CALCULATION OF GAS EXPLOSION RELIEF REQUIREMENTS: THE USE OF EMPIRICAL EQUATIONS

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Several empirical equations have been presented in the literature, relating the pressure generated in a vented gas explosion to parameters characteristic both of the gas-air mixture ignited and of the confining structure. However, there is some confusion concerning the application of the various formulae to practical situations, both as to which is the most appropriate formula to use and also as to the range of values of the various parameters for which the formulae are valid. This paper is intended to give guidance on these problems.

INTRODUCTION

There is a large volume of literature on the subject of gas-air explosions including a number of surveys which refer to explosion reliefs and the venting of plant [Maisey (1)]. However, the information on explosion venting is mostly empirical and related to experiments conducted with homogenous, quiescent gas-air mixtures contained in relatively small enclosures. Some large scale studies have been carried out [Bromma (2), Astbury et al (3), Astbury et al (4) and Dragosavic (5)], however, and these provide useful scaling points with which the smaller scale studies can be compared.

Several empirical equations, derived from the various experimental studies, have been presented in the literature, relating the pressure developed in a vented explosion to various parameters characteristic both of the gas-air mixture ignited and of the confining structure. These have been widely used since it is obviously desirable, for design purposes, to be able to assess the effectiveness of an explosion relief in a given situation by calculation rather than experiment. However, each of these equations relates to different experimental conditions and hence shows a different dependence of the pressure generated on parameters such as the burning velocity of the gas-air mixture ignited and the area, weight and breaking pressure of the explosion vent cover. There is, therefore, some confusion concerning the application of the various formulae to practical situations, both as to which is the most appropriate formula to use in a given circumstance and also as to the range of values of the various parameters for which the formulae are valid.

In practice, explosions can produce pressure-time profiles consisting of not one but two (or more) peaks [(2), (3), (4) and Cubbage and Simmonds (6)] and this can lead to further difficulties concerning the practical application of empirical equations since the various formulae are not intended to describe the pressure-time profile generated in an explosion but merely to predict the maximum presssure rise for particular situations. Consequently, some confusion could arise as to whether a given empirical equation predicts the pressure rise corresponding to that of the first peak, that of a subsequent peak, or whether it predicts whichever has the maximum value. Such a distinction has practical importance since the magnitudes of the various pressure peaks can be significantly different.

Two formulae in particular have been widely used to calculate the explosion relief requirements of structures [(6) and Rasbash (7)]. Recently, another formula has been proposed [Cubbage and Marshall (8)], based on an extensive series of tests under a wide range of experimental conditions, which appears to have a somewhat wider application than the earlier equations.

DISCUSSION OF EMPIRICAL FORMULAE

Although other authors have presented formulae from which explosion relief requirements of structures may be calculated [Runes (9) and Yao (10)] only those derived by Cubbage and Simmonds (6)

Rasbash (7) and Cubbage and Marshall (8) will be considered, these being the formulae in more common usage at present.

In all of these formulae, the parameter S_o (the fundamental burning velocity) is used to define the gas-air mixture ignited. In general, this is only correct when the equations are used to estimate *the maximum pressure rise generated on ignition of an initially quiescent gas-air mixture and when* little or no turbulence is generated. In other situations, a non-specific burning velocity, S, the value of which is characteristic of the particular circumstances (for example gas concentration, degree of turbulence, etc) should be substituted. To account for the effect of turbulence on S_o, it is necessary to introduce an empirical factor the value of which has to be assessed from limited experimental data. This is the approach adopted by, amongst others, Yao (10) and Rasbash (12). The value given to this numerical factor is, therefore, subjective; Rasbash, for example, suggests that S_o should be multiplied by a factor ranging from 1.5 to 5 depending on the number and distribution of turbulence promoting obstacles in an enclosure volume. Similar values are mentioned by Yao for his turbulence correction factor.

(a) Cubbage and Simmonds Formula

These authors investigated explosion relief for industrial ovens and similar low-strength plant in an extensive series of tests using a variety of fuel gases and flammable vapours in enclosures up to 14 m^3 (500 ft^3) volume. In many of the experiments, two pressure peaks developed. The magnitude of the first peak pressure (P_1) was found to conform to Equation (1), which contains terms expressing the effect of both the type of gas-air mixture and the characteristics of the enclosure:

$$P_1 V^{1/3} = S_o[0.3\ Kw + 0.4] \qquad \text{(imperial)} \qquad .....(1)$$

$$= S_o[0.45\ Kw + 2.6] \qquad \text{(SI)}$$

The second peak pressure (P_2) is given by the formula:

$$P_2 = S_o K/4 \qquad \text{(imperial)} \qquad .....(2)$$

$$= 5.84\ S_o K \qquad \text{(SI)}$$

Equations (1) and (2) can be used with any fuel gas since the effect on the pressure of the combustion characteristics of different fuels is described by the parameter S_o, the fundamental burning velocity. Experience has shown that the formulae are applicable to those situations which conform to the following restraints:

maximum and minimum dimensions of the enclosure have a ratio less than 3:1;

the vent area coefficient, K, is less than 5;

the weight of the vent cladding does not exceed 24 kg/m^2 (5.0 lb/ft^2);

the enclosure volume does not exceed 1000 m^3 (35 000 ft^3);

no restraining force (other than the minimum of friction) is used to maintain the vent cladding in position.

The vent cladding can be any material, provided that it conforms with the above restrictions concerning weight/unit area and the pressure required to remove it.

Two general requirements that any explosion relief must fulfil, regardless of other restrictions such as weight/unit area, etc., are that the vent cladding must be compatible with process requirements and also should not become a hazardous missile when the relief operates.

Although one of the restraints on the use of Equations (1) and (2) is that the maximum and minimum dimensions of the enclosure to which they are applied have a ratio less than 3:1, these formulae have been applied to structures not complying with this restriction, for example conveyor ovens [HMSO (11)]. This has been accomplished by regarding such structures as comprising a succession of continuous, approximately cubical, volumes and applying Equations (1) and (2) to each of these individual volumes in turn.

(b) Rasbash Formulae

Rasbash (7) conducted studies on small enclosures using propane-air mixtures, and, by correlating the results with those of other workers, derived the empirical equation below to describe the pressure generated in a vented explosion:

$$P_m = 1.5\ P_v + 0.5\ K \qquad \text{(imperial)} \qquad .....(3)$$

The first term on the right-hand side of Equation (3) expresses the effect of the relief material on the explosion pressure, whereas the second term represents the effect of the size of the vent. The coefficient of this latter term represents an attempt to make allowance for any turbulence produced by obstructions within the enclosure.

Characteristics of the gas-air mixture are not included explicitly in Equation (3). However, since available information suggests that P_m depends on the burning velocity, which for propane-air is S_o = 1.5 ft/s, Equation (3) could be re-arranged to:

$$P_m = S_o[P_v + K/3] \quad \text{(imperial)} \qquad .....(4)$$

$$= S_o[P_v + 7.76\ K] \quad \text{(SI)}$$

There is some justification for this, as the author states that the coefficients of P_v and K vary for different fuel gases. Hence Equation (4) could be applied with gases other than propane.

Although as indicated by Rasbash, P_v may vary slightly with the rate of pressure rise (as characterised by the parameter S_o), Equation (3) could be generalised to gases other than propane, with some approximation by the alternative re-arrangement:

$$P_m = P_v + S_o K/3 \quad \text{(imperial)} \qquad .....(4a)$$

$$= P_v + 7.76\ S_o K \quad \text{(SI)}$$

A disadvantage of these formulae, compared to Equation (1) for example, is that they do not include the volume of the enclosure as a variable. However, this is offset to some extent by the use of the vent coefficient (K), since it is this parameter, rather than the volume of the enclosure, that has the more dominant effect on the pressure generated.

It is considered reasonable to apply Equation (4) to enclosures so long as the following conditions are fulfilled (7):

maximum and minimum dimensions of the enclosure have a ratio less than 3:1;

the vent area coefficient, K is between 1 and 5;

the weight of the vent cladding does not exceed 24 kg/m² (5 lb/ft²);

the breaking pressure of the vent cladding, or the pressure required to remove it, does not exceed 7.0 kN/m² (1.0 lbf/in²).

The vent cover can be any (rigid) material, consistent with the restrictions placed on weight/unit area and breaking pressure, held in place by a positive force — as provided for example by magnetic catches, spring latches or beading around a glass window pane.

Equation (4) expresses the pressure generated in terms of the pressure required to release the vent cover (P_v) and the back pressure caused by the restricted flow of the gases through the vent opening. (Theoretically, this latter effect is proportional to the product $(S_o K)^2$; both Equations (2) and (4), however, show it to be proportional to the quantity $S_o K$). Essentially, therefore, Equation (4) should be viewed as predicting the second peak pressure, P_2.

In a recent publication (12), it has been stated that the back pressure due to the inertia of the vent cover (P_I) should also be taken into account. Accordingly, Rasbash has proposed that, for values of $P_m \leq 49$ kN/m² (7.0 lbf/in²), Equation (3) should be modified to:

$$P_m = AP_v + P_I + BK$$

where the 'constants' A and B take different values depending on the type of fuel gas. The parameter P_I is given by:

$$P_I = S_o(0.3\ Kw + 0.4)/V^{1/3} \quad \text{(imperial)}$$

$$= S_o(0.45\ Kw + 2.6)/V^{1/3} \quad \text{(SI)}$$

i.e. $P_I = P_1$, the first peak pressure as defined by Cubbage and Simmonds. The full equation is:

$$P_m = 1.5\ P_v + S_o\ [(0.3\ Kw + 0.4)/V^{1/3} + K/3] \quad \text{(imperial)} \qquad .....(5)$$

$$= 1.5\ P_v + S_o\ [(0.45\ Kw + 2.6)/V^{1/3} + 7.76K] \quad \text{(SI)}$$

This forumula could therefore be expected to predict the maximum pressure generated in a given situation irrespective of whether this relates to P_1 or P_2.

(c) Cubbage and Marshall Formula

Assuming that the pressure generated in a vented explosion can be adequately described in terms of parameters characteristic of the gas-air mixture ignited and the characteristics of the enclosure (in particular the explosion vent) the relationship

$$P_m - P_v \propto F\,(K,\ w,\ S_o,\ v)$$

can be postulated, where $F(K,\ w,\ S_o,\ v)$ describes the excess pressure developed during the time interval that occurs from vent removal until the instant at which the rate of production of combustion products is balanced by the rate of loss of gases through the vent opening. Using dimensional analysis the formula

$$P_m = P_v + BKwS_o^2/V^{1/3} \qquad .....(6)$$

is obtained, where B is a numerical factor. In practical situations an enclosure frequently has more than one explosion vent. If these are considered as paths of conductance for the combustion products formed in an explosion, by analogy with the electrical situation the parameter $(Kw)_{av}$ can be used to describe the multi-vent situation where

$$1/(Kw)_{av} = 1/(Kw)_i + 1/(Kw)_j + \ldots$$

The averaging of Kw in this manner is valid only if the breaking pressures of the various explosion reliefs are approximately equal.

In practice an enclosure is unlikely to become completely filled with gas-air mixture following a leakage; rather a pocket or a layer of gas-air mixture will be formed. Under these circumstances, Equation (6) will tend to overestimate the pressure developed and an additional factor, to take into account the volume of gas-air mixture contained in an enclosure prior to ignition is, therefore, required. Inclusion of this leads to the formula:

$$P_m = P_v + B\,[KwS_o^2/V^{1/3}][F(E,E_o)] \qquad .....(7)$$

where $F(E,\ E_o)$ is a measure of the energy contained in the gas-air mixture in excess of that required simply to remove the explosion vent. From previous investigations [Cubbage and Marshall (13)] it can be deduced that, for practical purposes, E_o and P_v are numerically equal when P_v is measured in lbf/in^2 and E_o in Btu/ft^3 of enclosure volume. Ideally, $F(E,\ E_o)$ should have a value of zero at $E = E_o$ and of unity for $E \gg E_o$, as in the case of an enclosure completely full of stoichiometric mixture.

Analysis of the results of an extensive series of experiments carried out on small test chambers and a full scale building [Cubbage and Marshall (14) and (8)], which covered a wide range of values of the various parameters, indicated that an appropriate value of the numerical factor B is 0.5 when the imperial system of units is used. (The numerical factor is required to accomodate the different units, in particular those for the pressure terms, expressed in lbf/in^2, and those for the weight/unit area, expressed in lb/ft^2. The theoretical value for the term B is 12/32, i.e. 0.375). In the metric system of units, the numerical term has the value B = 2.44 (i.e. the conversion factor is 4.88, the conversion factor lb/ft^2 to kg/m^2).

Comparison with the experimental results suggested that an appropriate form for $F(E,\ E_o)$ *would be:*

$$F(E,\ E_o)_1 = 1 - \exp\,[-(E - E_o)/(E + E_o)] \qquad .....(8)$$

Hence, the full equation is:

$$P_m = P_v + [0.5\ KwS_o^2/V^{1/3}][1 - \exp\{-(E - E_o)/(E + E_o)\}] \quad \text{(imperial)} \qquad .....(9)$$

$$= P_v + [2.44\ KwS_o^2/V^{1/3}][1 - \exp\{-(E - E_o)/(E + E_o)\}] \quad \text{(SI)}$$

A disadvantage of using $F(E,\ E_o)$, as given by Equation (8) is that for $E \gg E_o$, it approaches the limit 0.63 rather than the desired value of unity. However, in practical circumstances, an accidental ingress of gas into an enclosure is more likely to lead to a gas-air mixture distribution in the form of a pocket or layer, than to a uniform mixture completely filling the enclosure. Furthermore, the (mean) gas concentration will usually be below stoichiometric. Both these factors combine to produce low values of E [say, $E < 750$ kJ/m^3 (20 Btu/ft^3)] and in such circumstances Equation (9) is applicable. For hazard assessment however, when the maximum possible pressure rise that could be generated is required to be known, Equation (6) can be used, with the appropriate value for the numerical factor, B.

When applied to enclosures incorporating small vents with high breaking pressures [$K > 6$, $P_v >$ 35 kN/m² (5.0 lbf/in²)], Equation (9) will tend to underestimate the pressure developed, typically by about 20%. In these rather extreme situations, closer agreement to the experimental data can be obtained by replacing $F(E, E_o)_1$ by the expression:

$$F(E, E_o)_2 = (E - E_o)/E \qquad .....(10)$$

Comparison of the predictions of the appropriate version of Equation (6) with other data available in the literature, particularly large scale studies (2) to (5), produced excellent agreement between predicted and measured pressures. The formula may therefore be used with confidence in any situation for which the following conditions are fulfilled:

maximum and minimum dimensions of the enclosure have a ratio less than 3:1;

the pressure required to break, or remove, the vent cladding does not exceed 49 kN/m² (7.0 lbf/in²);

the vent area coefficient, K, is between 1 and 10;

the weight of the vent cladding lies within the range 2.4 to 24 kg/m² (0.5 to 5.0 lb/ft²);

the parameter (Kw) does not exceed 73 kg/m² (15 lb/ft²);

the enclosure volume is less than 570 m³ (20 000 ft³).

The vent cladding should, preferably, be a friable material but the formula can be used with any vent cover provided that it is held in place by a positive closing force.

Since Equation (7) contains terms which describe the effects on the pressure generated of vent removal, the inertia of the vent, and the flow of gases through the vent opening, it should, and indeed does, predict the maximum pressure generated in an explosion regardless of whether this is P_1 or P_2 (as defined by Cubbage and Simmonds).

COMPARISON OF EMPIRICAL FORMULAE

It is obvious from the previous discussion that none of the empirical formulae presented can be applied generally, i.e. each refer to a different set of circumstances. However, when used in structures complying with the stated range of the variables, the formulae proposed by Cubbage and Simmonds [Equations (1) and (2)] have been shown to give excellent results.

Similarly, both extensive experimental investigation (8) and (14) and comparison of its predictions with literature data (2) to (5) have shown that the formula derived by Cubbage and Marshall [Equation (7)] can be used with confidence.

The range of application of Equation (7) covers both that of the generalised versions of Equation (3) and of Equation (5). These formulae can therefore be compared directly and, since the Cubbage and Marshall formula gives good agreement with the published data, Equation (7) can be considered as predicting 'correct' pressure rises. On this basis, comparison with Equation (7) has indicated that the formulae proposed by Rasbash should be used with discrimination. For common fuel gases [that is for S_o less than about 0.75 m/s (2.5 ft/s)] these formulae will generally overestimate the pressure rise. However, in those situations characterised by small enclosure volumes and relatively heavy vent claddings, the Rasbash formulae will, in general, underestimate the pressure.

More precisely, Equations (4) and (4a) will tend to predict higher pressures than the Cubbage and Marshall formula for values of $V > 4$ m³ (140 ft³) and $w < 19.5$ kg/m² (4 lb/ft²) and underestimate the pressure in all other situations. Similarly, Equation (5) tends to overestimate the pressure except for those situations in which V is less than about 1.5 m³ (50 ft³) and $w > 19.5$ kg/m² (4 lb/ft²), when the formula predicts lower pressures than those given by the Cubbage and Marshall formula.

The predictions of Equations (7) and those of the Rasbash formulae can differ by as much as a factor of two. Whether this discrepancy is significant or not when translated into terms of pressure will depend largely on the magnitude of the pressure in question — a factor of two either way on a pressure of, say, 0.4 lbf/in² probably would not be significant but if the pressure was 4.0 lbf/in² then the discrepancy almost certainly would have practical significance.

TABLE 1 — Summary of range of application of empirical formulae

Formula	Authors	Range of Application	Comments
$P_1 V^{1/3} = S_o (0.45 Kw + 2.6)$ $P_2 = 5.84 S_o K$	Cubbage and Simmonds	$L(max):L(min) \leq 3:1$ $K \leq 5$ $w \leq 24$ kg/m^2 $V \leq 1000$ m^3	Vent cladding can be any material provided that no restraining force (other than the minimum of friction) is used to maintain the vent in position
$P_m = S_o (P_v + 7.76 K)$ $P_m = P_v + 7.76 S_o K$	Rasbash	$L(max):L(min) \leq 3:1$ $1 \leq K \leq 5$ $w \leq 24$ kg/m^2 $P_v \leq 7.0$ kN/m^2	Formulae essentially predict the second peak pressure, P_2. In general they overestimate the pressure generated. Vent cladding can be any material held in place by a positive force.
$P_m = 1.5 P_v + S_o (0.45 Kw + 2.6)/V^{1/3} + 7.76 K$	Rasbash	$L(max):L(min) \leq 3:1$ $1 \leq K \leq 5$ $W \leq 24$ kg/m^2 $P_v \leq 49.0$ kN/m^2	Predicts maximum pressure generated irrespective of whether this is P_1 or P_2. In general, overestimates the pressure generated.
$P_m = P_v + 2.44 (KwS_o^2/V^{1/3})[F(E, E_o)]$	Cubbage and Marshall	$L(max):L(min) \leq 3:1$ $1 \leq K \leq 10$ 2.4 kg/m$^2 \leq w \leq 24$ kg/m^2 $(Kw) \leq 73$ kg/m^2 $P_v \leq 49$ kN/m^2 $V \leq 570$ m^3	Predicts maximum pressure generated irrespective of whether this is P_1 or P_2. For $E \leq 750$ kJ/m^3, $P_v \leq 35$ kN/m^2 and $K < 6$, use $F(E, E_o) = 1 - \exp[-(E - E_o)/(E + E_o)]$. For $E \leq 750$ kJ/m^3, $P_v > 35$ kN/m^2 and $K > 6$, use $F(E, E_o) = (E - E_o)/E$. For hazard assessment i.e. when maximum possible pressure rise that could be generated is required, use $F(E, E_o) = 1$. Vent cladding can be any material (preferably friable) provided that it is held in place by a positive force.

Although the parameters w (weight/unit area of relief) and V (the enclosure volume) do not appear in the generalised versions of Equation (3), it can be easily shown that the predictions of these formulae and Equation (7) will be in good agreement provided that the condition

$$wS_o/V^{1/3} \sim 0.7$$

is satisfied.

The fact that, for most practical situations, the Rasbash formulae tend to overestimate the pressure rise generated in a vented explosion is not necessarily a disadvantage; in hazard assessment it is better to err on the side of safety than otherwise. However, use of these formulae to calculate the explosion relief requirements for a given situation would, in general, result in larger explosion relief areas than necessary. Since the relief area requirement is usually the most difficult to satisfy in practice (particularly on plant) this could create unnecessary difficulty and hence unnecessary cost.

A summary of the empirical formulae, together with their range of application as stated by the authors and the conditions under which they should be applied, is given in Table 1.

CONCLUSIONS

Provided that they are applied to situations complying with the stated limitations of the formulae, the equations proposed by Cubbage and Simmonds [Equations (1) and (2)] and Cubbage and Marshall [Equation (7)] can be used with confidence to predict the pressure generated in a vented enclosure. There are circumstances in which the formulae proposed by Rasbash lead to less accurate predictions of pressure rise.

LIST OF SYMBOLS

A,B = numerical factors

E = energy density (kJ/m^3, Btu/ft^3)

E_b = energy density required to remove explosion vent (kJ/m^3, Btu/ft^3)

K = vent coefficient defined as cross sectional area in plane of vent/area of vent

P_m = maximum pressure generated, (kN/m^2, lbf/in^2)

P_v = pressure required to remove vent (kN/m^2, lbf/in^2)

P_1 = first peak pressure (kN/m^2, lbf/in^2)

P_2 = second peak pressure (kN/m^2, lbf/in^2)

P_r = back pressure due to inertia of vent (kN/m^2, lbf/in^2)

S_o = fundamental burning velocity (m/s, ft/s)

S = non-specific burning velocity (m/s, ft/s)

V = enclosure volume (m^3, ft^3)

w = weight/unit area of vent (kg/m^2, lb/ft^2)

Subscripts

av means average

i, j refer to individual vents in a multi-vented enclosure

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