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RECENT ADVANCES IN THE RELIEF VENTING OF DUST EXPLOSIONS

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Summary

Relief venting is the principal direct means used for protection of industrial plant and buildings against dust explosions. Information on the design of adequate vents has accumulated over a long period, and this early work has been summarized.

More recently, a considerable amount of further data has become available and is reviewed, together with a description of the methods used to obtain it. The majority of data relate to explosions in compact enclosures, *i.e.* the three dimensions of comparable size, but some data are also reported for ducting and for specific plant units. The effect of vent covers on explosion pressures is also given some attention.

The importance of obtaining an adequate theoretical background to the empirical data is stressed, the present situation discussed, and future requirements commented upon.

Introduction

A dust explosion is the propagation of flame through a suspension of dust in air or a gas, accompanied by pressure effects. Not all combustible dusts can cause explosions, but many of the common industrial and household dusts can do so. These include foodstuffs, agricultural products, plastics, chemicals, pharmaceuticals, many other dusts of vegetable origin, and some reactive metals. Tests are used in various countries to assess the explosibility of dusts and their explosion parameters, such as minimum ignition energy and temperature, minimum explosible concentration, and maximum explosion pressure; a detailed account is available elsewhere [1]. Knowledge of the explosibility parameters is necessary before an adequate estimate of explosion hazard can be made.

If a dust suspension is in the open air when ignited, the likely outcome will be a flash of flame developing little hazardous pressure, although there is a risk of injury to operatives and of ignition of nearby flammable materials. A fall-out of burning particles frequently occurs, which continue to burn on the ground. If the suspension is confined, as in a plant or building, pressure effects can develop. These arise from the heat released during the burning, sometimes accompanied by gases evolved from the dust, causing expansion of the air originally present. Unless precautions are taken, the pressure is likely to cause rupture or displacement of the enclosing surfaces of the plant or building, hazarding both life and the structures. Experiments in closed vessels, usually small, have shown that with many dusts the maximum explosion pressure, under the most severe conditions, can be 700 kN/m^2 (100 lbf/in^2) or higher. Explosion protection measures have to be taken to reduce these maxima to more acceptable levels, to prevent damage.

The methods of obtaining explosion protection most commonly used are relief venting, automatic suppression, and the use of inert gas in the plant during normal running. Explosion relief venting is used because it is often the simplest and most economic solution, and involves the provision of vents to relieve pressure whilst the explosion proceeds. If the vents are of the correct size and distribution, pressures can be reduced to values below those able to damage the plant or building. Automatic suppression and the use of inert gas can be used for the protection of plant, and not buildings, and operate on the principles of quenching an incipient explosion or preventing it from being initiated, respectively. These techniques have particular advantages for a plant which is awkwardly sited, or for dust which cannot be discharged to atmosphere because of toxicity, or where supplies of inert gas are readily available. Both methods do require constant monitoring of conditions within the plant and, with automatic suppression, there may be complications in protecting large volumes. Because of the relatively greater complexity, these methods are used less frequently than relief venting.

Much dust handling plant, particularly collection equipment, is of sheet metal construction and may be able to withstand pressures of only about 15 kN/m^2 (2 lbf/in^2) without suffering damage. Indeed, flat sheet metal surfaces of several metres width may be unable to withstand even these low pressures, without additional bracing. It is an essential requirement that the high pressures which can be generated in completely enclosed equipment should be much reduced if damage to weak units is to be avoided, and the provision of adequate relief venting is one means of obtaining this reduction. When venting is used for protection, other factors must also be taken into account. Discharge of flame and combustion products through the vents should, if they are adequate, protect the plant units against internal pressures but may cause hazard outside the unit unless properly controlled. Where plant units are inside buildings it is frequently necessary to provide ducting from the vents to the outside atmosphere to permit safe discharge of the hot products of explosion. There are restrictions on the geometry of such ducting, which must be met if excessive back pressures within the unit being protected are to be avoided. Also, in normal working, the relief vents usually have to be closed but should open up readily as soon as the explosion commences and pressure starts to rise. The vent covers must be subject to careful design to ensure that they meet these requirements. In providing relief venting for the protection of dust handling plant the associated covers and ducting must therefore also be considered, as well as the area and positioning of the vents themselves.

The customary method of calculating the area of vents has been on the basis of the vent ratio, that is the area of vent per unit volume of plant. The vent ratio can be related to the maximum rate of pressure rise of the dust, as measured in a small-scale standard apparatus, according to Table 1. This method of procedure is described and assessed in detail elsewhere [1] and although unsatisfactory in some aspects has, on the whole, given good service in the past. The data on which it is based have been mainly obtained from experimental explosions in relatively small vessels. As the vent ratio is dependent on the area/volume ratio, there is a residual dimension of length which must be taken into account in scaling-up. The vent ratio specifies large vents on units of large volume, although there is some rule-of-thumb relaxation of area for very large volumes, but because of the uncertainty further data were needed. This need has been the stimulus for a good deal of the recent work on dust explosion venting, which has led to an increased understanding.

TABLE 1

Guide to vent ratios for dusts of different explosibilities

Maximum rate of pressure rise		Vent ratio	
$kN/m^2\,s$	$lbf/in^2\,s$	m^{-1}	ft^{-1}
< 35,000	< 5,000	1/6	1/20
35,000—70,000	5,000—10,000	1/5	1/15
> 70,000	> 10,000	1/3	1/10

The purpose of this paper is to review recent experimentation on the venting of explosions, in relation to earlier work which has been considered already [1]. This earlier work consisted of isolated experimental programmes, often concerned with specific dust and plant geometries, and provided a fragmentary basis for the design of vents. Recently, more systematic work has been published, involving experiments on plant scale. The results have been considered in associated theoretical work with a view to providing a more unified basis to the information. Experiments have been reported on various dusts, including coal, handled in industrial plant, but the special factors associated with coal mining explosions have not been considered.

Summary of previous work

An outline of the experimental methods and results of earlier work is presented in Table 2; for details of the findings reference should be made to the original publications. The list of investigations in Table 2 is not exhaustive, but the major series are listed and their findings have strongly influenced the design of vents. In each case the vent was open, or provided with a very light cover, and investigations aimed specifically at studying the effect of vent covers on explosion pressures were not considered for Table 2.

TABLE 2

Explosion pressures in vented enclosures*

Type of enclosure	Dimensions	Dust	Range of explosion pressures		Other variables	Reference number
			kN/m^2	lbf/in^2		
Compact	Cubes of sides 0.3, 1.2, 1.8 m	Cornstarch	10—250	1.5—35	—	2
	Cube of side 0.3 m	Cellulose acetate	3—140	0.4—20	—	3
	Oblong, volume 120 m^3	Cornstarch	not measured directly		—	4
Long ducting	Diameter 1.2 m Length 17 m	Wheat Provender Cork	2.5—170	0.4—24	Distribution and number of vents	5
	Diameter 0.75 m Length 15 m	Cork	40—110	6—16	Power of ignition source	6
Plant unit	Silo, diameter 2.3 m Height 18 m	Rice meal Ground nut Sunflower cake Palm kernel cake	3.5—120	0.5—17	—	7
	Coal pulverising mill, volume 5.2 m^3	Coal	up to 200	up to 28	Internal and external ignition sources	8
	Cyclone Volume 1.2 m^3	Cork	4—90	0.6—13	Distribution of vents	9

*This Table is a summary of venting data from ref. (1).

The types of enclosure used in the experiments have been divided into three categories. Compact enclosures have their three dimensions of the same order and include cubical boxes. Enclosures of this geometry are convenient for experimental purposes, and are frequently present in industrial plant. Long ducting, where one dimension is much greater than the other two is also common in industry, and the spacing of the vents is more important than with compact vessels. Finally, specific plant units have been subject to investigation and the results are directly applicable although generalization from the results tends to be more difficult.

With compact enclosures, the explosions in cubes of sides up to 1.8 metres showed three features plainly. The scatter of the experimental points was small, indicating good reproducibility, the relation between maximum explosion pressure and vent ratio was independent of the volume of the enclosure, indicating an absence of scale effect, and finally the maximum explosion pressure, plotted on a logarithmic scale, varied directly with the vent ratio. The relationship broke down at pressures of 20 kN/m^2 (3 lbf/in^2) and below and the observed pressures were higher than would be predicted. This was unfortunate because these pressures are of particular practical interest in the safe design of plant and an empirical relationship would have been valuable. The conditions of test were severe, so that the results were unlikely to have given a low estimate of explosion pressures under practical conditions. The appropriate vent ratio for the dust used was 1 m^2/5 m^3 (1 ft^2/15 ft^3), from Table 1, and this ratio gave an explosion pressure more than twice that of the 15 kN/m^2 (2 lbf/in^2) expected with the empirical approach.

Explosions in long ducting (Table 2) involving wheat, provender and cork dusts, showed that relatively high pressures were obtained when the dust was ignited remote from a vent whether or not the full cross-sectional area of the ducting was available for venting. A vent near the ignition source reduced the pressures, and the vent half-way along the ducting also gave benefit. If the vent ratio was in accordance with Table 1, low pressures were readily obtainable. The ignition source in these tests was a small transient flame, and the effect of increasing the size of the source was investigated using ducting of different length and diameter. The new ignition source consisted of a 3-m length of 0.25-m-diameter ducting bolted on to the closed end of the main ducting. Using cork dust, the maximum explosion pressure with this ignition arrangement was about double that for the smaller source.

When individual plant units were tested, additional factors became important. These included the non-uniformity of the dust cloud concentration throughout the volume, and the interference with the propagation of the flame caused by internal metal components and structures. For example, with a cyclone the distribution of dust was non-uniform, being concentrated near the upper part of the walls, and the vent could either be on the flat top of the cyclone or on the air outlet pipe. In the latter case the frictional resistance of the pipe to the rapid discharge of flame increased the explosion pressure. Only one geometry of cyclone was studied, and no results have been reported for high-efficiency cyclones which would contain the finest fractions of dust.

The investigations summarized in Table 2 gave valuable experimental data but the absence of an underlying theoretical approach is noticeable. The application of results from generalized systems, such as cubes and long ducting, to actual plant units is not straightforward and hence investigations on typical units were necessary. Because of the large number of designs of units only a few have been adequately studied, leaving many gaps. Although this approach can give results for immediate problems, a lack of a generalized treatment means that in the long term much more of this type of work would have to be done.

Recent data

During the past few years a number of important investigations have been carried out, in various countries, on the relationship between explosion pressure, area of relief vent, and characteristics of the vent cover. Details of the experiments are summarized in Table 3; for the detailed results reference to the original publications is needed.

Compact enclosures

A comprehensive series of investigations has been sponsored by some chemical companies in Germany using spherical or approximately cubical explosion vessels of up to 60 m^3 volume. The vents were covered with diaphragms which burst at designed pressures, with a minimum of 10 kN/m^2 (1.5 lbf/in^2). In many cases the explosion pressures were considerably higher than the value of 15 kN/m^2 (2 lbf/in^2) quoted above and hence the data are applicable principally to relatively strong vessels such as chemical reactors, and not to the much weaker units constructed from sheet metal. The enclosures used in experiments were strong, and with some the maximum explosion pressure with no vents was reported. With closed vessels, and the range of volumes studied, the maximum rate of pressure rise varied inversely with the cube root of the vessel volume; the "cube root" relation was also found in parallel experiments using gas mixtures. When the maximum rate of pressure rise of the dust was extrapolated back to a volume of 1.2 litres, that of the small-scale standard apparatus used for Table 1, the extrapolated value was several times greater than that measured. The discrepancy increased markedly with the less explosible dusts. It was concluded that the results from the small-scale apparatus could not be applied directly to the larger volumes and a correction factor was proposed. The reason for the discrepancy has not yet been proved, but may be related to the rate of propagation of flame through the dust cloud in the test apparatus being in balance with the rate of combustion of individual dust particles. Under these conditions the "cube root" relation would not be expected to apply. In larger volumes, where the flame was essentially an expanding thick-shelled sphere the relation would hold, and there would be a critical volume, depending on the explosibility of the dust, at

TABLE 3

Recent information on dust explosion pressures in vented enclosures

Type of enclosure	Dimensions	Dust	Range of explosion pressures kN/m²	lbf/in²	Other variables	Reference number
Compact	Sphere, cubes, approximate, volume 1—60 m³	Coal Dextrin Organic pigment Aluminium	10—800	1.5—115	Vents covered with diaphragms bursting at 10—150 kN/m²	10—16
Compact	Short cylinder, volume 5 m³	Polyacrylonitrile Organic sulphur compound Methyl cellulose Starch	80—400	11—57	Vents covered with diaphragms bursting at 12—80 kN/m²	18—20
Compact	Short cylinder, volume 5 m³, with attached pipe used as ignition source, 6 m length and 0.2 m diameter	Polyacrylonitrile/aluminium (1:1) in pipe. Not stated in cylinder	20—700	3—100	Ignition sources, and ignition delays	21
Compact	Cylindrical or oblong, volumes of 1, 10,100 m³	Flour	0—300	0—43	Flame speed measured	22, 23
Compact	Cubical, volume 300 m³	Coal	0—330	0—47	—	24
Ducting	Horizontal, length up to 40 m, diameters 0.2—0.7 m	Coal Dextrin Organic pigment Aluminium Methyl cellulose Wood Sugar	0—2500	0—360	Flame speed measured	15, 16
Ducting	Horizontal, length 40 m, diameter 1.4 m	Sugar	not reported		Flame speed measured	25
Ducting	Horizontal, length 200 m, diameter 1.8 m	Coal	0— 80	0—11	—	26
Cyclone	Volume 1.2 m³	Cork Phenol formaldehyde Flour Polypropylene	4—100	0.6—14	Weight of vent cover	9, 27

which the relation would become valid. Further work is required in this area, because the small-scale pressure test apparatus is convenient for routine use, but for maximum benefit the ability to scale-up the results directly is necessary.

Two types of ignition source were used in the tests, a 4-mm-long electric spark and a pyrotechnic igniter which was more severe. Both sources were sited at the centres of the vessels. With a given enclosure and vent area the more powerful ignition source gave a higher explosion pressure, indicating that in interpreting the results of tests for the design of plant some allowance must be made for the power of the ignition source in any likely explosion.

For use as a source of design data the results were tabulated in a form such that the maximum explosion pressure could be related to the vessel volume, vent area, bursting pressure of vent closure, and the explosibility class of the dust. This latter quantity was related to the maximum rate of pressure rise as measured in the small-scale standard apparatus, in principle similar to the approach in Table 1. The data should be valid for enclosure volumes within the range covered by tests, and the corresponding vent areas, and the maximum explosion pressures can then be derived.

Some consideration was given to vent closures other than bursting panels, particularly hinged doors. The effect of the inertia of the door and pressure required to open it on the maximum explosion pressure was not studied in detail, but it was clear that the construction had to be relatively massive. Possibly this was a consequence of the relatively high maximum explosion pressures that were developed in some of the tests. Some data for explosions in the 1-m^3 vessel, fitted with explosion doors, were reported elsewhere [17] and the method was thought to be promising although the data were insufficient for general application.

A theoretical investigation is now overdue on the relationship between maximum explosion pressure, vent area, and characteristics of the vent cover. The case of bursting diaphragms is probably simpler, as these open the vent at a predetermined pressure, and subsequently take no further part in the development of pressure. Hinged doors or lids may also be designed to open at a predetermined pressure, but the inertia of the door as it opens has a continuing effect on the development of the explosion causing a more complex process. First, however, the relationship between maximum explosion pressure and vent area, for uncovered vents must be understood; some progress in this direction has already been made, see below.

A further experimental investigation, with theoretical treatment also presented, involved tests on a cylindrical explosion vessel of 5-m^3 volume, and with explosion pressures again being relatively high [18—20]. Tests with the vents completely closed enabled the maximum explosion pressure and maximum rate of pressure rise for various dusts to be measured directly. In tests with the vessel vented, different bursting diaphragms were used over vents and the effect of turbulence on the burning characteristics was noted qualitatively. Use of the "cube root" relation to correlate maximum rates of pressure rise in the experimental vessel with those in the small-scale standard test apparatus[1] showed a discrepancy, the smaller apparatus giving rates of rise greater than expected, by a factor up to 2. Use of this factor enabled the small-scale test to be related to practical conditions, by use of the appropriate equations, and the predictions for an enclosure of 5-m^3 volume were in satisfactory agreement with experiments. A nomogram was given relating the volume of the vessel to the desired maximum explosion pressure, the maximum rate of pressure rise of the dust and the area of the vent, for a given bursting pressure of the vent cover[20].

The effect of turbulence on the burning of dust suspensions was investigated by modifying the explosion vessel by the addition of a pipe in which dust was dispersed and then ignited[21]. The flame from the pipe propagated into the 5-m^3 vessel, the flame jet being 2 m in length and 0.8 m in diameter. The first series of tests was with a closed system in which the dust in the 5-m^3 vessel was either a deposit or had been dispersed before the arrival of the igniting flame from the pipe. With the deposited dust the maximum explosion pressures were slightly less than with the dispersed dust condition, but the maximum rate of pressure rise was much less. With flame jet ignition the maximum rate of pressure rise was also greater than when the dust in the 5-m^3 vessel was dispersed and then ignited by an electric spark instead. The time between dispersing the dust and passing the spark was also varied. In vented explosions the flame jet ignition of dispersed dust gave slightly higher pressures than did spark ignition, for the smaller vent areas, but with larger vents the situation was reversed. The ignition of deposited dust by the flame jet gave lower pressures than ignition of dispersed dust by electric spark. The effects of turbulence and of the power of the ignition source on the maximum explosion pressure in a vented vessel are clearly complex and await a satisfactory theoretical explanation. In plant design it is clear that where a unit can be exposed to the sudden propagation of an igniting flame into it, the pressure that develops can be appreciably higher than when the ignition source originates within the unit itself. This conclusion is in agreement with earlier findings.

Tests with flour were carried out with three oblong enclosures of 1—100 m^3 volumes, having the ignition source at one end and the vents remote[22,23]. The vents were covered with diaphragms, which burst at pressures below 20 kN/m^2 and the principal aim of the investigation was to decide whether the vent ratio required for a given maximum explosion pressure varied with the cube root of the vessel volume. In general, this was so, for several concentrations of dust in the suspension. The vent requirements for large volumes would tend to be overestimated using this procedure. The relation between maximum explosion pressure and the vent ratio was also investigated, and for pressures below 50 kN/m^2 the pressure varied inversely with the square of the vent ratio. For higher values, the maximum explosion pressure (absolute), varied inversely with the vent ratio having an exponent between one and two. When compared with predictions based on the German work[10—16] the measured explosion pressures for flour were in reasonable agreement.

The cubical explosion enclosure used for coal dust [24], of 300-m^3 volume, was provided with sixteen circular vents in the roof. The vents could be closed either by screwed steel lids or by rubber plates placed loosely on top of the openings. The ignition source, a pyrotechnic composition, was initiated electrically and was situated in one of the lower corners of the chamber. Eight piezoelectric gauges recorded pressure simultaneously in the explosion. The relation between maximum explosion pressure and vent ratio was studied, for different dust concentrations, and a power law rather than an exponential function was found to give best correlation with experiment. Increase in the vent ratio led to a reduction in the time from ignition to development of maximum pressure. The pressure/time record was complicated, with the larger vent ratios, by the development of fluctuations in the record, several peaks being obtained in some experiments. Further tests would be needed to ascertain whether these vibrations were dependent on the size of the vents or their arrangement. If the peaks were highly transient, they might have been due to resonance in the gas within the enclosure and could then put relatively little stress on the structure.

Ducting

Tests involving the venting of explosions in ducting have all been concerned with the provision of a fully open vent at one end of the ducting, with the ignition source close to the other, closed, end. Vents along the length of the ducting have not recently been studied (Table 3). With horizontal ducting up to 40 m in length and 0.2—0.7 m in diameter, the amount of venting provided by one open end was relatively low, and therefore the explosion pressures could reach high values. In fact, with many of the dusts tested, flame speeds up to 2,000 m/s were achieved, with pressures of 2,000 kN/m^2, indicating detonation conditions. The explosion pressure was directly proportional to the flame speed, which in turn was related to the explosibility of the dust as expressed by the maximum rate of pressure rise in the standard apparatus. Because of the high pressures in explosions, the use of hinged flap vent closures was not successful, closures of massive construction being damaged.

A similar design of experiment, but in a ducting 1.4 m in diameter, using sugar dust, gave flame speeds up to 500 m/s. These explosions were initiated by a methane/air mixture behind a diaphragm at the closed end of the pipe; after ignition the pressure rise in the gas mixture burst the diaphragm and injected a large flame into the previously raised dust cloud. The effect of varying the particle size of the sugar was also studied [25].

A 200-m-long ducting, 1.8 m in diameter, was used for coal dust explosions [26] but because of environmental problems only part of the volume of the ducting was filled with suspension. Ignition was again by a methane/air mixture at the closed end. The explosions were relatively mild, because of the restriction on quantity of dust, and clearly showed fluctuations in the flame propagation due to shock waves reflected from the ends of the system. The vent ratio was low, and the results are not generally applicable to industrial designs.

Cyclone

The most detailed recent work on a plant unit has involved a cyclone [9,27]. Venting data for several dusts of differing maximum rates of pressure rise have been presented [27] and the vent ratio required to reduce pressures to safe values was considerably less than indicated by Table 1. Unlike the venting of compact enclosures, the distribution of the vents on the cyclone had a noticeable effect on the maximum explosion pressure, the position giving the lowest pressures being that near the suspension inlet, the highest pressures being recorded with a vent on the outlet pipe. The relatively lower pressures with the cyclone were attributed to only a fraction of its volume being filled with an explosible suspension whilst in normal working, whereas with other compact vessels the most severe situation which can arise in practice is with the entire volume filled with suspension. However, only one geometry of cyclone was investigated, and the venting requirements for high-efficiency cyclones have not yet been examined. In the experiments, vent covers were either bursting panels, operating at low pressures, or hinged covers of various weights. Increase of the weight of the cover, leading to increased inertia, was shown to significantly increase explosion pressures and reinforced the recommendation derived from practical experience that the weight of the cover should be kept as low as possible, consistent with adequate provision of strength.

Theoretical aspects

A number of theoretical treatments of the venting process in dust explosions have been published recently. The common assumption is made that the vents are open, so that the effects of covers can be ignored; in several instances accoun is taken of the adiabatic expansion through the vent, the pressure differential being sufficiently high for the flow to be sonic.

The method used by Heinrich [18, 28—30] was to consider the gas flow when the maximum explosion pressure was reached, equating the rate of discharge to the rate of generation of combustion products. The resulting equation becomes indeterminate when the vent area is zero, *i.e.* for a closed vessel, but on the whole gave good agreement with experimental results [19, 20]. As mentioned above, the maximum rate of pressure rise measured from the small-scale test apparatus needs to be adjusted by a factor before it can be applied in the equations.

An alternative approach to systems where explosion pressures are relatively high was to calculate the loss of combustion products from the vent during the explosion, to compare the loss with the amount of dust suspension originally present, and to derive the maximum pressure in terms of the maximum explosion pressure in a closed vessel with no vents [31]. The resulting equation contained terms for both the maximum rate of pressure rise and the maximum explosion pressure in a closed vessel and was applied to results published elsewhere [10]. Satisfactory agreement was obtained, but the need for more experimental data against which to compare the equation was pointed out. A second regime was also considered, relating to relatively low explosion pressures, and where the velocity of discharge through the vent was less than sonic. The assumption was made that the maximum explosion pressure would be generated when the rate of formation of combustion products within the vessel reached a maximum. The equation showed that the explosion pressure was proportional to the square of the maximum rate of pressure rise, and inversely proportional to the square of the vent ratio [1]. When applied to published data for various dusts the measured explosion pressures varied approximately linearly with calculated values, with some scatter. There was insufficient data for a thorough testing of the method but it was shown to give calculated vent ratios reasonably in accordance with the requirements in Table 1, assuming typical explosion parameters for a dust of moderate, intermediate and severe explosibility.

A further equation has been obtained for application to both gas and dust explosions. The rate of generation of products was again equated to the rate of discharge through the vent, and the burning velocity of the mixture was included as one of the variables. When data for gas mixtures were applied to the equation, satisfactory agreement was reported [32]. One advantage of the method was that a turbulence factor could be introduced, although this would probably be more significant with gas mixtures than with dusts. Gas mixtures would normally be stationary when ignited, and would then generate turbulence during an explosion, whereas dusts would be turbulent before ignition because of the need to disperse the dust in advance. A brief review of a theoretical analysis of gas and dust explosions is available [33] in which various equations are compared, and the vent ratios calculated for different dusts and gases. The spread of values was too large for accuracy of design, and hence some selection would be needed in a particular case. Those equations with experimental backing clearly have an advantage, and the optimum procedure is probably to choose data based on experimentation which is as close as possible to the actual problem.

Conclusion

The data which have recently become available from the investigations in Table 3 have significantly increased the knowledge of the venting requirements, particularly of compact enclosures up to 100 m^3 volume. On the whole, the areas of vent investigated were relatively small so that the explosion pressures were correspondingly high, and would be greater than the safe maximum for many designs of dust collection unit in common use. Where stronger vessels can be employed, the data is directly applicable and for simple units of this type is probably sufficient for economic design. Other information is needed on the effects of vent closures on maximum pressures, and also the more generous venting requirements needed for weaker units.

Less data have been provided for ducting and other elongated enclosures, but the hazards of permitting long lengths without regularly spaced vents have been clearly demonstrated. For weak units, such as bucket elevator casings, the position is relatively unchanged and designs must be based on the earlier data.

Apart from detailed study of the venting requirements of the cyclone, there has been little work on other plant units. There is a clear need for further information on other geometries of cyclone, and also units where because of internal complexity the simplified design represented by most of the work on compact enclosures would not be directly applicable, and realistic adjustments for internal complexity cannot at present be made. In particular, the venting of fabric filter units needs further study, particularly as these are often relatively weak and large vent ratios would be needed.

Research into dust explosion hazards is expensive, because of the complexity of the experimentation, and the work recently reported must have absorbed considerable resources. For the future, if expenditure is to continue at the same level, it would be profitable to use a minor part of it to strengthen the theoretical background to the dust explosion venting process. A start has already been made, but a good deal more needs to be done and the results to date are encouraging. By this means, the effects of plant scale can be more readily assessed than by the empirical approach and also more generalized design data would become available. For some plant units, however, because of their complexity direct experimentation may be the only means to obtain data, at least in the foreseeable future. It is also time that both experimentalists and theorists should turn their attention to the venting of flammable gas/dust mixtures, which is a serious practical problem for which little data are available.

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