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Improving explosion protection methods for industrial processes : the collaborative project DELFINE

(Evolution des méthodes de protection des procédés industriels contre les effets des explosions : le projet DELFINE)

Emmanuel LEPRETTE [a1], Stéphane COUSIN [b], Jef SNOEYS [c], Christophe PROUST[a, d]
[a] INERIS, Parc Technologique ALATA, B.P. 2, 60550 Verneuil-en-Halatte
[b] DELTA NEU SAS, Z.I. rue Ampère, B.P. 10, 59932 La Chapelle d'Armentières Cedex
[c] FIKE Corp., Toekomstlaan 52, B-2200 Herentals, Belgique
[d] UTC, Laboratoire TIMR, EA4297, Centre Pierre Guillaumat, 60200 Compiègne

Summary

Classical methods for vent sizing are based on experimental correlations coming from academic test situations, sometime quite different from real industrial conditions. Thus, they do not take into account the variation of turbulence in industrial enclosures, which may alter drastically the explosion violence. The DELFINE installation presently in construction will allow studying dust explosions in real working conditions of a dust collector. Preliminary experiments in an instrumented small size filter are presented, which allow characterizing the turbulence level in every work phase of the system. It appears that the turbulence level is generally lower than in the standard conditions for vent testing, even during reverse jet cleaning. It should offer perspective for optimization of the venting areas for dust collectors. Explosion tests in real conditions on the DELFINE installation will be performed to try to confirm these first observations.

Keywords: Explosion, protection systems, venting, dust, turbulence

1. Background

Dust explosions continue to represent major risks in the process industries. Some accidents, such as the explosion of the 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.

Vent sizing methods have received considerable attention, especially since the work of Donat (1971), followed by experimental test programmes by Pineau (1982), Radandt (1983), Lunn (1988, Bartknecht (1993), and Eckhoff (1991). A number of correlations have been proposed, deriving more or less explicitly, from the theory of flames (Rust, 1979; Runes, 1972). It can be recalled (Proust and al., 2009) that, if *A* is the size of the vent aperture in a vessel of volume *V*, the internal overpressure *ΔPred* ("reduced explosion pressure") can be expressed as

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

With C_d the discharge coefficient of the orifice, A_f the flame area, S_t the burning velocity and E_{exp} the expansion ratio of the burnt products. The "expansion velocity" S_t. (E_{exp}-1) mainly depends on the

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[1] emmanuel.leprette@ineris.fr

properties of the cloud itself (particle size and distribution, dust concentration, turbulence level, etc.) so that for a "given cloud" the explosion overpressure will correlate to the geometrical parameters implicitely contained in A_f (and explicitely in A). The practical use of [1] is not straightforward because the determination of the expansion velocity S_t. (E_{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:

$$K_{ex} = \left(\frac{dP}{dt}\right)_{\max} \cdot V^{1/3} \approx P_{\max} \cdot S_t \cdot (E_{\exp} - 1) \qquad [2]$$

Thus, the "flame speed" parameter K_{ex} is much more conveniently determined indirectly at standard conditions in, for instance, the 1m^3 ISO vessel (ISO6184/1) and is 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 (Proust et al., 2007), the variation of the K_{st} between dusts certainly reflects the differences in terms of powder reactivity.

Usually the flame theory cannot be applied directly and some fitting with the experimental data is required. Some of those fitted correlations have been incorporated into guidelines and standards (NFPA 68, VDI 3673, EN 14491). Most process parameters suggested by [1] are covered such as the volume of the vessel, the shape factor from the proportionality between A_{ch} (internal area of vented vessel) and $V^{2/3}$ and the reactivity of the dust cloud via K_{St} and P_{max}. The European standard (EN 14491) for example proposes the following relationship [3]:

$$\frac{A}{V^{0.753}} = \left[3.264\times10^{-5} \times p_{\max} \times K_{St} \times \mathrm{P}_{red}^{-0.569} + 0.27\times\left(P_{stat} - 0.1\right)\times \mathrm{P}_{red}^{-0.5}\right] \times \left[1 + \left(-4.305 \times \log \mathrm{P}_{red} + 0.758\right) \times \log\left(\frac{L}{D}\right)\right]$$

where *L/D* represent the shape factor of the vessel.

Table 1 : vented dust explosion experiments in real or "realistic" equipments

ref	Author	Equipment	Dispersion of the powder	Injection velocity-pressure (m/s-barg)	Pipe diameter (m)	Volume of the vessel (m3)	Aspect ratio	Area of the opening (m2)	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 m3 vessel with pressurised injection

Eckhoff discussed this kind of approach and recalled that K_{st} is not a material constant (Eckhoff et al., 1984; Eckhoff et al., 1986; Eckhoff et al., 1988) and should depend also on the turbulence. Eckhoff produced data in very large silo explosions which showed that the severity of the explosion was greatly affected by the state of the dust cloud at ignition. Further controlled experiments (table 1 from the data of Eckhoff et al., 1984; Eckhoff et al., 1986; Eckhoff et al., 1988; Tonkin et al., 1972; Pineau et al., 1985), including large tests which more closely resembled real processes, facilitated the confrontation between the "K_{st}" based correlation (as [3]) and the realistic experimental results.

A comparison between calculated vent areas (by using [3]) and experiments in close-to-real configurations is shown in figure 1. The calculated vent areas diverge significantly from the measurements with some significant over estimations of ΔP_{red} but also severe underestimations.

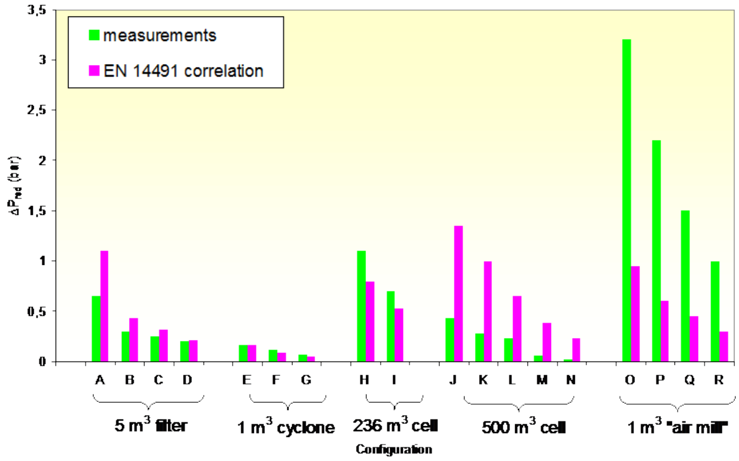


Figure 1: Calculated (by using [3]) and measured overpressures for vented dust explosions developing in real process equipment

This situation is by no means acceptable from a safety point of view and not even more from the industrial point of view because the safety performance is not ensured. One likely reason for these discrepancies is the significant influence of the initial turbulence of the cloud (Amyotte, 1985, Eckhoff et al., 1984; Zalosh, 2006; Proust et al., 2009) 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). One of the aims of DELFINE project is to be capable of better predicting the course of the explosion to achieve a better explosion projection by venting.

2. DELFINE experimental setup

Experiments will firstly be performed in filtration process in a filter not only because dust collectors are involved in a majority of the reported dust explosions, but also because the reverse jet cleaning system (RJC) –very frequently used in dust collectors- is often invoked as being the reason for explosions.

The experimental setup will consist in a DELTA NEU dust collector (volume about 4 m^3) connected to an open dust circulation duct (figure 2). The duct will be equipped with a dust injection system (constant mass flow rate injector). The injector is designed to deliver dust fuel to a flowing system in a known feed rate, thereby allowing for the creation of a homogeneous concentration atmosphere in the whole system.

The dust collector will be modified for the implementation of various explosion protection systems (venting, suppression, isolation) at different locations, and will offer many ports with large possibilities for measurement: turbulence, concentration, flame and pressure. Additionally videos from the inside of the collector and the pipe will be captured through transparent walls and windows.

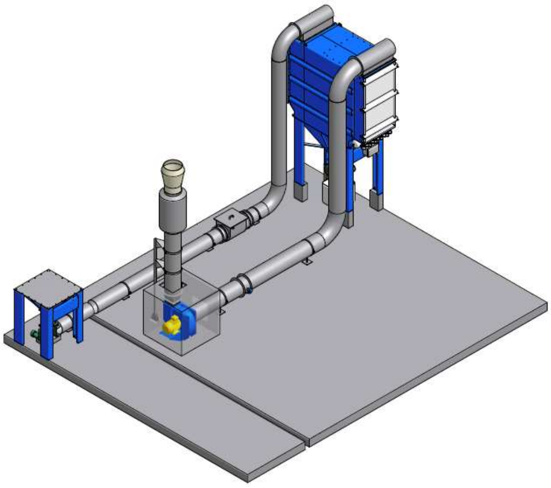


Figure 2: View of the future DELFINE experimental set-up

As a first step, preliminary work was performed in a real dust collector at small scale to test the instrumentation and help the design of the future installation. A 1/3 scaled down filter + pipe device available in the premises of one the partners (FIKE) was used to prepare the instrumentation and begin the physical analysis. A full operational dust collector with piping was purposely built (figures 3 and 4). Two different lengths of filter bags or 'envelopes' are used to represent a small (index 9 on figure 4) and larger filter area (index 8), and different distances from filter bag to filter bag and filter bag to walls. The flow rate can be adjusted. The reverse jet cleaning system consists of a 1 L tank pressurized to 5 bar, solenoid valves release short (typical duration 0,2 sec) blasts of air into the filterbags (index A). During RJC, short blasts of high pressure air are introduced through venturi's and nozzles inside the sleeves (figure 5). This pulse of air travels through the filter sleeve, causing it to flex out from the cage to dislodge the dust accumulated on the filter sleeve (figure 6). During this period of time, the flow is globally "reversed", large amounts of dust fall into the hopper and it is believed that a significant degree of turbulence appears.

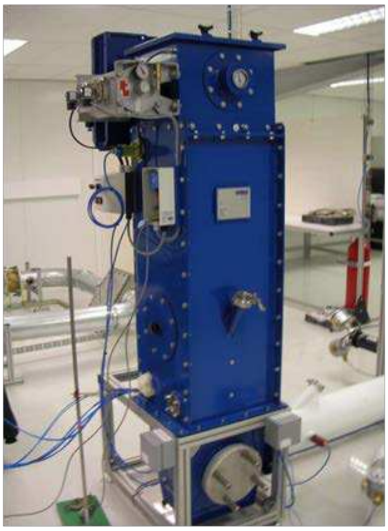


Figure 3: Purposely built dust collector

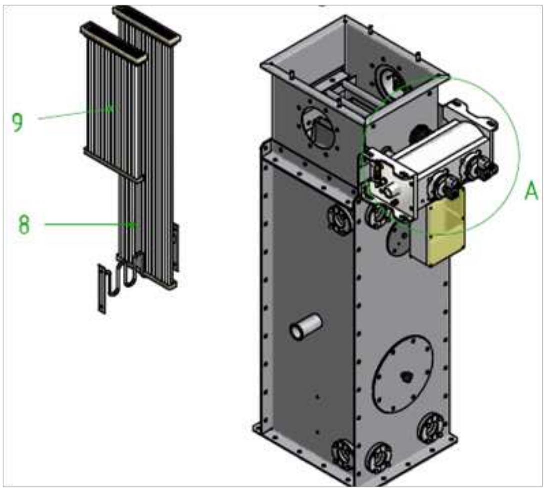


Figure 4: Short and long filter bags
(height 1 m, side 0.4 m, pipe 200 mm I.D.)

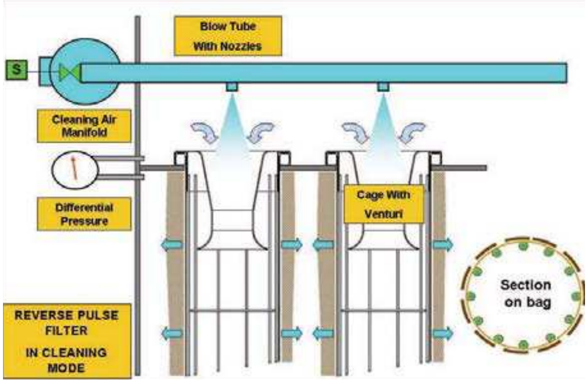
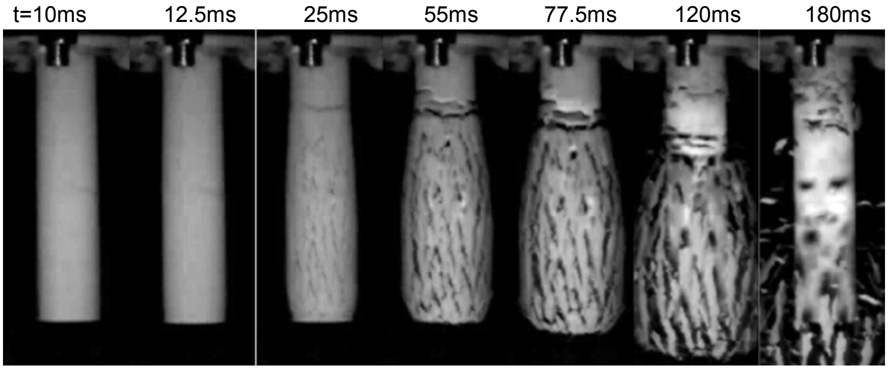


Figure 5: Illustration of RJC on a dust collector



(c) Cleaning pressure 300kPa

Figure 6: Release behavior of non-consolidated dust during the reverse jet cleaning (from Mitsuhiko Hata et al.)

In the real system the turbulence should be measured while a large quantity of dust will be conveyed so that LDA techniques will not work anymore. To overcome this very important difficulty, the bidirectional probe system (McCaffrey, 1976) once used by Tamanini (1990) to measure turbulence was further developed (figure 7). The gauge is a small portion of a cylinder with a separating wall in the middle (10 mm outer diameter, 20 mm long). The difference of pressure measured on both sides of the separation is proportional to the dynamic pressure applied along the axis.

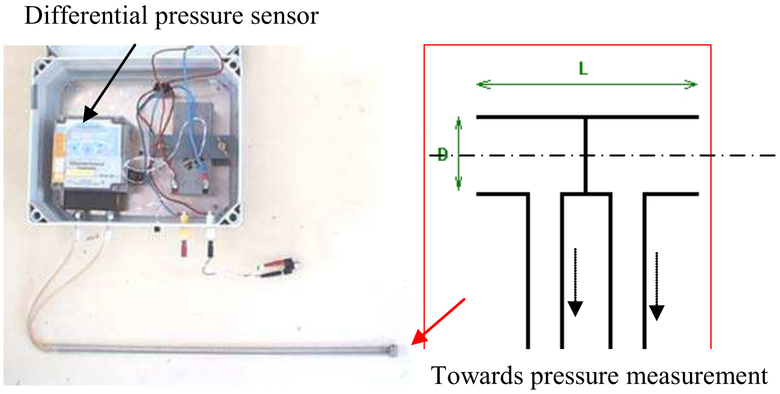


Figure 7: Schematic principle of bidirectional probe

The instantaneous velocity is deduced directly from the measurement. A Furnace Control type of sensor was used enabling velocity measurement in the range ±10m/s with a cutoff frequency of some tens of Hz. having a sufficient dynamics (10 Hz) and accuracy (±100 Pa). A detailed description of the techniques falls out of the scope of this paper but the results obtained with this technique can be compared with known data. For instance, the mean velocity (U) and turbulence intensity (u' : root means square of the fluctuations of the velocity around the mean value) of the flow was measured inside the feeding pipe (at a location where the flow field was established, far from the inlet) and at several position across the section. An excellent agreement is found between the measurements and the available data from the literature (figure 8).

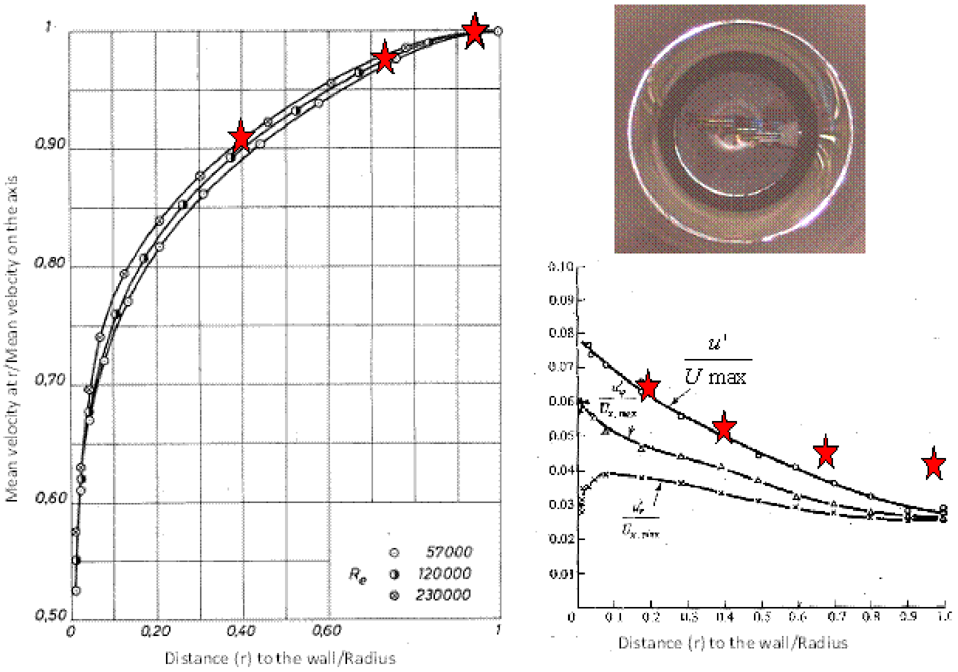


Figure 8: arrangement of probes in the inlet tube and results (curves : original graphs from Comte-Bellot and Hinze stars : present measurements) no dust in the flowfield

3. Flowfield and turbulence inside the experimental setup

Measurements were performed at several locations inside the filter (figure 9), during normal steady state operations and during reverse jet cleaning. All the tests were performed without dust added although it is possible to do the measurement with a dust cloud with the bidirectional probes.

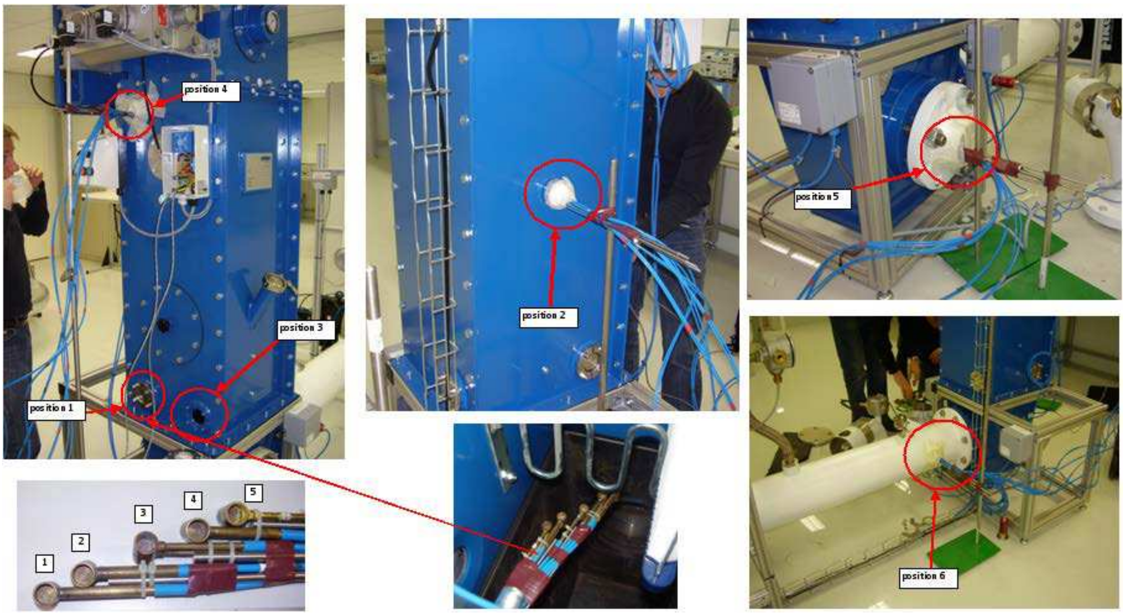


Figure 9: locations of the measuring points in the filter (location 6 is on the inlet pipe, 1&3 below the sleeves, 2 between the sleeves, 4 top between wall and short sleeves)

Steady state operation

The flow in the inlet pipe (location 6) during steady state operation was measured as outlined above described above (figure 10 and 11): with an average velocity of 7 m/s (resp. 10 m/s), the turbulence intensity was on the order of 0.4 m/s (resp. 0.6 m/s).

Location 1 represents what happen just below the bags in the empty space of the filter. It can be seen (figure 10) that gauges 1&2 detect a globally positive velocity[2], gauges 4&5 see a negative flow whereas for the central gauge (n°3) the average velocity seems close to zero. This suggests a swirling flow. The average velocity over all the probes amounts about 2 m/s (absolute value) when the flow velocity in the pipe is set to 10 m/s. Since the cross section of the filter is about 0.16 m^2 and that of the pipe 0.03 m^2, the average velocity seem to be in proportion to the cross section ratio. Note however that the turbulence intensity is significantly larger than in the pipe, typically more than 1.1 m/s, which might result from the velocity gradient induced by the swirling flow. In location 2 (between the sleeves), the flow seems mainly orientated in the same direction with an average velocity (calculated on all the gauges) of about 1m/s (absolute value). The turbulence intensity is about 0.8 m/s, smaller that in location 1. The presence of the sleeves may dampen slightly the velocity fluctuations. A summary of all the measurements done at all locations is presented in figure 11.

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[2] The sign depends on the orientation of the probe. Positive here means from the top to the bottom of the filter

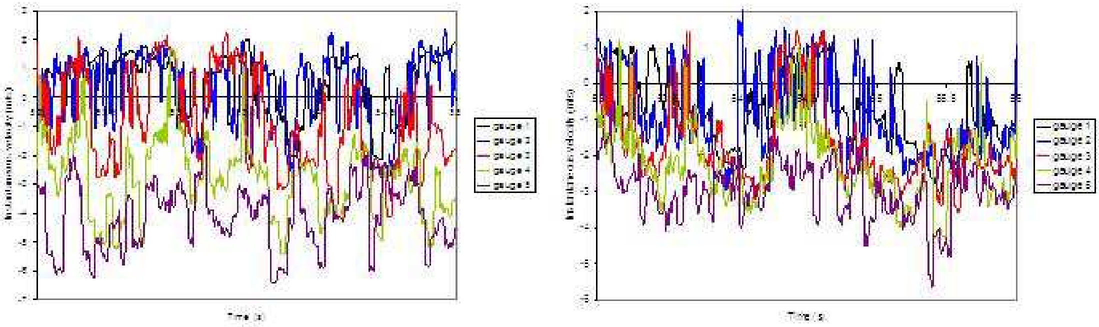
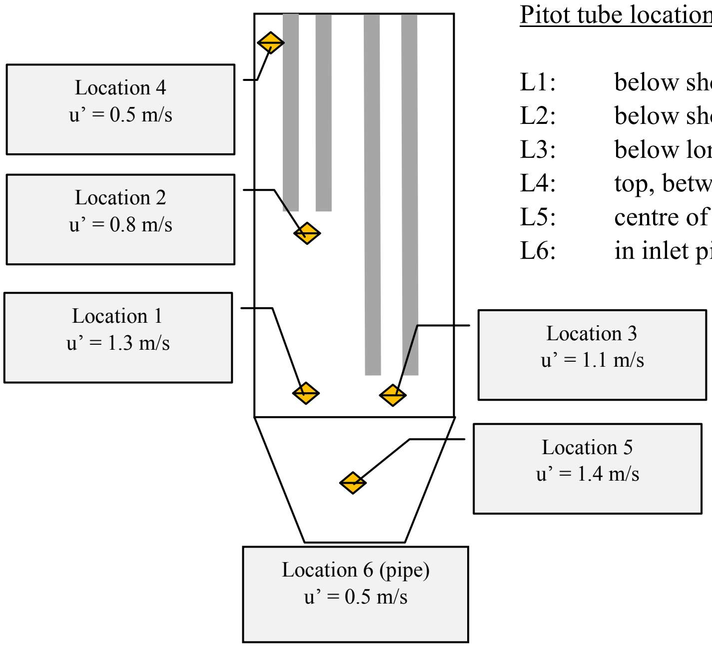


Figure 10: flowfield at location 1 (left: inlet velocity10 m/s) and 2 (right: same velocity)



Pitot tube locations overview

L1: below short bags, above the hopper
L2: below short bags, middle of vertical wall
L3: below long bags, above hopper
L4: top, between short bags
L5: centre of hopper
L6: in inlet pipe

Figure 11: flowfield at all locations (inlet velocity10 m/s) during filtering operation

During reverse jet cleaning operation

A significant influence of RJC operation on the turbulence is expected. Statistical averaging was applied on a batch of about 30 identical pulses (figure 12 for two gauges at location 1). Note that the average flow is largely positive so that it is now going from the top toward the bottom of the filter with a significant velocity, peaking up at about 8-10 m/s during the pulse. It is on the same order than the steady state flow at this particular location. Fluctuations in time are noticeable, with a frequency of 15 to 20 Hz which seems a natural acoustic resonance of the filter/duct assembly. This last remark suggests that rather than producing a turbulent flow, the air-pulse, triggers the acoustic vibration of the filter with is more a kind of plug pulsating flow with no randomly distributed eddies (which we would expect from a turbulent flowfield). This result would suggest that this kind of RJC process would not degenerate in more turbulence than in the mean flow during normal filtering operations. This important point will be verified in the final DELFINE setup using transparent walls.

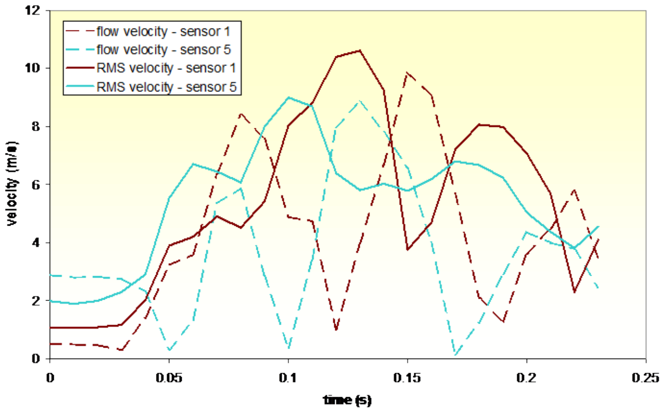


Figure 12: RMS velocity and flow velocity modulus–location 1 (during reverse jet cleaning pulse)

6. Implications and conclusion

In vent sizing equations, the severity of the explosion is represented by the coefficient K_{St}. It is measured in very specific turbulence conditions (ISO6184-1) which were characterised in a preceding paper (Proust and al., 2007). In particular, the turbulence intensity in the ISO chamber is about 2 m/s which is about twice that measured in the filter. In another paper (Figure 13 from Schneider and Proust, 2007), a link could be made between u' and S_t which should be roughly proportional to K_{st} (expression [2]). It can be realized that S_t, and following Kst, is roughly halved when u' drops from 2 m/s to 1 m/s. Refering to expression [3], all other parameter being conserver, a decrease of Kst by 50% would result in a decrease of 50% for the required vent area.

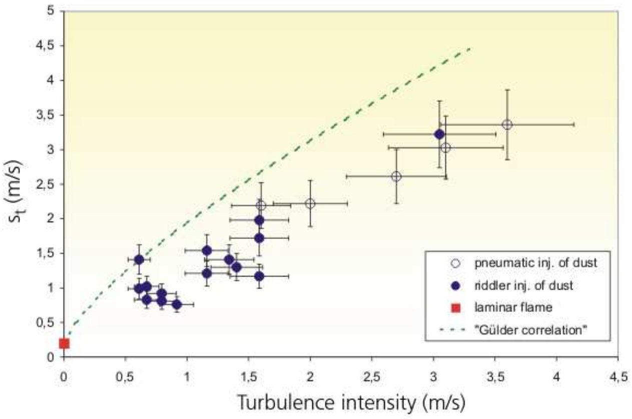


Figure 13: Turbulent burning velocities measured in a 30 cm diameter tube (starch-air clouds from Schneider and Proust, 2007)

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FSA ((Forschungsgesellschaft für angewandte Systemsicherheit und Arbeitsmedizin), Work Package 6: Validation of the Dust Explosion Simulation Code - Final Report of Measurements of Flow Field and Dust Concentration, July 2006

Résumé

Les méthodes classiquement utilisées pour le dimensionnement d’évents reposent sur des lois expérimentales obtenues dans des conditions d’essais académiques, parfois fort éloignées des conditions industrielles réelles. C’est ainsi qu’elles ne prennent pas directement en compte la turbulence dans les enceintes industrielles, qui affecte pourtant fortement le développement de l’explosion. L’installation DELFINE actuellement en construction permettra d’étudier le développement d’une explosion de poussières dans les conditions réelles de fonctionnement d’un dépoussiéreur. Des expériences préliminaires dans un filtre instrumenté de petite taille sont présentées, qui permettent de caractériser le développement de la turbulence dans les différentes phases de fonctionnement du système. Il ressort que le niveau de turbulence est globalement plus faible que dans les conditions « standard » d'essais des évents d'explosion, même pendant les phases de décolmatage. Cela laisse entrevoir des possibilités d'optimisation des surfaces d'évents dans les dépoussiéreurs. On tentera de confirmer ces conclusions à l'aide d'essais d'explosion en conditions réelles sur l'installation DELFINE.

Mots-clés: Explosion, systèmes de protection, évent, poussière, turbulence