To recorder
Pressure transducer
Steel electrode
Non-return valve
Solenoid valve
Air reservoir
Pressure gauge
Air
Deflector
Dispersion cup

(a)

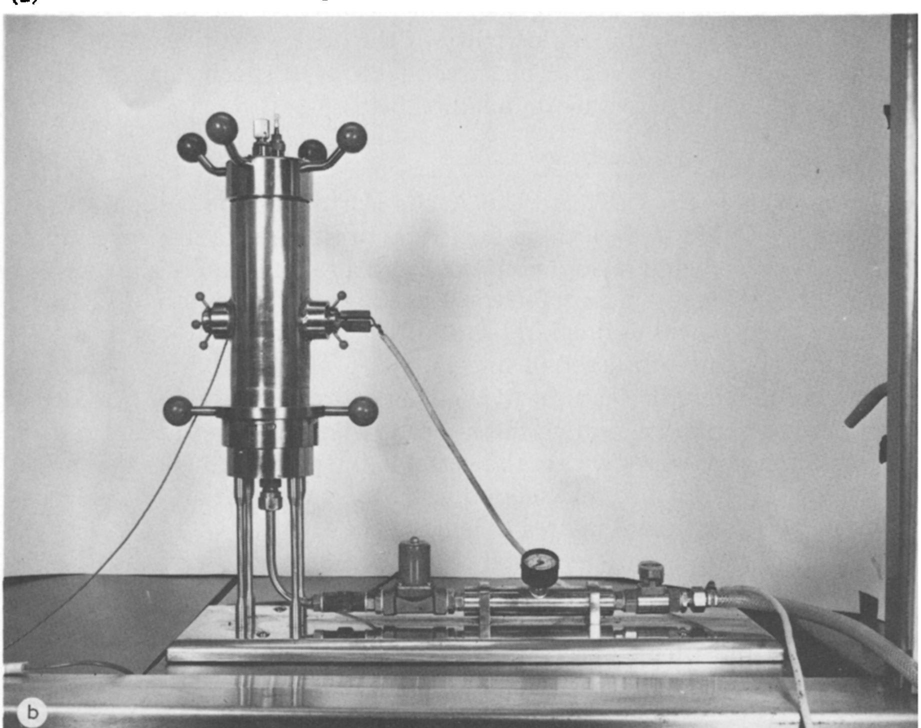

b

TABLE 1

Vent ratios for dusts having maximum rates of pressure rise determined in the Hartmann bomb

Maximum rate of pressure rise		Vent ratio	
(bar/s)	(lbf/in^2 s)	(m^2/m^3)	(ft^2/ft^3)
<345	<5,000	1/6.1	1/20
345—690	5,000—10,000	1/4.6	1/15
>690	>10,000	1/3.1	1/10

volumes up to 30 m^3 while for vessels in the range 30—300 m^3 the vent ratio is reduced linearly from 1/6 m^{-1} to 1/25 m^{-1}. For vessels having volumes in the range 300—700 m^3, particularly if they have large length to diameter ratios, it is common to prescribe vent areas equal to half the cross-sectional area of the vessel for dusts having maximum rates of pressure rise less than 345 bar/s (5000 lbf/in^2 s) and equal to the entire cross-sectional area for more explosible dusts. The latter is applied to very large vessels in excess of about 700 m^3 handling any explosible dust.

The vent-ratio approach to relief venting of dust explosions has been criticised for its tendency to prescribe overlarge, uneconomic and in some cases impracticable relief areas. This criticism has emanated from industries in which the powder handling plant is relatively strong, certainly being capable of withstanding pressures in excess of 0.14 bar (2 lbf/in^2), possibly as high as 0.7 bar (10 lbf/in^2).

It is not unreasonable to argue that in the cases where a vessel is relatively stronger the vent areas could be smaller than those prescribed by the vent ratio, allowing explosion pressures within the vessel to exceed the vent-ratio limit of 0.14 bar (2 lbf/in^2).

The cube root law and nomograph method

Until recently, the argument mentioned above was difficult to substantiate conclusively from practical experience. Although logically it was generally agreed that smaller vents could be prescribed, the acceptance of this fact presented problems in precribing the size of the relief area. This has, however, largely been overcome by the guidelines given in VDI Richtlinien 3673 [4] and the National Fire Protection Association Venting Guide [5] which are based on the most comprehensive approach to the sizing of relief vents.

These guidelines, which are now accepted in the U.K. by HSE in appropriate cases, are based on extensive vented explosion experiments in vessels having

Fig. 2a. The Hartmann bomb apparatus.

Fig. 2b. The Hartmann bomb apparatus.(photograph).

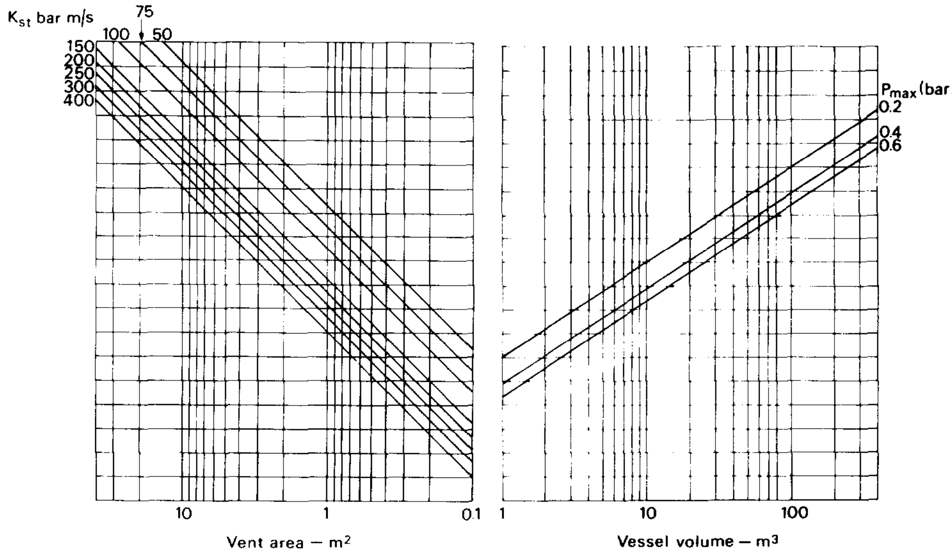


Fig. 3. Nomograph to determine vent areas for combustible dusts subjected to strong ignition conditions; vent opening pressure 0.1 bar (using K_{st} values). P_{max} = maximum pressure obtained in the vessel during venting [4].

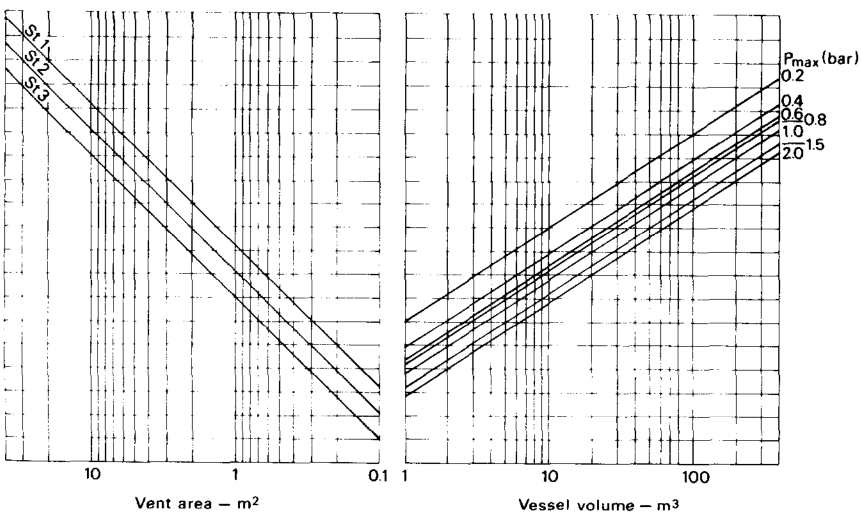


Fig. 4. Nomograph to determine vent areas for combustible dusts subjected to strong ignition conditions; vent opening pressure 0.1 bar. P_{max} = maximum pressure obtained in the vessel during venting.

volumes in the range 1—60 m^3; the work has been extensively published and is largely attributed to Bartknecht [3, 6—11] and Donat [12—14]. A series of nomographs has been derived from this work. Two typical nomographs are shown in Figs. 3 and 4 from which the vent area for a given vessel volume can be determined providing that the K_{st} value or the explosion class of the

TABLE 2

Relationship between K_{st} and explosion class

K_{st} (bar m/s)	Explosion class
0	St 0
>0–200	St 1
>200–300	St 2
>300	St 3

dust (see Table 2), the vent cover opening pressure, and the maximum reduced pressure in the vessel are known. It should be noted, however, that nomographs have only been derived for plant having a design strength capable of withstanding a minimum pressure of 0.2 bar (2.9 lbf/in^2). The explosion class of the dust required for the use of these nomographs is not related to the traditional classification into Group A and B dusts adopted in the U.K.; the former is a quantitative classification while the latter is qualitative. The quantitative classification of dusts is related to the cube root law which has been found to apply to dusts as well as gases [3]. It should be noted that the St nomograph (Fig. 4) is determined from the dust explosion hazard classes whereas the K_{st} nomograph (Fig. 3) is derived from a mathematical approximation [4].

The use of St and K_{st} nomographs for the same conditions may result in slight differences of the calculated vent area. This anomaly is most noticeable for $P_{max} \geqslant 0.6$ bar; a condition which should not concern the majority of those in the U.K. powder handling industry. If any doubt exists concerning vent sizing by the nomograph method, the St nomograph is recommended as being the most straightforward to use and interpret.

$$\frac{dp}{dt}_{max} \cdot V^{\frac{1}{3}} = K_{st} \tag{1}$$

where $(dp/dt)_{max}$ is the maximum rate of pressure rise of a dust (bar/s), V is the volume of the vessel (m^3) in which it was measured, and K_{st} is a constant for a given dust (bar m/s). This law has been found to hold for vessels having length to diameter ratios not greater than 5 to 1, and for volumes not less than 17 litres, this being the minimum volume for which K_{st} values for a given dust were found to be in agreement with those determined in larger vessels (1 m^3) [3, 15].

Since there was likely to be a wide range of K_{st} values for the many known combustible dusts, a classification system, shown in Table 2, was developed in order that explosion protection measures could be applied more simply, by referring to the explosion class of the dust.

The relationship given in Table 2 is only applicable if the dust has been tested in the prescribed manner (see later) in a vessel where length to diameter ratio is less than 5 to 1 and where volume is not less than 17 litres.

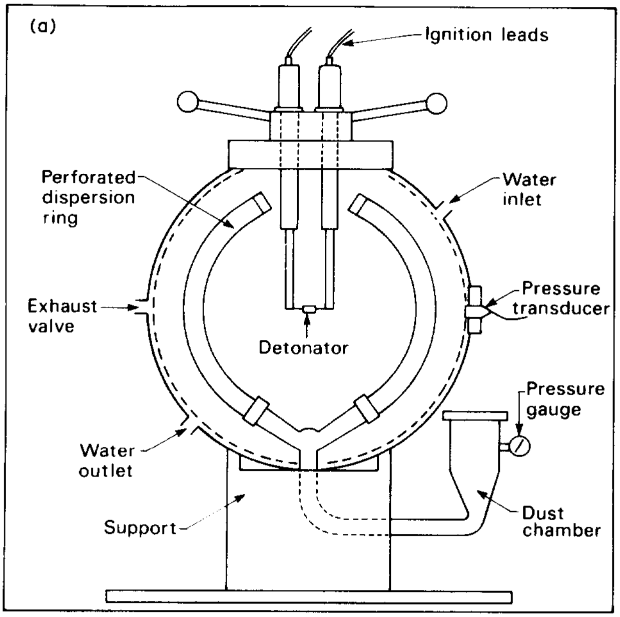


Fig. 5a. 20 litre spherical explosion apparatus.

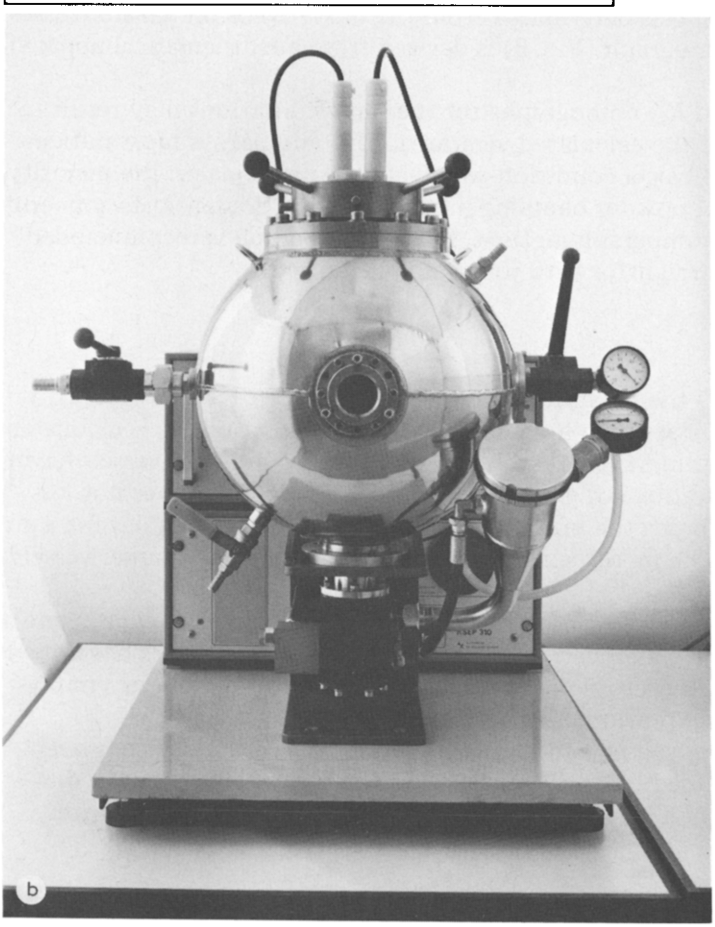


Fig. 5b. 20 litre sphere (photograph).

The reason is that the K_{st} values determined in large vessels were obtained from explosions in which a specific level of turbulence had been selected, and unless these conditions are reproduced in experiments with other suitable vessels, K_{st} values will not equate to predefined large-scale conditions and cannot therefore be used uncritically for vent sizing via the nomographs.

The initial work which resulted in the new approach to the sizing of explosion reliefs was carried out mainly in a 1 m^3 vessel, but since the operation of this vessel on a routine basis requires considerable effort and large quantities of material, it proved necessary to develop a more convenient laboratory vessel. A series of experiments involving spherical vessels having different volumes was carried out and it was established that a vessel volume of 17 litres was the minimum for which K_{st} values could be correlated to the 1 m^3 vessel and hence to the nomographs [15]. This study resulted in the development of the 20 litre sphere (Fig. 5) which, if used in the prescribed manner, enables K_{st} value and the dust class (St 0—3) to be determined and hence the size of relief vent for a given vessel to be estimated.

Rust theoretical method

A theoretical approach to the sizing of explosion reliefs has recently been derived by Rust [16] which has subsequently formed the basis of a method for determining relief vent areas for plant handling soap and detergent dusts [17]. This method has a potential advantage over the two methods described above since it is capable of being applied to both high- and low-strength plant. The equation derived by Rust and given below takes account of the explosibility of the dust, the maximum allowable pressure in the vessel to be vented together with its volume and shape.

Rust equation:

$$A = \frac{8.35 \times 10^{-5}\, F\, (PV)^{2/3} K^{1/3}}{(P_A)^{1/2}} \qquad (2)$$

where A = vent area (ft^2); F = shape factor, for a rectangular vessel of sides a, b, c where $a > b$ and $a > c$, $F = 0.65\,(bc/a^2)^{1/3}$; P = maximum pressure in test vessel (Hartmann) (lbf/ft^2); V = volume of vessel to be vented (ft^3); K = Rust constant for dust, where $K = [(dp/dt)/16]^3$; (dp/dt) = maximum rate of pressure rise (Hartmann) (lbf/in^2 s); and P_A = maximum allowable pressure (lbf/ft^2) of vessel to be vented.

K factor

A fourth method of vent area calculation involving a term known as K factor deserves a mention. K factor or "K" equals the area of cross-section of a vessel divided by the area of the relief vent and has been shown to be directly proportional to the maximum explosion pressure for gases. The extent to which this method can be applied to dust explosions depends on how closely gas and dust explosions can be equated. Difficulties arise in determining which of the numerous available equations is most suited to a particular problem. This paper is concerned with commonly used venting methods and although K factor has been used successfully, its use is not wide enough to warrant a full discussion here. For those requiring detailed information reference should be made to the literature, which although extensive, has been summarized [1].

Experimental

Different dusts were tested in the Hartmann bomb and the 20 litre sphere in the manner described below; the data obtained were then used to calculate vent areas by the methods described earlier.

Hartmann bomb apparatus

This apparatus (Fig. 2) was used to determine the maximum explosion pressure and the maximum rate of pressure rise of the range of dusts included in this study. An ignition delay (electric spark ignition only) of 60 ms after dispersion of the dust was included for tests with a number of different dust concentrations. The dusts were exploded by dispersing different masses of dust in the range 0.1—3 g by air pressurised at 8.3 bar (120 lbf/in^2) from a reservoir of volume 50 cm^3. The ignition source was either 10 kV inductive electric spark formed between the points of electrodes set 5 mm apart or a hot filament of about 1000° C. The pressure/time history was measured by a piezoelectric transducer and digitized by a transient recorder, a micro-computer being used to process the required data.

20 litre sphere

In order that K_{st} values determined in this apparatus (Fig. 5) could be used to classify the dusts accurately, prescribed conditions of turbulence and ignition had to be met. This involved evacuating the sphere to 0.4 bar (5.8 lbf/in^2), pressurising the dust reservoir to 20 bar (290 lbf/in^2), and selecting an ignition delay (time between initiation of dispersion and ignition) of 60 ms. An automatic test sequence ensures that reproducible ignition of the dust takes place under the same conditions of turbulence. A range of dust concentrations was examined by placing in the dispersion reservoir masses of dust in the range 2—100 g and ignition was affected by two 5 kJ chemical detonators. The pressure/time history was measured in an identical manner to that of explosion in the Hartmann bomb.

Results

The results of the experiments in the Hartmann bomb and the 20 litre sphere are given in Table 3; also included are data from the specimen venting examples given by Rust [16] and the Soap and Detergent Industry Association [17].

The purpose of this paper is to compare the three approaches to the sizing

TABLE 3

Explosibility data

	Median[a] particle size (μm)	Hartmann data[b]		K "Rust"	Sphere data, K_{st} (bar m/s)
		P (lb/ft²)	dP/dt (lb/in² s)		
Lycopodium	27	18375	14355	7.22×10^8	135
Woodflour	29	18375	8584	1.55×10^8	104
Aluminium	17	14616	9005	1.78×10^8	155
Polyethylene	14	14407	23867	3.32×10^9	135
Polyester	30	15034	6003	5.28×10^7	85
Acrylic	38	16287	8222	1.36×10^8	124
Iron	32	8561	421	1.82×10^4	11
Zinc	17	12528	1682	1.16×10^6	35
Benzoic acid	53	14199	10861	3.13×10^8	199
Epoxy	32	17330	8918	1.73×10^8	125
Soya meal	70	12528	1494	8.14×10^5	26
Calcium stearate	23	17957	16704	1.14×10^9	122
Zinc stearate	23	16287	22707	1.86×10^9	74
Magnesium stearate	15	15869	23258	3.07×10^9	135
Tinuvin	22	13990	23258	3.07×10^9	244
Irganox	88	12320	10701	2.99×10^8	138
Filter dust [16]	--	8640	5080	3.2×10^7	75[c]
Toilet soap [17]	--	15840	2130	2.36×10^6	50[c]

[a]The median size, d_{50}, is the 50% size on a cumulative frequence curve. The sieve fractions were determined by a jet sieve.
[b]Highest maximum values obtained with either coil or spark ignition.
[c]These are likely maximum values.

TABLE 4

Vessel parameters

Vessel	Side *a*		Side *b*		Side *c*		Volume		F	P_A	
	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft³)	(m³)		(lb/ft²)	(bar)
V1	10	3.0	3.3	1.0	3.3	1.0	100	3	0.3015	403	0.2
V2	25	7.6	6.0	1.8	5.0	1.5	750	21	0.237	403	0.2
V3 [17]	31.6	9.6	10.56	3.2	10.56	3.2	3524	99	0.3123	1044	0.5
V4 [16]	28.0	8.5	18.0	5.5	11.0	3.4	5544	157	0.40	403	0.2
V5	50.0	15.2	15.0	4.6	10.0	3.0	7500	210	0.253	403	0.2

of explosion relief vents which were detailed earlier. In order to do this effectively, the data given in Table 3 have been applied to five vessels of volumes in the range 3—200 m^3; for simplicity the vessels have been taken as rectangular. Dimensions of the vessels are given in Table 4 together with the

TABLE 5

Vent areas determined by vent-ratio, nomograph and Rust methods

Dust	Vent-size method[a]	Vent area (m^2) for vessel				
		V1	V2	V3	V4	V5
Lycopodium	VR[b]	0.9	7.1	4.0	9.2	8.5
	N	0.5	1.7	3.0	6.3	8.5
	R	1.6	4.6	10.9	27.9	23.6
Woodflour	VR	0.6	4.3	4.0	6.3	8.5
	N	0.4	1.5	2.5	5.3	7.0
	R	1.0	2.8	6.5	16.7	14.0
Aluminium	VR	0.6	4.3	4.0	6.3	8.5
	N	0.5	2.0	3.3	8.0	10.0
	R	0.9	2.5	5.8	15.0	12.7
Polyethylene	VR	0.9	7.1	4.0	9.2	8.5
	N	0.5	1.7	3.0	6.3	8.5
	R	2.2	6.5	15.4	39.4	33.4
Polyester	VR	0.6	4.3	4.0	6.3	8.5
	N	0.3	1.1	2.3	4.2	5.5
	R	0.6	1.7	4.0	11.1	7.1
Acrylic	VR	0.6	4.3	4.0	6.3	8.5
	N	0.4	1.6	2.8	6.2	8.0
	R	0.8	2.4	5.3	14.7	12.5
Iron	VR	0.5	3.6	4.0	6.3	7.0
	N	0.2	0.7	1.2	2.5	3.0
	R	0.03	0.08	0.2	0.5	0.4
Zinc	VR	0.5	3.6	4.0	6.3	7.0
	N	0.2	0.7	1.2	2.5	3.0
	R	0.15	0.4	1.0	2.5	2.2
Benzoic acid	VR	0.9	7.1	4.0	9.2	8.5
	N	0.7	2.8	4.8	10.0	15.0
	R	1.0	3.0	6.9	17.3	15.0
Epoxy	VR	0.6	4.3	4.0	6.3	8.5
	N	0.4	1.6	2.8	6.2	8.0
	R	1.0	2.8	6.5	16.7	14.0
Soya meal	VR	0.5	3.6	4.0	6.3	7.0
	N	0.2	0.7	1.2	2.5	3.0
	R	0.13	0.4	0.9	2.3	1.9
Calcium stearate	VR	0.9	7.1	4.0	9.2	8.5
	N	0.4	1.6	2.7	6.3	8.0
	R	1.8	5.3	12.5	32.0	27.0
Zinc stearate	VR	0.9	7.1	4.0	9.2	8.5
	N	0.3	1.0	1.8	4.0	5.0
	R	2.3	6.7	15.9	41.0	34.0
Magnesium stearate	VR	0.9	7.1	4.0	9.2	8.5
	N	0.5	1.7	3.0	6.5	8.5
	R	2.3	6.8	18.0	41.3	34.7
Tinuvin	VR	0.9	7.1	4.0	9.2	8.5
	N	0.8	3.1	5.5	13.0	17.0
	R	2.2	6.2	14.7	38.0	32.0
Irganox	VR	0.9	7.1	4.0	9.2	8.5
	N	0.5	1.7	3.0	6.5	8.5
	R	0.9	2.6	6.2	16.0	13.5
Filter dust [16]	VR	0.6	4.3	4.0	6.3	8.5
	N	0.3	1.0	1.8	4.0	5.0
	R	0.4	1.0	2.3	6.0	5.0
Toilet soap [17]	VR	0.5	3.6	4.0	6.3	7.0
	N	0.2	0.7	1.2	2.5	3.0
	R	0.2	0.6	1.5	3.8	3.2

[a]VR = Vent ratio, N = Nomograph, Fig. 3, R = Rust.
[b]For vessels V1 and V2 the vent ratios 1/6 m^{-1}, 1/5 m^{-1} and 1/3 m^{-1} were used. For vessel V3 the vent ratio 1/25 m^{-1} was used. For vessel V4 the vent ratio 1/25 m^{-1} was used for dusts having Hartmann rates of pressure rise less than 10,000 lbf/in^2 s and half cross-sectional area (cross-section = smallest side) was used as a vent for dusts having higher explosibility. For vessel V5, the smallest vent was given by half cross-sectional area and was used for weakly explosible dusts (<5,000 lbf/in^2 s, in Hartmann bomb); 1/25 m^{-1} was used for all other dusts.

maximum allowable pressure, P_A, and the shape factor, F, as defined above. The vent areas required for a particular dust in a given vessel and determined by each of the three methods are given in Table 5.

Discussion

Since the nomograph approach is the only method considered in this paper to be derived from extensive experimental data, it is assumed, in the absence of other proven work, to prescribe vents that are capable of relieving pressure without damage to plant, etc. The vent areas determined by this approach are precise and related to the explosibility of the dust, the vessel volume (vents can be sized for vessels up to 1,000 m^3 providing that the length to diameter ratio does not exceed about 5), the maximum allowable pressure within the vessel on venting, which must be capable of withstanding at least 0.2 bar (2.9 lbf/in^2) and the pressure required to completely open the vent cover.

The data required for this approach to be employed can only be obtained from experiments performed in a prescribed manner in appropriate test vessels, e.g., 20 litre sphere, 1 m^3 vessel [1, 3]. It should be realised that data from the Hartmann bomb cannot be used directly in the nomograph method.

The vent-ratio approach is empirical, based on maximum rates of pressure rise determined in the Hartmann bomb, the vent areas being sized depending on the volume of the vessel (i.e., it is dimensional). The vents are sized on the assumption that the vessels being relieved are unable to withstand pressure greater than about 0.14 bar (2 lbf/in^2). As a consequence, excessively large vent areas may be prescribed for plant which either has a relatively large volume (> 30 m^3) or is capable of withstanding pressures in excess of 0.14 bar (2 lbf/in^2).

It can be seen from Table 5 that, as would be expected, the nomograph approach generally gives smaller vent areas than the vent-ratio approach for vessels capable of withstanding at least 0.2 bar (2.9 lbf/in^2); a comparison cannot be made for relatively weak plant since nomographs have not been published for such plant.

The Rust approach can be compared to the other two methods since its equation takes into account the maximum allowable pressure in the vessel during venting which encompasses both relatively weak and strong plant. As might be expected, this approach is in better agreement with the nomograph approach than the vent-ratio approach, particularly for dusts having maximum rates of pressure rise in the Hartmann bomb of less than 345 bar/s (Table 5). For dust having higher rates of rise there is some agreement in the middle range (345—690 bar/s) but there is poor agreement at higher rates of rise and for large volumes (> 100 m^3). Under these latter conditions, excessively large vents may be prescribed by the Rust approach with the vent-ratio method providing smaller, more realistically sized vents.

Conclusions

For the dusts and vessels considered in this paper the following is concluded.

General

(1) The vents prescribed by the nomograph are generally smaller than those determined by either of the other methods but they are for plant that is relatively strong — being able to withstand at least 0.2 bar (2.9 lbf/in^2).

(2) For dusts having rates of pressure rise in the Hartmann bomb less than about 345 bar/s (5000 lbf/in^2 s) being handled in vessels having volumes up to at least 200 m^3, the Rust approach gives vent areas that are in fairly close agreement with those determined by the nomograph method.

(3) Since soap and detergent dusts normally give rates of pressure rise in the Hartmann bomb much less than 345 bar/s (5,000 lbf/in^2 s), vents determined by the Rust method are likely to give satisfactory results; the vent-ratio method tends to prescribe oversize vents for weakly explosible dusts (< 140 bar/s) such as soaps and detergents.

(4) For dusts having rates of pressure rise in the Hartmann bomb in the range 345—690 bar/s (5,000—10,000 lbf/in^2 s), agreement between the Rust and nomograph methods is unpredictable; the vent-ratio approach is often in better agreement with the nomograph method in this range.

(5) For dusts having rates of pressure rise in the Hartmann bomb greater than 690 bar/s (10,000 lbf/in^2 s), vents prescribed by the Rust method tend to be excessive, particularly for vessels having volumes greater than about 100 m^3. The vent-ratio method prescribed vents that are closer to those determined by the nomograph method, although still larger.

Application to plant

(1) *Strong plant:* For plant that is relatively strong, i.e., capable of withstanding pressures greater than 0.2 bar (2.9 lbf/in^2), the nomograph approach should be used if appropriate data are available (i.e. K_{st} or St values for the dust being handled). If these data are not available, and cannot be determined, the vent-ratio and Rust approaches can be applied and the smaller vent area prescribed by the two approaches should be adopted (since both are likely to be larger than necessary).

(2) *Weak plant:* For plant that is relatively weak, i.e., capable of withstanding only about 0.14 bar (2 lbf/in^2), the nomograph approach cannot be used. The vent-ratio and Rust approach can again be employed and the smaller vent area adopted. The work carried out for this paper indicates that the Rust method can be used satisfactorily for dust giving rates of pressure rise in the Hartmann bomb up to about 345 bar/s (5,000 lbf/in^2 s) (larger vents are likely to be prescribed by the vent-ratio method). For dusts giving rates of pressure rise in the range 345—690 bar/s (5,000—10,000 lbf/in^2 s), a useful approach would be to use the smaller vent prescribed

by the Rust or vent-ratio methods. For dust giving rates in the Hartmann bomb greater than 690 bar/s (10,000 lbf/in^2 s), vents determined by the Rust method are likely to be excessively large, particularly for large volumes. The vent-ratio method is preferred.

(3) *General:* If the vent area prescribed by the Rust or vent-ratio method can be accommodated without difficulty or unreasonable burden, this should be done; since — although it may be larger than necessary — it will more than adequately cope with the explosion pressure, i.e., it will err on the side of safety.

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