On the Usefulness of Phenomenological Approach to Model Explosions in Complex Industrial Systems

Grégoire Y.[1,] *, Leprette E.[1], Proust C.[1,2]

[1] INERIS, PHDS Department, Parc Technologique ALATA, Verneuil-en-Halatte, France
[2] UTC, TIMR laboratory (EA4297), Compiègne, France
**Corresponding author's email: yann.gregoire@ineris.fr*

ABSTRACT

Explosion protection is the object of various national and international documents, which are focused on the functions, the intended uses or the dimensioning rules for specific systems. However, despite a few application examples are described in the usual guidelines, they are limited to the description of a protection that can be added on a single piece of equipment while it is not the case in industrial processes. Furthermore, in an ATEX explosion there is a strong coupling between the explosion and its environment. Because of this the guidelines recommendations cannot be transposed on an industrial site without due consideration. In this paper, a way to consider the real explosion conditions is given allowing a choice and dimensioning of a set of safety systems. An example is shown based on the example of a model of a real installation. The functional properties of the safety system are extracted from the certification tests whereas the explosion characteristics are extracted both from the standard combustion properties of the dust and from the latest knowledge about flame propagation. A specific focus is made on two fundamental aspects: on the one hand, the critical importance to understand how the flame propagates in a given complex system. On the other hand, the behaviour of the protection systems that can be used with caution as they quite systematically influence the explosion driven flow

KEYWORDS: Dust explosions, explosion mitigation, phenomenological modelling.

INTRODUCTION

ATEX directives introduce everywhere in Europe the obligation to take dispositions to protect the workers in industry from the explosion risk. In many situations, and especially when dust explosions are identified, prevention measures are insufficient, and protection should be ensured. Explosion protection is the object of various national and international documents that are focused on the functions, the intended uses or the dimensioning rules for specific systems: NFPA68:2012 [1], EN14797:2007 (testing) [2] and EN14991:2014 (dimensioning) [3] for dust explosion venting techniques. Despite a few application examples are described in the usual guidelines, they are limited to the description of a protection that can be added on a single piece of equipment in which an explosion may occur, in quite an ideal configuration with fully known turbulence conditions, combustible reactivity, repartition or concentration. Such observation is general to most of the safety barrier used in the industry. However, in real installations, the device to be protected is rarely isolated but often connected to various ducts and vessels in which the explosion may propagate. This is a critical point as in an ATEX explosion there is a strong coupling between the explosion and its environment. A direct consequence of this is that the guidelines recommendations cannot be transposed on an industrial site without due consideration. In such occurrence modelling of the explosion phenomenon at stake can be helpful firstly to understand the possible course of events, then to dimension a protection strategy accordingly. When a complex system at an industrial scale is

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considered, the most evolved tools such as CFD models can be used but their use can be associated with prohibitive costs. They most often require, in addition to engineering skills, large computing power as well as significant post-processing works to ensure the consistency of the results. In this paper a phenomenological approach is suggested in view of grasping the physics at stake. An example is show based on a real installation. The example of coal grinding installation is considered and is schematized in Fig. 1. It consists of a mill, a cyclone and a dust collecting filter, connected by pipes. The supply and product circuits are excluded from the present study. After passing through the mill, the grinded coal-gas mixture is sucked into the cyclone, where the coarsest particles are isolated, then resent towards the mill. Alternatively, the thinner particles travel towards the filter after which they are collected. The major objective is to protect the installation from the explosion effects as well as to limit the explosion effects in the medium range.

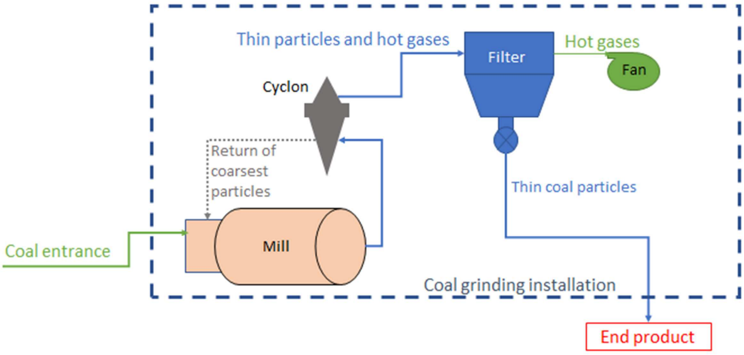

Fig. 1. Schematized coal grinding installation.

However, the very first step is to identify the explosion risk. Filters are prime causes of powder explosion but the same can be said on the mills. In fact, not only there is a large multiplicity and complexity of industrial installations, but also, once the choice is made on a setup, the process itself can vary. For example, some coal installations may also operate occasionally with petcoke. Different phases of the process (starting, usual operation, maintenance) imply different risks. At last the explosion may be triggered at various stages of the installation then propagate to the totality of it. This illustrates the needs behind the use of comprehensive phenomenological tools such as the one described here.

PHENOMENOLOGICAL MODELLING OF THE EXPLOSION IN A PROCESS

To model such explosion phenomena and keep a satisfying understanding on the course of the events, INERIS developed the EFFEX code [4], phenomenological software consisting of interlinked models each dedicated to a single aspect such as flame propagation in a volume, turbulence characteristics prediction, combustion rates, mechanical resistance, pressure effects… Most of the physics is derived from fundamental research. Each model is qualified separately, and the overall consistency can be compared to realistic full-scale experimentation or actual accidents.

The typical situation is that of a flammable cloud of suspended particles in a confined or semi-confined space. A reactive fuel-air mixture is formed. The size, composition and internal level of agitation ("turbulence") depend on the type of leakage and the geometric characteristics of the containment. If an adequate source of ignition is present inside the flammable area of the cloud, it will ignite, and a flame will propagate step by step from the ignition point. Figure 2 illustrates the development of the flame in the containment.

The flame develops spherically around the source of ignition. On its way, it almost instantaneously transforms cold reactants into hot combustion products (typically from 1000 to 2000 ° C). Hot gases being less dense than cold ones, it results in a high-volume expansion of the gases. This process is directly responsible for increasing the pressure in the enclosure.

The pressure rise due to the dust explosion is directly linked to the quantity of gases produced by the combustion minus the gases lost by the various openings on the filter (ducts, opened vents). Thus, the pressure rise curve as function of time can be estimated with a model such as that of Lewis and Von Elbe [5]:

$$\frac{1}{P}\frac{dP}{dt} = \gamma\,\frac{Q_{produced} - Q_{lost}}{V} \tag{1}$$

where P, V and γ are the enclosure pressure, its volume and the specific heat ratio of the gaseous species. $Q_{produced}$ and Q_{lost} are respectively the volumetric fluxes produced by the combustion and lost through the vent.

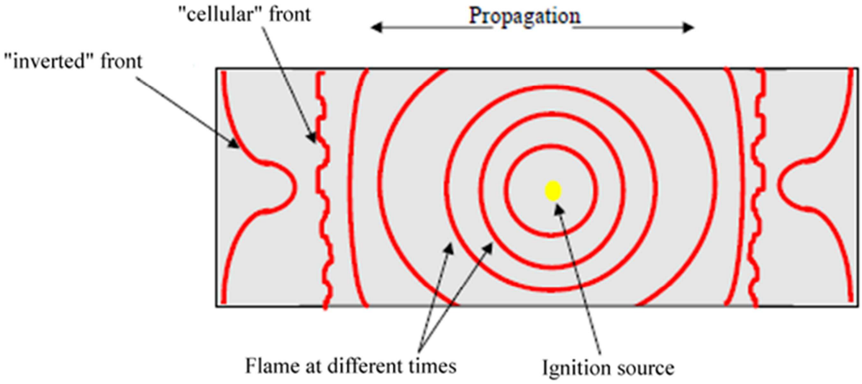

Fig. 2. Flame front evolution as a function of time.

Such model clearly indicates that the effect of the explosion will be directly linked to the reacting products, which will determine the rate of the gases production and the environment through the action of the vents in the Q_{lost} parameter. Q_{lost} can be estimated through some various models derived from the generalized Bernoulli's laws. In practice whether the flow is subsonic or supersonic it is possible to estimate the Q_{lost} term through equation (2) or (3) respectively for the subsonic and supersonic cases:

$$Q_{lost} = C_d S \left(\frac{P_2}{P_1}\right)^{1/\gamma} \sqrt{\frac{2\cdot\gamma}{\gamma-1}\cdot\frac{P_1}{\rho_1}\cdot\left(1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right)}\ , \tag{2}$$

$$Q_{lost} = C_d S \sqrt{\gamma\frac{P_1}{\rho_1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\ . \tag{3}$$

However, the problem of the estimation of the produced gases flux $Q_{produced}$ is more challenging as it depends both on the products that are reacting but also on their environment which will influence the flame surface or impose concentration or turbulence gradients. The excess volume produced per unit of time, is proportional: on the surface of the flame, the burn rate of reactant consumed per unit of flame surface (this parameter has the dimension of a speed and is often called "burning rate"), and the volume expansion ratio (which is linked to the temperature of the products: the hotter the more volume is produced). Gas production through combustion can be approximated as follows in our model: the fresh combustible mixture is instantaneously transformed in hot burnt products through the passage of the flame whose thickness is zero. Thus, it is a function of the area of the reacting surface *Af*, its velocity *St* and an expansion ratio α:

$$Q_{produced} = St \cdot Af(\alpha - 1) \tag{4}$$

Firstly, the expansion ratio α is a thermodynamic data which depends only on the heat released by the combustion and can be expressed through the first principle of thermodynamics:

$$\alpha = \frac{\rho_{fresh}}{\rho_{burnt}} \approx \frac{T_{burnt}}{T_{fresh}} = \frac{\Delta H_{Comb}}{C_P T_{fresh}} + 1\ , \tag{5}$$

where ΔH_{Comb} is the reaction enthalpy, T_{fresh} and T_{burnt} are the temperatures of the reactants and the burnt products, ρ_{fresh} and ρ_{burnt} are the densities of the reactants and the burnt gases, and C_P is the specific heat of the burnt products. The expansion ratio α is a fundamental parameter which depends strongly on the combustible mixture composition and is poorly influenced by the propagation. For most common mixtures found in the process industries it is comprised between 6 and 8 [6]. Alternatively, the shape of the confined structure suffering the explosion can have an influence on the flame surface *Af* and so is the case for the local flow velocities, or when obstacles are present. Even in a medium initially at rest, the flame grows spherically until the spherical front reaches the closest wall. When contacting the wall, the flame front is stopped then reversed. During this phase the flame front surface can become cellular or be curved toward the combustion products most likely because of local perturbations such as Landeau-Darrieus instabilities [7]. In all case the maximal flame area is linked to the dimensions of the volume and its cross section. Extensive comparisons of EFFEX calculations with experiments indicate that a decent agreement can be achieved when the flame surface is roughly equivalent to the largest inscribed sphere in the enclosure [8].

Finally, the flame velocity in a mixture attached referential is also expected to be a property intrinsic of the mixture. The fundamental combustion velocity S_{lad} obeys to the laws of thermokinetics (thermodynamic equilibrium, Arrhenius law) and can be described as the volume of reactants consumed by a square meter of the flame surface. However, this definition corresponds to a configuration in which the reactive mixture is at rest in which case the effect of an explosion would be limited to the maximum. For a more realistic approach, it is necessary to consider a turbulent flame velocity St that can be determined for industrial applications based on the empirical definition of K_{st}:

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} V^{1/3} \tag{6}$$

Replacing this in equation (1) (and assuming no openings on the vessel), we obtain:

$$\frac{1}{P_{max}} K_{St} = \gamma \frac{St \cdot Af_{max} \cdot (\alpha - 1)}{V^{2/3}} \Rightarrow \quad St \approx \frac{K_{st}}{\gamma P_{max}(\alpha - 1)} \tag{7}$$

Even in the isolated enclosure the effects of the dust explosion are strongly dependent not only on the nature of the reactants but also on the specificities of their environment such as the geometry or local turbulence effect. The model described in the previous paragraphs is only applicable if the flame propagation velocity is sufficiently low (typically < 30 m/s) for the internal pressure to remain “uniform”. This condition is very generally satisfied when the ratio between the largest and the smallest dimension of the apparatus is less than 5 [4], which is not the case for pipes for example. In practice, there would be an explosion at one end, for example in a mill and the atmospheric pressure at the other end. For ST1 class dusts (which is the case here), the contribution of the duct combustion to the overpressure in the installation studied is low and the flow is largely dominated by the pressure differences between the upstream and downstream sides of the pipes [9]. A direct consequence of this is that the flame velocity in such situation quickly reaches hundreds of meters per second. Empirical data show that the flame velocity in a duct downstream an enclosure is well correlated with the square-root of the overpressure P_{red} (stands for "reduced explosion pressure" a term often used to design the maximal overpressure in a vented vessel) in the enclosure (analogy to a Bernoulli model):

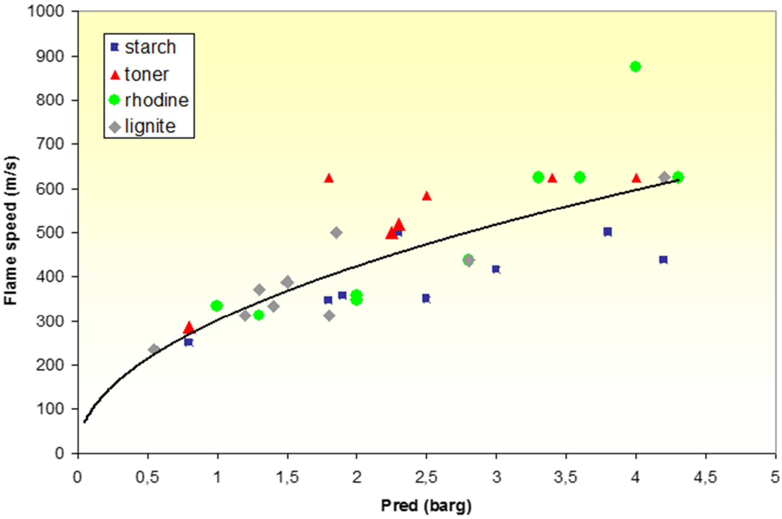

Fig. 3. Correlation between vessel overpressure and maximal flame velocity in a connected in a duct [10].

In this last situation, the velocity flow is driven by the pressure difference between both ends of the pipe, and so is the flame. It is also noted that in such case, until the flame has reached the other end of the pipe, the pressure in the upstream equipment (the mill) continues to increase as if the duct was closed [10]. The pressure rise is then less related to thermal expansion than to the inherent dynamics of the flame (speed and acceleration). There is therefore a piston effect and the main problem of the propagation of the explosion in a pipeline is to determine the speed of the flame, because ducts usually show large overpressure resistance and it is this same fast flame that is transmitted in equipment downstream. Moreover, the presence of singularities on the pipe such as bends is likely to modify the flame surface and accelerate it. In EFFEX, a relatively simple model of the compressible Bernoulli equation type has been implemented to estimate this velocity. The basic assumption is that the flame propagates at a speed *St** which depends, as for non-elongated enclosures, on the turbulence and reactivity of the dust (thus on the usual turbulent flame velocity *St*) but also on "*Ve*", the forced flow by the pressure difference between the upstream and downstream of the pipeline. Singularities such as elbows are therefore ignored. The cases of subsonic and shocked flows are differentiated. Noting P_1 and P_2 the pressures at each sides of the duct, and with $P_2 > P_1$. If the condition $\frac{P_2}{P_1} > \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}$ is fullfield then the flow is chocked, and the Mach number M is 1. In the other case, M can be computed as follows:

$$M = \sqrt{\frac{2}{\gamma-1}\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}} . \tag{8}$$

From the temperature T and the molar mass M, we obtain the flow velocity by computing the speed of sound which depends on the temperature T. In the chocked and subsonic case, we obtain respectively these 2 equations for the flow velocity:

$$Ve = \sqrt{\frac{8.314}{M}\frac{2\cdot\gamma}{\gamma+1}T} \quad \text{and} \quad Ve = M\sqrt{\frac{8.314}{M}\frac{2\cdot\gamma}{\gamma+1}\frac{T}{\frac{\gamma-1}{2}\cdot M^2+1}}\,. \tag{9}$$

Although they remain approximate, the results provided by this model give satisfactory orders of magnitude, they have been successfully confronted with experiments carried out at INERIS as well as with published data. Again, the major objective here is to be able to estimate the characteristic times of the explosion propagation rather than the pressure built up in the pipes. When an explosion occurs in a structure made of interconnected enclosures the explosion can be transmitted from one vessel to its neighbours and the flame propagation can become of an extreme complexity [11]. In such case. A schematic of a possible course of events is presented in Fig. 4: the dust ignition in the primary enclosure induces a first explosion (4a) and generates a significant turbulence and flow velocity in the connected pipe (4b). Then large quantities of the combustible mixture will be pushed in the downstream enclosure and pressurize it. After its significant acceleration in the duct, the flame will enter the pressurized and highly turbulent combustible mixture in the secondary volume. A secondary explosion, of much greater violence can then happen (4c). It can also reverse the flow completely and push the reactive front back in the primary vessel where the combustion is not terminated (4d).

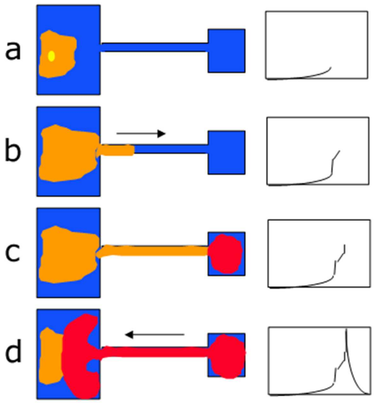

Fig. 4. Schematic representation of explosion development in interconnected enclosures [11].

Because in a wide range of situation the decoupling of 2 enclosures in only partial or impossible, it is of a great importance to account for this phenomenon. In other words, it is necessary to estimate the turbulence in the model structure and adapt the turbulent flame velocity *St* in the downstream equipment accordingly. Phenomenological semi-empirical models are available to estimate the pressure effects due to the flame arrival in the turbulent mixture of the secondary volume. In most situations, the turbulent flow will be induced by jets which characteristics are relatively well known (see [12] for further details on jet theory). A prediction tool was elaborated from this knowledge database. Analytic models can be to estimate the local turbulence velocity u' and the characteristic sizes of the turbulent structures *Lt* were proposed by Hinze [13]. The two flow turbulence parameters *u'* and *Lt* can then be used to estimate the turbulent flame velocity with a Gülder empirical model [14]. Further details on the application of this model have been published more recently by Proust [4]. The main interest here is the order of magnitude to the flame velocities enhancement due to the turbulence effect that can be on the order of 5 to 20 times that observed in the same mixture at rest. Empirical estimations can be made on the turbulence parameters *Lt* and *u'*.

Tamanini [15] proposed an integral version of the well-established k-epsilon model for turbulence. For the present illustration, we retain the steady state version of k-epsilon equation where the production rate (P_k) is equal to the dissipation rate (ε). Proust [16] assumed that *Lt* might be chosen constant and proportional to a linear dimension of the volume since this parameter can be seen as a measure of the mean velocity gradients so that:

$$Lt = C_L V^{\frac{1}{3}} \quad k = \frac{3}{2} u'^2 \quad P_k = \frac{1}{2} q_m U_{inj} \quad \varepsilon = \frac{P_k}{M} \quad Lt = C_\mu^{\frac{3}{4}} \frac{k^{\frac{3}{2}}}{\varepsilon} . \tag{8}$$

where q_m is the injected mass flowrate with the velocity U_{inj} in the volume *V* of mass *M*. C_μ and C_L are constants of the order of 0.05 and 0.09 [15]. Proust compared the model results with experimental results and published data and showed a satisfying compatibility in both cases [16].

THE EXPLOSION SCENARIO

Because of the specific phenomenology of flame development in the complex structure made of interconnected enclosures it is necessary to define first an explosion scenario which is the baseline for the comprehensive analysis of the explosion effects in the structure. In face of the multiplicity of the possible explosion scenario at stake in the current example, we will consider the example of an ignition in the mill during normal operation, that is then transmitted to the cyclone and to the filter. In the present case, the explosible dust is coal powder which is known to have a K_{St} value close to 150 bar.m/s and a $P_{\max}$ on the order of 8 bar (data from the Staubex database). Depending on the technology, mills and cyclones can resist to explosion pressures up to 3 bar. The filter is however of a lesser resistance, 500 mbar in this example. For this reason, let’s assume it is sold to the industrial already equipped with 5 m^2 of vent panels. In this case we consider a volume of and 60, 20 and 300 m^3 respectively for the mill, cyclone and filter. They are connected by DN800 ducts of length 15 m.

The explosion is initiated in the mill and is transmitted to the first duct. The flame propagates to the cyclone, pushed by the overpressure in the mill at a speed of 200 m/s. Under these conditions, when the flame arrives in the cyclone, the mixture is highly turbulent as not only the flame has a very high velocity but also it is pushing large amounts of the reactive dust (as much as 70 to 90 % of the reactants in the duct [9], [11]) inside the cyclone. The combustion occurs at a quasi-constant volume inside the cyclone will occur (despite the exhaust ducts). An overpressure of the order of the dust $P_{\max}$, 8 bars seems possible but again a complete failure of the cyclone happen before reaching this value (we assume a resistance of the cyclone of 3 bar in this case study). Such scenario was simulated with the EFFEX code and the results support this summary of events:

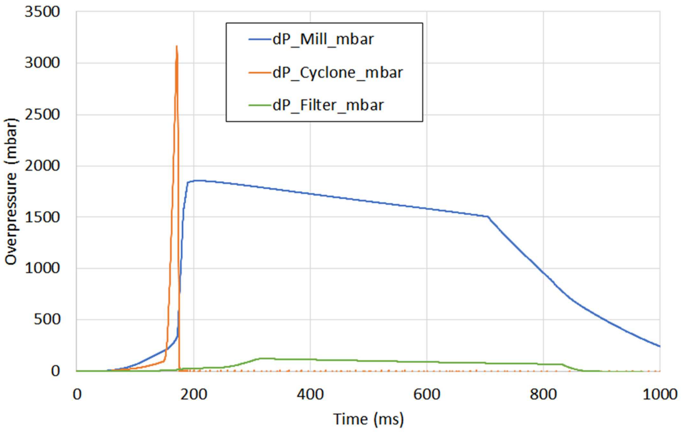

Fig. 5. Overpressure calculated in the mill, cyclone and duct; explosion ignition in the mill.

The flame should continue to the filter at speeds more than 400 m/s at the beginning of its propagation but is eventually slowed down to less than 100 m/s before reaching the filter, because of the sudden bursting of the cyclone. Note that while the vents in the filter strongly limited the overpressure, in the mill the reversal of the flow lead to a significant increase of turbulence and an intensification of the combustion. It appears that in the current example, the filter and the mill withstood the internal explosion, but the consequences of such scenario are not acceptable because of the bursting of the cyclone. It implies the projection of fragments up to several tens of meters and the emission of a pressure wave corresponding to a bursting energy of 20 MJ, that is roughly equivalent to the detonation of 5 kg of TNT, the effects of which are known to be dangerous for humans from 20 to 40 m in open field.

IMPLEMENTING THE EXPLOSION PROTECTION STRATEGY

The potential effects of an explosion within such installation are not acceptable and make it absolutely essential to equip it with explosion protection devices. As the most fundamental principle is the safety of people. As a result, the cyclone protection is a requirement here. Different techniques may be used such as deflagration venting which consists in discharging the explosion through an orifice. The vent area must be calculated so that the maximum pressure reached in the protected vessel, P_{red} remains significantly lower than the mechanical pressure resistance of the enclosure. A mistake would be to consider the cyclone separately: knowing the dust reactivity parameters (K_{St} = 150 bar.m/s, $P_{\max}$ = 8 bar) in this "independent" volume, one would estimate vent areas on the order of 0,5 m^2 to limit the P_{red} to 1 bar in the cyclone (calculations based on EN14991:2014 [3]). However, proceeding such way completely occults the flow and flame acceleration effects in the pipes (supported by the upstream exploding enclosure) and the significantly enhanced combustion effects downstream the pipes, thus rendering the protective equipment completely inefficient. A simulation of this scenario in EFFEX shows that despite the vent, the cyclone burst because of the large flame velocity transmitted from the pipe. Thus, a much larger vent area is needed, 3 m^2 are computed with EFFEX. However, protecting the cyclone alone is not sufficient:

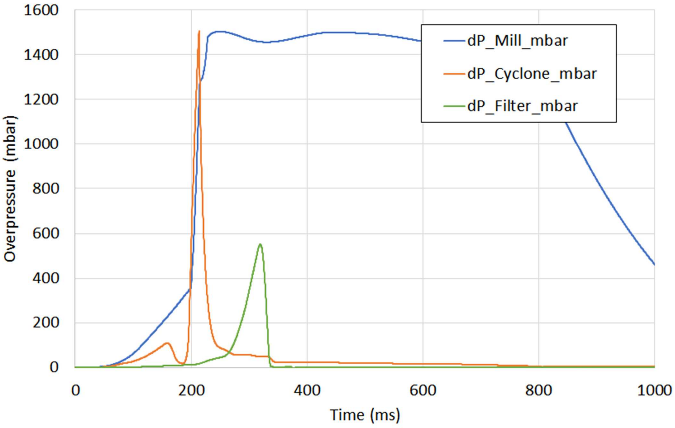

Fig. 6. Overpressure calculated in the mill, cyclon and duct; with 3 m^3 vents protection on the cyclone.

Now that the mill-cyclone system is protected, there is still a large overpressure responsible for significant flame acceleration in the second duct section, between the cyclon and the filter. The flame reaches the filter at a velocity close to 300 m/s, and the vent area installed on the filter becomes clearly insufficient.

A critical aspect in this example scenario is the coupling between the three enclosures, that need to be accounted for when choosing and dimensioning an explosion mitigation technique. Several options exist, a few are presented in the subsequent paragraphs:

- vents protection of the cyclone and the filter,
- vents protection in addition to decoupling system on the ducts,
- isolation of the duct and vent protection of the enclosures,
- explosion suppression,
- mixed systems protection.

Vents protection of the cyclone and filter

In the normative document EN14491:2014 [3], a dimensioning method is proposed to limit the violence of the explosion in an assembly "enclosure 1 – duct – enclosure 2". The vent areas to install are often much wider as those predicted by the usual method in the same document. In such situation, the purpose of the vents is not only to unload the explosion but also to reduce the flame acceleration in the duct. The EN14491:2014 [3] document indicates an order of magnitudes for these vent areas, which imply typically a coefficient ($Av/V^{0,753}$) of 0,4. It can be highlighted that inconsistencies exist between such recommendations and the calculations that can be made with the formulas concerning the vents connected to ducts. Nonetheless the use of such technique is theoretically feasible in the present case with some additional calculations. Knowing the available vent area on the cyclone and the acceptable reduced explosion pressure P_{red}, one can estimate a maximal flame velocity acceptable in the duct. Then the vent area to install on the filter will selected in view of unloading the explosion but also limiting the flame velocity in the duct to the maximal acceptable value. In practice, this is barely achievable on the scale considered: according to Fig. 3, one would need to limit the overpressure in each enclosure to 0.5 bar, so that the flame speed remains low enough to allow a vent protection. This implies the use of much larger vent areas. Consequently, this is not a practical solution for the current example.

It is also important to point out that these vents only solution relies on the hypothesis of an ignition in the mill. When the explosion starts in the filter it is be necessary to perform new, yet similar, calculations. Also note that the environment around the enclosures (a road, workers, a wall, etc.) may impose to have vent ducts, deflectors or flame arrestors at the exhaust of the vents. All these systems impede the explosion discharge and induce a lower vent efficiency, thus the necessity again to install larger vent areas.

Vents protection in addition to decoupling system on the ducts

The previous mitigation solution imposes to have large vent areas on each device, which may not be feasible for practical reasons such as the bulk around the structure. The smallest possible vent areas Av, for each equipment, can be estimated separately form the EN14491:2014 [3] formulas. For instance, for the cyclone we computed earlier 0.5 m^2, and for the furnisher of the filter sold it with 5 m^2 of vent area. In the case of isolated enclosures, this is expected a conservative approach as the $P_{\max}$ and K_{St} terms are measured in more penalizing conditions (dust concentration, turbulence) than they are supposed to exist in the industrial process. However, for this model to be valid for connected enclosures, the violence of the explosion must correspond to the limitations defined in the standard, which implies that the turbulence level must remain in the range of the test that were performed to establish this formula. A direct consequence of this is that these lower venting areas may be used provided the duct effect can be neglected, which can be done when the explosion is either decoupled or isolated. Firstly, we will consider the option of the explosion decoupling.

Explosion decoupling devices are designed to limit the flame velocity in a duct. It can be realized by adding vents on the duct that are designed to open before the flame arrival and slow down the flow in the event of an explosion. Such systems may also be constructed in view of forcing the flame to change directions, to prevent excessive accelerations. Those decoupling systems can be dimensioned so that the turbulence induced in the downstream enclosure remain at an acceptable level, however they will not stop the flame but only slow it down. Experiments performed at INERIS confirmed that an explosion generating a 2 bar overpressure in an enclosure can induce a flame velocity on the order of 400 m/s in the connected duct without any protection while having vents on the duct close to the exploding vessel can limit significantly the pressure effects and reduce the flame velocity by a factor 2 to 4 [17]. In the present case this would not be sufficient but reducing the flame velocity level between the two enclosures can make it possible to use smaller vent areas than those presented in the earlier paragraph, in fact one can use the vent area calculated earlier with EN14491:2014 [3] for the isolated cyclone. A calculation was performed with two explosion decouplers located at the middle of each duct, and with the 0.5 m^2 vent on the cyclone (in addition to the already installed 5 m^2 vents on the filter). The measured overpressure are presented in Fig. 7.

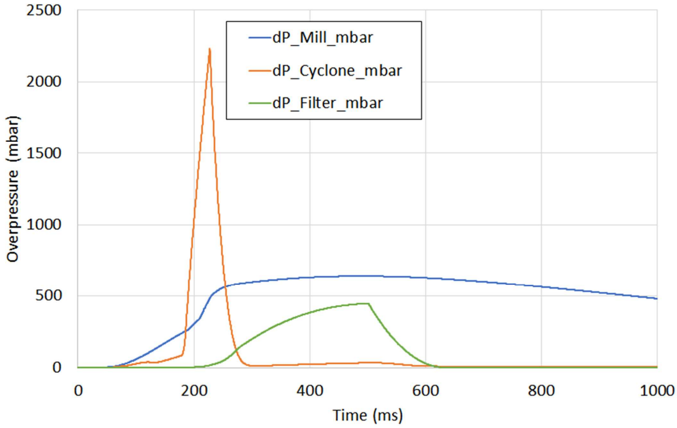

Fig. 7. Overpressure calculated in the mill, cyclone and duct; with 0.5 m^3 vents protection on the cyclone and an explosion decoupler on each duct.

In this case the installation is protected. Thanks to the decouplers, the flame velocity is sufficiently limited in the ducts, also leading to a lesser turbulence level in the cyclone and the filter, thus allowing the vents to fulfil their role efficiently.

Isolation of the duct and vent protection of each volume

If an isolation system is present on the duct, the flame will not propagate from one enclosure to the other one and then standard venting protection rules for isolated enclosures may be applied. These isolating devices can be of several types and based on very different technologies, for example: active (electronic detection of the explosion) or passive (purely inertial) flap valves, gate valves, pinch valves or chemical flame extinguishers. However, as any explosion mitigation device, they have their own limits that need to be accounted for. Firstly, some of those, such as the flap valves can only function in one direction, to stop a flame traveling in a direction opposed to the usual flow observed during the functioning of the process. Secondly some of these systems rely on the mechanical closing of the duct, which imply there are not efficient before a certain amount of time. From past experience on systems tested at INERIS, sometimes in the scope of ATEX certification, this delay is typically ranging around a few ms for active devices (with actual explosion detection and non-passive closing system such as in the case of gate valves or pinch valves) to a several dozens of ms when the device is fully passive and actuated by the explosion generated flow. Depending on the flame velocity (which can hardly be lower than 150 m/s in the present configuration) and the duct length (15 m here) it is necessary to ensure that the chosen system is really able to stop the flame. Also, quite regularly singularities, such as bends or a restriction generating a Venturi effect, are present on the ducts of industrial processes; they may alter the flow significantly. This needs to be considered when installing the isolation devices. Finally, there is also an upper limit in time (chemical isolation) or installation distance (mechanical isolation) after which the extinguishing cloud has settled down or the duct pressure has become too high and the isolating system will fail mechanically.

Explosion suppression in the mill and the cyclone

Alternatively, it is possible to use explosion suppressors on the mill and the cyclone. Those are based on the active and early detection of explosions coupled with a chemical agent that is injected at a sufficient rate so that the explosion can be quenched before it becomes too damaging for the structure. Typical delays for flame quenching are on the order of a few dozens of ms. As it is intended to extinguish the flame in each of the capacities, there should not be significant acceleration effect through the pipe between the cyclone and the filter, so that it is not necessary to install an isolation device. However, this is only true in the specific case of this installation and because a ST1 dust is chosen. Under these conditions, the risk of dust explosion in the filter persists. It is therefore a fundamental requirement to have vents on the filter. Methods for modelling the suppression devices have been implemented in EFFEX but they will not be described at this stage. Further details on this specific aspect may be found in [18].

Mixed systems protection

The solutions presented in the previous paragraphs can be combined, but again without losing the perspective that the enclosures are connected by a duct. For example, if the filter is outside of the building and the cyclone is located inside, the former can be protected by a vent while the later cannot (it is assumed that people are working in the same building). It would be possible in such case to protect the cyclone with explosion suppressor. Again, it cannot be done without a due consideration of flame velocity / acceleration in the duct. Explosion suppressors are certified within limits in terms of dust reactivity (among other limits such as the throw of the extinguishing cloud or the activation delay) that are applicable to the case of isolated enclosures. This is not the case if the flame has been significantly accelerated in a duct before reaching an enclosure in which the turbulence has been significantly increased compared to the standard process conditions. Consequently, for the suppression technique to remain effective in this situation a decoupling device or an isolation valve might be needed between the mill and the cyclone. The limitations referred to in the preceding paragraphs for the different explosion mitigation devices apply.

CONCLUSION

A strategy to implement an explosion mitigation solution has been presented around the example of a simplified industrial coal grinding process made of a mill, a cyclone, and a filter. A phenomenological analysis of explosion development and propagation in dual enclosure-duct systems was presented. The scenario of an explosion starting from the mill was selected as a reference to highlight the critical mechanisms involved when explosions propagate between interconnected enclosures. In the fourth part a way to account for the real explosion conditions is given, allowing a choice and dimensioning of a set of safety systems. Vent area calculations were presented together with the order of magnitudes of the characteristic functioning parameters of the other safety systems that may be implemented. Beyond that an important focus is given on the actual strategy of protection to implement, which aims at protecting firstly the people working close by then the structure and must always rely on a physical understanding of the dust flame propagation (in enclosures and in ducts) as well as its interaction with its environment (turbulence generation, pressure effects). A specific focus can thus be made on two fundamental aspects: on the one hand, it is of critical importance to understand how the flame propagates in a given complex system. On the other hand, the behaviour of the protection systems that might be used must also be carefully studied as it cannot be dissociated form the previous analysis, those systems will indeed systematically have an effect on the explosion driven flow.

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