THE ROLE OF TURBULENCE IN EXPLOSION VENT SYSTEM DESIGN

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The most commonly used method of protection is explosion venting. In its simplest form, a vent is an aperture in the top or side of a vessel to provide a means of pressure relief during an explosion in order to achieve a reduced explosion pressure P_{red}. The efficiency of this protection method has been proven by a large number of experiments and documented industrial explosions by which the explosion venting provided adequate protection. From these experiments several correlations have been established to design venting systems. When compared with realistic, less controlled experiments, it appears that the reduced explosion overpressures may be over predicted but also under predicted. During the last ten years, researchers have devoted significant effort and time to study this problem. The state of the dust cloud at ignition and more specifically the initial turbulence has been identified as being a major contributing factor. This paper aims at presenting a technique to take the turbulence into account when designing an explosion venting system.

INTRODUCTION

Dust explosions do still represent major risks in the process industries. Some accidents, such as the explosion of the a grain silo in Blaye, France (August 1997, 12 victims: Masson, 1998), remind us that explosions in the industry can have serious consequences. There is an obvious need to be capable of "engineering" the safety to reduce the consequences of such accidents.

In Europe, a legal framework has been imposed to implement prevention and protection measures (EU directives 94/9/CE and 99/92/CE) and practical guidelines and standards have been issued. One of these standards, EN14491 describes a comprehensive method to calculate vent areas and design venting systems. This standard is an interpretation of preceding guidelines (VDI 3673, NFPA68) by a panel of European experts. In the USA, the venting guideline NPA68 was substantially revised and the 2007 version became a standard.

However it has recently been pointed out (Zalosh, 2006) that these design methods may overlook some key process parameters such as the initial turbulence of the dust-air cloud. The objective of this paper is to discuss the importance of this parameter and to propose a method for taking turbulence into account when designing venting solutions.

VENT SIZING AND FLAME PROPAGATION THEORY

Vent sizing methods have received considerable attention, especially since the beginning of the seventies with the impulse given by the work of Donat (1971). A number of very valuable contributions followed including the experimental test programmes by Radandt (1983), Bartknecht (1993), and Eckhoff (1991).

In addition to this empirical based approach, analytical models were developed which implement the theory of propagating flame in closed vessels, extended to the situation of open-vented-vessels. The basic equations and justifications for the application of the theory may be found for example in the work of Bradley and co-workers (Bradley et al., 1978).

Controlled experiments facilitated a comparison between the empirical and analytical approach. In addition, large scale experiments were carried out which were closer to real process conditions and geometries.. A very wide debate in the scientific community resulted as a result of this comparative work, which continues up until now. During this process, consensus on some key aspects of vent sizing have been achieved.

If A is the size of the opening in a vessel of volume V, the maximum flowrate Q^- of gases of specific mass ρ through A is linked to the maximum internal overpressure ΔP_{red} ("reduced explosion pressure") in the following way:

$$Q^- = C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta P_{\text{red}}}{\rho}} \qquad [1]$$

at least for small overpressures where C_d is the discharge coefficient of the orifice. The maximum rate of production of volume by the flame Q^+ due to the expansion of the burnt product can be written as:

$$Q^+ = A_f \cdot S_t \cdot (E_{\text{exp}} - 1) \qquad [2]$$

where A_f is the maximum flame area, S_t the burning velocity of the flame and E_{exp} the expansion ratio of the products of combustion. A_f should be linked to some geometrical area of the vessel like its internal area, A_{ch}, as suggested previously by Ellis et al. (1925) on the basis of his excellent experiments.

In principle, the maximum internal overpressure is expected to be reached at the point where $Q^- = Q^+$ so that:

$$\Delta P_{\text{red}} = \frac{\rho}{2} \cdot \left(\frac{A_f \cdot S_t \cdot (E_{\text{exp}} - 1)}{C_d \cdot A} \right)^2 \qquad [3]$$

In this expression, the expansion velocity $S_t \cdot (E_{\text{exp}} - 1)$ mainly depends on the properties of the cloud itself (particles, concentration, turbulence level, etc) so that for a "given cloud" the explosion overpressure will correlate to the geometrical parameters.

The practical use of [3] is not straightforward because the determination of the expansion velocity $S_t \cdot (E_{\text{exp}} - 1)$ is rather difficult. Fortunately, flame theory suggests a direct link between the expansion velocity and the maximum rate of pressure rise of the explosion in a closed vessel. The compression effect inside the vessel can be estimated from the expansion of the burnt gases (Q^+) :

$$\frac{dP}{P \cdot dt} = \gamma \cdot \frac{Q^+}{V} \qquad [4]$$

Assuming that the maximum rate of pressure rise occurs when $A_f = A_{\text{ch}}$ and that A_{ch} is proportional to $V^{2/3}$, at least in compact vessels, then [4] becomes:

$$K_{\text{ex}} = \left(\frac{dP}{dt} \right)_{\max} \cdot V^{1/3} \approx P_{\max} \cdot S_t \cdot (E_{\text{exp}} - 1) \qquad [5]$$

Because of the difficulty to measure flame speeds of dust flames in closed vessels, this relationship remained until now relatively theoretical but recent progress (Snoeys et al., 2008) indicate that [5] seems reasonable. Today, the "flame speed" parameter K_{ex} is determined at standard conditions in for instance the 1 m^3 spherical vessel and is much better known as K_{st}. Note that there is no evidence that the way in which the flame propagates in these standard test conditions corresponds to any practical situation. However since the experimental conditions are kept constant in this standard testing, the variation of the K_{st} between dusts certainly reflects the differences in terms of reactivity.

A number of correlations have been developed on this basis of which some have been incorporated into guidelines and standards (NFPA 68, EN 14491, VDI 3673). Most process parameters suggested by [3] are covered such as the volume of the vessel, the shape factor from the proportionality between A_{ch} and $V^{2/3}$ and the reactivity of the dust cloud via K_{st} and $P_{\max}$. For example, the European standard (EN 14491) proposes the following relationship:

$$\begin{aligned} A/V^{0,753} = {} & [3.264.10^{-5} \cdot P_{\max} \cdot K_{\text{st}} \cdot P_{\text{red}}^{-0,569} \\ & + 0.27 \cdot (P_{\text{stat}} - 0.1) \cdot P_{\text{red}}^{-0,5}] \cdot [1 \\ & + (-4.305 \cdot \log P_{\text{red}} \\ & + 0.758) \cdot \log (L/D)] \end{aligned} \qquad [6]$$

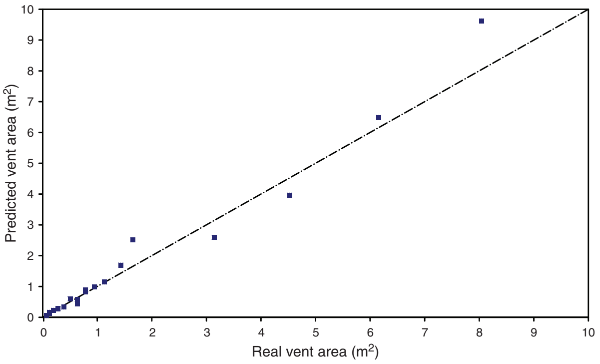

Figure 1. Experimental points of vented explosions from vessel volumes ranging from 2 to 250 m^3. Cellulose dust ($K_{\text{st}} = 200$ bar · m/s, $P_{\max} = 9$ bar) dispersed pneumatically by pressurized gas containers compared to calculated areas according EN14491

In this equation, A is the effective vent area. The units are bar, metre and second and the following boundaries apply:

- $0.1 < P_{\text{red}} < 1.5$ bar
- $0.1 < P_{\text{stat}} < 1$ bar
- $5 < P_{\max} < 10$ bar if $10 < K_{\text{st}} < 300$ bar · m/s, or $5 < P_{\max} < 12$ bar if $300 < K_{\text{st}} < 800$ bar · m/s
- $0.1 < V < 10\,000$ m^3
- $L/D < 20$

This correlation was used to calculate the vent area of documented laboratory experimental data in which the dust cloud was produced by "similar means" (Bartknecht, 1986; Lunn, 1988) so that the flame speed parameter was the same throughout the experiments (Figure 1). The agreement seems excellent.

Even if the intrinsic robustness of such formulae might be convincing, it is important to verify if the relationship still holds by investigating large scale experiments which were closer to real process conditions and geometries. A direct comparison with experiments (still with dust explosions) in real or realistic configurations (Table 1: data from Eckhoff et al., 1984; Eckhoff et al., 1986; Eckhoff et al., 1988; Tonkin et al., 1972; Pineau et al., 1985) is shown in Figure 2. Assuming the trends are correctly featured, the calculated values differ significantly from the measurements.

Clearly, the agreement between calculations and experiments is not so good. One likely reason is the significant influence of the initial turbulence of the cloud (Amyotte, 1985) on the combustion (via S_t). Because the turbulence level depends strongly on the flow field inside the vessel prior to ignition, it is natural to think that a more accurate prediction of the course of explosions can only be achieved if sufficient details on the flow field could be entered into the combustion model (incorporating explicitly the influence of turbulence).

Table 1. Vented dust explosion experiments in real or "realistic" equipment

Ref	Author	Equipment	Dispersion of the powder	Injection velocity-pressure (m/s-barg)	Pipe diameter (m)	Volume of the vessel (m^3)	Aspect ratio	Area of the opening (m^2)	Dust
A	Eckhoff, 1988	filter	tangential flow of dust from a pneumatic transport line	35 - 0	0.155	5.8	2	0.11	Maize starch
B	Eckhoff, 1988	filter	tangential flow of dust from a pneumatic transport line	35 - 0	0.155	5.8	2	0.2	Maize starch
C	Eckhoff, 1988	filter	tangential flow of dust from a pneumatic transport line	35 - 0	0.155	5.8	2	0.4	Maize starch
D	Eckhoff, 1988	filter	tangential flow of dust from a pneumatic transport line	35 - 0	0.155	5.8	2	0.55	Maize starch
E	Tonkin, 1972	cyclone	tangential flow of dust from a pneumatic transport line	13 - 0	0.23	1.2	1	0.06	Wheat flour
F	Tonkin, 1972	cyclone	tangential flow of dust from a pneumatic transport line	13 - 0	0.23	1.2	1	0.08	Wheat flour
G	Tonkin, 1972	cyclone	tangential flow of dust from a pneumatic transport line	13 - 0	0.23	1.2	1	0.12	Wheat flour
H	Eckhoff, 1986	silo cell	coaxial flow of dust from a pneumatic transport line	38 - 0	0.155	236	6	3.4	Maize starch
I	Eckhoff, 1986	silo cell	coaxial flow of dust from a pneumatic transport line	38 - 0	0.155	236	6	5.7	Maize starch
J	Eckhoff, 1984	silo cell	coaxial flow of dust from a pneumatic transport line	12 - 0	0.2	500	3.5	2	Wheat dust
K	Eckhoff, 1984	silo cell	coaxial flow of dust from a pneumatic transport line	12 - 0	0.2	500	3.5	3	Wheat dust
L	Eckhoff, 1984	silo cell	coaxial flow of dust from a pneumatic transport line	12 - 0	0.2	500	3.5	5	Wheat dust
M	Eckhoff, 1984	silo cell	coaxial flow of dust from a pneumatic transport line	12 - 0	0.2	500	3.5	8.8	Wheat dust
N	Eckhoff, 1984	silo cell	coaxial flow of dust from a pneumatic transport line	12 - 0	0.2	500	3.5	14	Wheat dust
O	Pineau, 1985	featured air mill*	coaxial flow from a pressurised line	250 - 4	0.025	1	3.5	0.03	Wheat flour
P	Pineau, 1985	featured air mill*	coaxial flow from a pressurised line	250 - 4	0.025	1	3.5	0.05	Wheat flour
Q	Pineau, 1985	featured air mill*	coaxial flow from a pressurised line	250 - 4	0.025	1	3.5	0.07	Wheat flour
R	Pineau, 1985	featured air mill*	coaxial flow from a pressurised line	250 - 4	0.025	1	3.5	0.1	Wheat flour

*1 m^3 vessel with pressurised injection

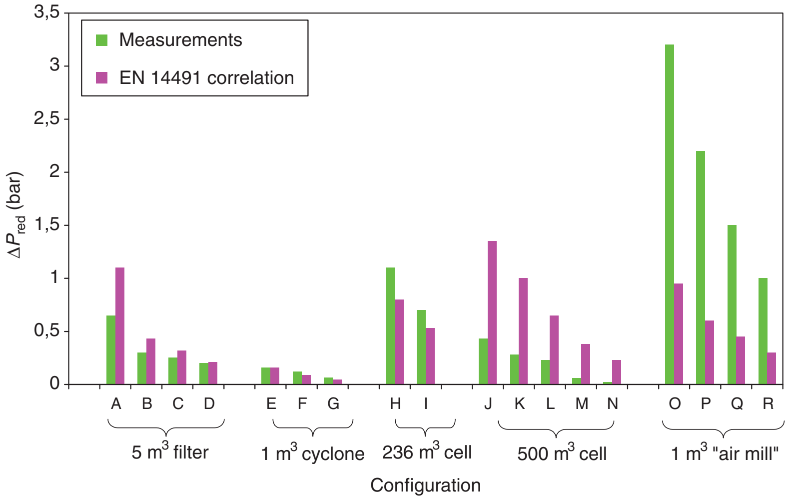

Figure 2. Calculated (using [6]) and measured overpressures for vented dust explosions developing in real process equipment

VENT SYSTEM DESIGN INCLUDING TURBULENCE

Tamanini (1996) evaluated the role of turbulence in the course of vented explosions. He (Tamanini, 1998) also proposed an integral version of the well-established k-epsilon model for turbulence (Hinze, 1975).

For the purpose of this paper, we retain the steady state version of *k*-epsilon equation in which the production rate (P_k) equals the dissipation rate (ε). L may be assumed constant and proportional to a linear dimension of the volume as this parameter can be seen as a measure of the mean velocity gradients so that:

$$L = C_L \cdot V^{1/3}$$

$$k = \frac{3}{2} \cdot u'^2$$

$$P_k = q_m \cdot \frac{1}{2} \cdot U_{inj}^2$$

$$\varepsilon = \frac{P_k}{M}$$

$$L = C_\mu^{3/4} \cdot \frac{k^{3/2}}{\varepsilon} \qquad [7]$$

where q_m is the injected mass flow rate of mass M at velocity U_{inj} in the volume V. C_μ and C_L are constants of the order of 0.1 (0.09 and 0.05 respectively). When this model (Figure 3) is compared to turbulence measurements performed in dust clouds under various conditions, including realistic ones (Hauert et al., 1994), a good agreement is achieved.

In 2008 Proust, Leprette and Snoeys proposed an approach by which the explosibility parameter K_{st} is

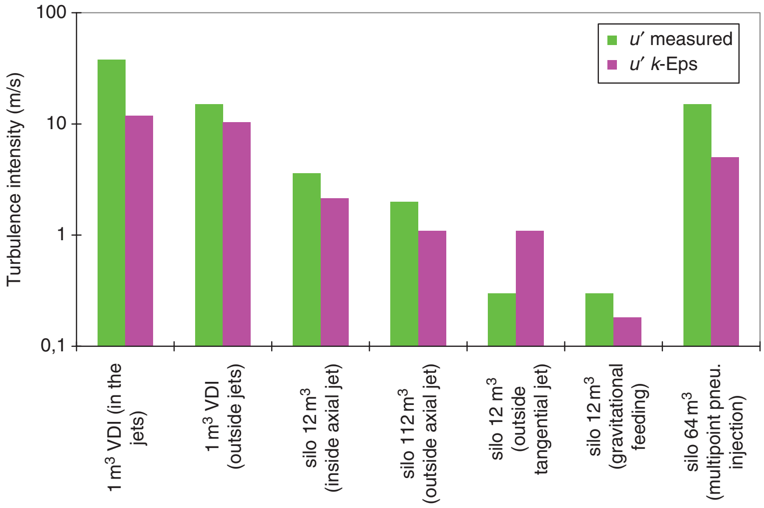

Figure 3. Comparison between turbulence measurements in realistic situations and prediction by the integrated *k*-epsilon model

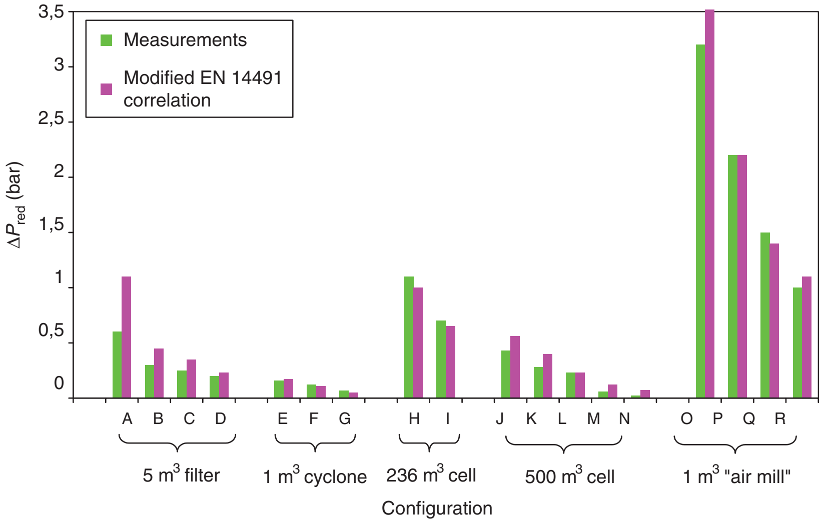

Figure 4. Comparison between calculated (phenomenological model) and measured overpressures in vented isolated vessels (configurations from table 1)

multiplied by a coefficient of turbulence, τ. A power law ($S_t \sim u'^{0.75}$ [8]) was proposed by Schneider and Proust (2007) to express the variation of S_t with the turbulence of the dust/air cloud.

The proposed turbulence coefficient is the ratio between the real flame parameter K_{ex} and K_{st}. From equation [5] and [8], we obtain:

$$\tau = \frac{K_{ex}}{K_{st}} = \left(\frac{u'}{u'_{st}}\right)^{0.75} \quad [8]$$

where u'_{st} is the turbulence level in the 1 m^3 vessel (close to 2 m/s according to Proust et al., 2007). When applied to the scenarios of table 1, the calculations show that τ ranges from 0.5 for the very low turbulence silo experiments by Eckhoff up to 4 for the extremely turbulent "mill" experiments of Pineau. When this specific turbulence effect is included in equation [3] (replacing K_{st} by $\tau \cdot K_{st}$) gives a significantly better agreement with the data of realistic experiments (Figure 4).

CONCLUSIONS

In this paper, the specific role of turbulence in dust explosion vent system design is addressed. It is shown that the equation proposed by EN14491 may give a good estimation of the vent area provided that the explosion in the protected volume develops "as in the 1 m^3 cubic vessel" which is used to measure the K_{st} coefficient. On the other hand it is also suggested that ignoring the influence of the turbulence may lead to a significant under estimation of the venting requirement.

A possible method to include the effect of turbulence in the vent system design is proposed. At present the proposed method may be somewhat difficult to apply. An alternative method could be to classify the various type of equipment in "turbulence classes" as suggested previously by Eckhoff (Eckhoff, 1984).

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