Function Testing of Passive Explosion Isolation Flap Valves

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ABSTRACT

Passive isolation flap valves are relatively simple devices that are widely used in the process industries. However, as an explosion mitigation technique, they function only within well-defined conditions and the physics at stake make their definition challenging. INERIS method and findings are presented in the current paper. They concern passive flap valves tested on 1 and 10 m^3 vessels with pipes of diameters of 150, 300 and 800 mm. The relatively simple configuration of a flap valve connected to a vented vessel-straight duct arrangement is considered. The initially opened flap valve is triggered by the explosion in the vessel and must close within a delay, short enough to prevent the flame passing. Before valve closure, the flow is accelerated by the explosion and large velocities can be reached in the duct (typically on the order of 200 m/s with a vented vessel, but as much as 800 m/s is possible). Upon valve closing the kinematic energy of the flow is converted into heat and pressure in front (on the explosion side) of the valve while a depressurisation is observed behind it (on the isolated side). Typically, a factor of 4 between the pressure in the vessel and the pressure measured at the valve can be observed. Phenomenological modelling is used in extension to a parametric experimental study to investigate the limits of the valve, its possible installation distances and a practical method for dimensioning is proposed.

KEYWORDS: Dust explosions, explosion mitigation, phenomenological modelling.

INTRODUCTION

As a notified body, INERIS performs functioning tests of various explosion protection devices from many manufacturers, as a means of assessing their efficiency, and limits whilst eventually delivering an ATEX certificate. This is required for their distribution on the European market. Certification of such devices may be done following specific standards, such as EN14797 [1] for vent panels. However, in some occurrences the standard requirements for the testing are very unpractical or lack fundamental information and need the use of equipment, barely accessible to any notified body. For instance, the EN16447 [2] standard for isolation flap valves requires the largest size of the valve to be tested on a vessel duct arrangement with a volume corresponding to the minimum accepted for the intended use of this valve. Several reasons motivate these choices: in smaller volumes, the pressure rises more significantly, while larger devices are less resistant to the explosion and usually slower (as the flap is bigger it has more inertia, but it can be compensated by a spring). In practice several questions appear, some concern the physical mechanisms investigated, and other the limits of the testing capabilities. According to the standard, it is necessary to use a fan on the installation, to produce the "pushed" or "pulled flow" situation needed for the tests. However not only can such a system be tremendously costly (as the valve diameter can be of the order of 1 m), but it is also very unpractical. From a purely scientific point of view, controlling an explosive dust atmosphere (concentration, turbulence) then becomes extremely complicated. When it comes to modelling, significant difficulties are encountered [3], as the problem formulation is complicated: the effects observed are dependent, not only on the experimental set-up (vessel volume, vent

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dimension, ignition location), but also on the chosen location for the valve on the pipe. Therefore, there is a need to find other solutions. INERIS methods and findings are presented in the current paper: they concern 3 types of passive flap valves tested on 1 and 10 m^3 vessels, with pipe diameters of 150, 300 and 800 mm.

GENERAL FUNCTIONING OF THE SYSTEMS CONSIDERED

This paper considers 3 types of devices produced by different manufacturers: one type in DN150, another in DN300, and the third in DN300 and DN800. These were tested to assess their performance. Despite the devices being of different designs (use of counterweight or springs, variable angular amplitude), all relied on the same general principle of an inclined flap in a cylindrical tunnel that is kept open by the flow during normal operation, and closed by flow reversal in the event of an explosion (see Fig. 1.)

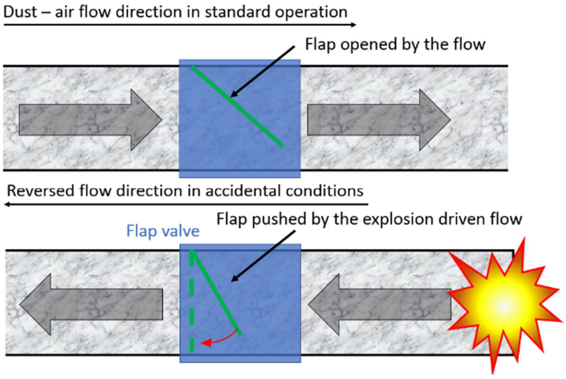

Fig. 1. Functioning of a passive flap valve.

When such a system is to be installed in an industrial application, certain conditions must be fulfilled. As in any explosion mitigation system, these flap valves only function within a well-defined range. The passive valve is triggered by the explosion and must close within a delay short enough to prevent the flame passing. Before and during the valve closing, the flow is accelerated by the explosion and large velocities can be reached in the duct, typically of the order of 200 m/s, with a vented vessel, but as much as 800 m/s is possible [5] and [6] for experimental measurements). For this reason, and because the valve closing cannot be instantaneous, (in comparison to the explosion characteristic times), it is quite intuitive to understand that the shorter the flap closing delay is, the closer it can be placed from the explosion origin. This limiting distance is referred to as a minimum installation distance or $L_{\min}$ in the EN16447 standard. Also, explosion in long ducts are often associated with flame acceleration and pressure build-up, which implies that after a certain distance the explosion effects can become too large and exceed the valve resistance. This leads directly to the possible existence of a maximum installation distance of the valve, named $L_{\max}$. As both distances are linked to very different aspects, it makes it possible to have a wrongly conceived valve with $L_{\max} < L_{\min}$. In this case either the flame passes before the flap closes, or the device is destroyed potentially leading to flame propagation downstream of it. Because there is necessarily a limit to the pressure from which the flap valve integrity cannot be guaranteed, the certificate of such devices also mentions a maximum admissible pressure. However, as the pressure at the valve in the event of an explosion is hardly accessible to the end-users, this pressure limit is traduced in terms of the maximum P_{red} allowed in the vessel. Constraints also exist on the rate of pressure rise (K_{St}), the nature of the dust (organic, metallic, etc.), and the vessel to be connected to the ducts (volume, presence of vents, or suppressors). When testing such devices the scope of certification of all those constraints on the intended uses, as well as the dimensioning model, must be verified.

EXPERIMENTAL SETUP

The experimental campaign followed at INERIS slightly differs from what is stated in the normative document EN16447. This document is organized around 3 modules which aim, respectively, at assessing the explosion pressure resistance of the valve, and examining the flame isolation capabilities of the closed valve. The third module consists in verifying the functioning of the initially opened valve within its installation distances $L_{\min}$ and $L_{\max}$ on a vessel-pipe arrangement in which a dust air flow must be produced. In practice the tests of the first two modules can be performed on the relatively simple setup consisting of a vessel being connected to a short piece of duct, then the flap valve, which does not require additional dust injection devices in the duct. According to the third module, it is necessary to use a fan on the installation, to produce a “pushed” or “pulled flow” situation (if the fan is placed after the valve, or before the vessel). However not only can such system be tremendously costly (as the valve diameter can be on the order of 1 m), but it is also very unpractical as controlling an explosive dust atmosphere (concentration, turbulence) becomes extremely complicated. An alternative is proposed at INERIS: an explosive dust atmosphere is generated in the whole volume (vessel and ducts). After dust ignition in the vessel, the flame expands then propagates in the duct. However; the flap valve is maintained open by an external device until the flow velocity, due to the explosion, exceeds a certain limit (typically of the order of 10 to 30 m/s) representative of the valve’s intended use. Once this velocity threshold is reached, the flap is released and starts closing freely. To attain better control of the events observed, at small scale (up to a DN300 for the pipes), transparent ducts are used. A picture of this setup, for the 1 m^3 vessel is presented in Fig. 2.

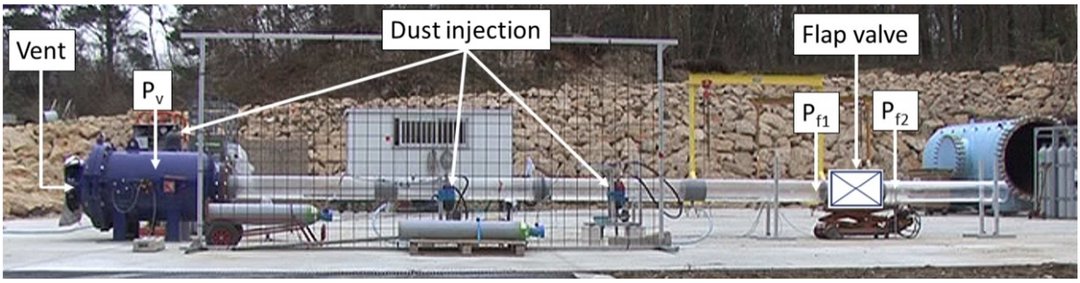

Fig. 2. Image of the test setup for a DN300 flap valve located at 8 m from the explosion vessel. The flap valve is hidden due to confidentiality reasons. P_v, P_{f1} and P_{f2} indicate the positions of the pressure sensors.

The events are recorded by a high-speed camera at 2000 frames per second and with a window resolution wide enough to see the whole pipe. An indicator is systematically added on the valves tested to measure the flap opening angle as a function of time. Pressure is measured in the dust injection bottle (P_b), in the vessel (P_v), just before (P_{f1}) and after (P_{f2}) the flap valve (following the explosion direction). In this study organic dusts of wheat flour, cornstarch and maltodextrine were tested, with K_{St} varying from 100 to 200 bar.m/s. This test setup was used for the DN150 and DN300 valves. A DN800 valve was tested on a 10 m^3 vessel. In such a case the transparent pipes cannot be used, and steel pipes equipped with photodiodes, are used to track flame positions. The overall setup remains the same. When necessary (above 4 m of pipeline) an additional injection of dust is added in the pipes, so that the whole experimental device is filled with an explosive atmosphere. The dust injection devices are placed at regular intervals on the transparent tubes. They allow having a combustible atmosphere along the entire length of the pipe. Calibration tests are systematically performed to ensure the combustible atmosphere is present when the flame enters the pipes and allows its propagation over the whole length of the pipe. The vessel is vented on the side opposite to the pipes. However, this new setup imposes two main restrictions: first it is necessary to ensure the closing delay of the device is predictable as in the absence of the fan, the differential pressure applied on the flap at the beginning of its trajectory could be higher than in a pushed flow situation. Consequently, the testing is first performed in the absence of any explosion, in view of assessing the flap closing delay when it is submitted only to the gravity force. Second, a fan driven flow may lead to re-openings of the valve once the explosion has been vented. To ensure we remain far from this situation, it is necessary to measure the flame position during the experiments, which is done thanks to the use of transparent pipes when possible (<DN300) or with several photodiodes for large scale tests.

TESTS RESULTS

Three sizes of valves (DN150,300 and 800), of different industrials, were tested on the 1 and 10 m^3 vessels. Test configurations and measurements are summarized in Tables 1 and 2.

Table 1. Summary of the tests performed with the 3 types of flap valve

Test #	Type of flap valve	Diameter (mm)	Installation distance (m)	Dust type	Vessel volume (m^3)	Vent area (m^2)	Ignition location
1	A	150	4	maltodextrin	1	0.096	Back of vessel
2		150	4	wheat flour	1	0.096	Back of vessel
3		150	3	wheat flour	1	0.096	Back of vessel
4		150	3	maltodextrin	1	0.096	Back of vessel
5		150	2	wheat flour	1	0.096	Back of vessel
6		150	2	maltodextrin	1	0.096	Back of vessel
7	B	300	6	wheat flour	1	0.159	central
8		300	6	cornstarch	1	0.159	central
9		300	8	wheat flour	1	0.159	central
10		300	8	cornstarch	1	0.159	central
11		300	8	cornstarch	1	0.159	central
12	C	300	8	wheat flour	1	0.159	central
13		300	8	wheat flour	1	0.159	central
14		300	8	wheat flour	1	0.159	central
15		300	8	wheat flour	1	0.159	Pipe entrance
16		300	8	wheat flour	1	0.159	Pipe entrance
17		800	18	wheat flour	10	1	Pipe entrance
18		800	18	wheat flour	10	1	Back of vessel
19		800	13	wheat flour	10	1	Back of vessel

Reactivity parameters K_{St} and P_{max} were characterised in closed vessel tests in the 1 m^3 vessel (ISO 6184-1) for 1000 g/m^3 of maltodextrin (200 bar·m/s and 7.4 bar), 1000 g/m^3 of cornstarch (150 bar·m/s and 7.1 bar), 1000 g/m^3 of wheat flour (95 bar·m/s and 7.25 bar) and in the 10 m^3 vessel with 700 g/m^3 of wheat flour (105 bar·m/s and 7.3 bar).

Pressure and time values are rounded up to the closest multiple of 5. The experimental measurement error given by the pressure sensors producer is ± 2 mbar, at a sampling frequency of 5 kHz. In Table 2, the columns t_{act} and t_d correspond respectively to the time from which the flap valve starts to move and the duration up to its full closing. Note that the flow reversal at the valve position is always reached a few dozen ms after ignition of the dust-air mixture in the vessel. In test 3, with a type A valve, the vent on the vessel opened during dust injection, leading to a depression in the duct shortly after the flap started to move. The pressure rose again a few ms later, with the growth of the fireball in the vessel. The closing delay time of the valve was increased because of a lack of upstream pressure compared with other tests with the same equipment. The type B valve of DN300 was not able to isolate the explosion, for the pipe length investigated, due to a too large closing delay. In test 13 the transparent duct burst a few hundred ms after reaching the complete closure of the valve and successful isolation. In test 14 the transparent ducts burst about at the same time the flap closed. For this reason, it is impossible to tell whether the isolation would have been successful or not. Furthermore, the P_{f1} sensor was ejected after reaching an overpressure of 1500 mbar, which made the calculation of P_{fM} uncertain.

Table 2. Pressure measurements (mbar) and times (ms) corresponding to the configurations listed in Table 1

Test #	$P_{v,\max}$	$P_{f1,\max}$	$P_{f2,\max}$	$P_{fM} = \max(P_{f1} - P_{f2})$	$P_{fM}/P_{v,\max}$	t_{act}	t_d	Success of isolation
1	315	665	280	750	2.4	25	65	yes
2	195	410	75	500	2.6	35	45	yes
3	155	340	115	400	2.6	40	100	yes
4	685	1185	143	1200	1.8	20	50	yes
5	150	340	105	450	3.0	30	60	yes
6	435	870	190	1000	2.3	20	50	yes
7	265	130	85	105	0.4	35	245	no
8	270	165	105	80	0.3	30	240	no
9	420	250	150	125	0.3	55	230	no
10	255	130	85	80	0.3	35	340	no
11	335	200	120	205	0.6	35	n.d.	no
12	390	485	205	695	1.8	55	85	yes
13	420	870	215	1110	2.6	55	110	yes
14	740	> 1500	160	> 2000	>2.7	55	60	n.d.
15	325	825	300	1040	3.2	55	85	yes
16	335	865	295	1220	3.6	55	85	yes
17	100	120	65	165	1.7	165	180	yes
18	95	175	95	225	2.4	285	170	yes
19	170	300	115	365	2.1	155	145	yes

DISCUSSION

In the successful isolation tests (with no flame passing), the comparison of the maximum pressure levels recorded before and after the valve, respectively named $P_{f1,\max}$ and $P_{f2,\max}$ give a rough indication of the isolation capabilities of the valve. The maximum pressure in front of the valve is always higher (roughly by a factor 2 to 2.5) than that measured in the vessel. A phenomenological analysis is needed to shed light on these results. A representative test is chosen as an example to illustrate some of the specific phenomena involved in explosion isolation by a flap valve. The case of test 17, a DN300 flap valve located at 8 m from the 1 m^3 vessel is considered. Wheat flour at a concentration of 1000 g/m^3 is ignited in the vessel near the entrance of the pipeline. A set of images captured with the high-speed camera during this test are presented in Fig. 5.

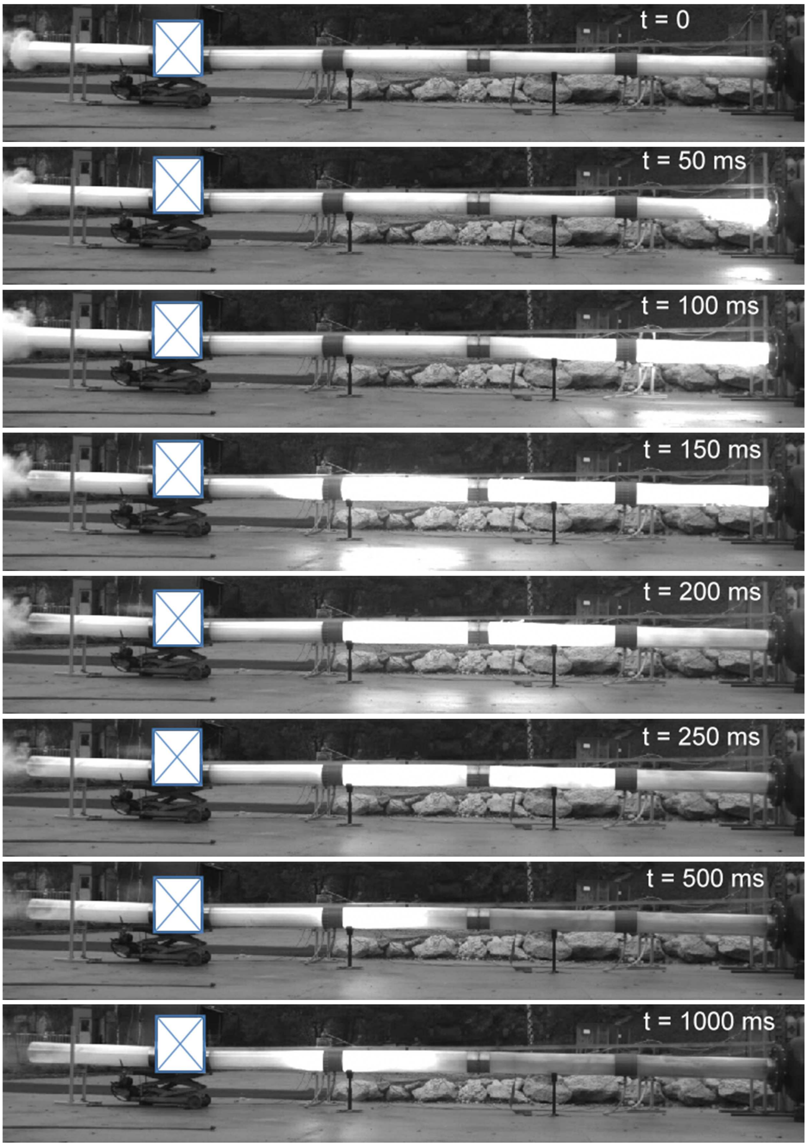

Fig. 3. Images of a representative isolation test (17) with a DN300 pipe and a wheat flour explosion (vessel on the right side of the frames).

The flame progresses in the tube for 150 ms then stops only 1 m from the flap valve. From *t* = 150 ms, it is observed that the tube downstream of the valve is emptied and gradually becomes transparent, at which time the valve is closed. This observation is correlated with the pressure signals shown later (Fig. 4) where the maximum overpressure is applied on the flap around $t = 140$ ms. Due to confidentially reasons, the part with the valve indicator is not visible in Fig. 4, but it shows that the flap reopens from $t = 250$ ms (as there is no flap locking device in the sample tested). At $t = 500$ ms, it is still open. Initially the flap bounces under the effect of the shock when it closes, then it is sucked towards the vessel because of the pressure difference in the pipe (the pressure is larger around the valve than in the vessel, despite the explosion, see Fig. 4). Then the visible area occupied by the flame in the tube is decreased significantly, probably because all the combustible dust in the first half of the pipe is burned. Finally, at this point the explosion is over: the pressure effects have become negligible. Later ($t = 1000$ ms), the valve closed by gravitational effect and the flame is eventually extinguished (after 1.5 s).

The pressure signals measured in the vessel (P_v), and in the pipe before and after the valve, respectively P_{f1} and P_{f2}, as well as the difference $P_f = P_{f1} - P_{f2}$, are represented in Fig. 5 (left). P_v and P_f are then plot together with flame position in the pipe in Fig. 5 (right).

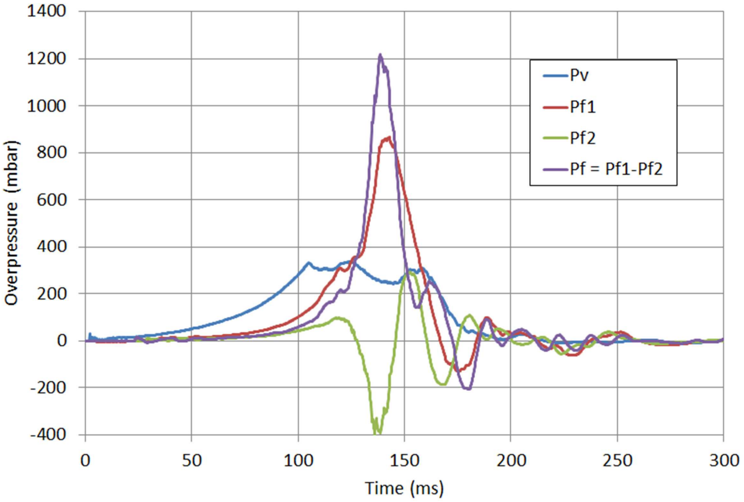

Fig. 4. Pressure measurements at each sensor location (left side)) and comparison with flame position (right side) for the representative test with a DN300 flap valve and wheat flour.

In Fig. 4, the three pressure signals have a similar evolution (but shifted in time) in the first moments of the explosion. During this period, the difference between the green curve corresponding to the rear of the valve and the red curve corresponding to the pressure in front of the valve is due to head losses at the valve and to the influence the end of the pipeline. The dust explosion in the vessel pushes the flow into the pipeline. Towards $t = 100$ ms the vent on the vessel opens and the pressure rise is stopped. Combustion is not complete yet, as there is competition between two phenomena, the discharge of the explosion gases through the vent and the explosion that continues in the vessel and produces flue gas. The valve starts closing at t = 53 ms and is completely shut at $t = 138$ ms, when a maximum pressure is observed on the front face of the flap and the minimum on its rear face. A few milliseconds before its complete closure, there is a break between the front pressure curves (in red) and after the valve (in green). At the sensor in front of the valve the pressure increases rapidly while behind the inner flap of the valve it becomes negative. On one side of the valve the air flow is stopped, and the pressure wave is reflected. On the other side of the flap, the flow velocity in the pipe (which depends on the pressure in the vessel but remains strictly positive) suddenly goes to zero: it creates a suction on the back of the flap, theoretically equal to the opposite of the dynamic pressure. When the flame passes before the valve has been able to close, the pressure signals are very different from those shown in Fig. 4. There is no blockage of the flow and the sensors before and after the valve have a similar evolution (with a delay in time and a lower amplitude for the sensor downstream of the valve).

The force applied on the flap of the valve is the difference between the pressure applied on its front face, measured by the sensor P_{f1} and the pressure measured on its rear face, at the P_{f2} sensor, the signal thus constructed being $P_f = P_{f1} - P_{f2}$. The maximum pressure actually applied to the flap is therefore 1200 mbar, instead of the 850 mbar suggested by the P_{f1} curve. A direct implication for the design of such device is that the actual pressure resistance of the flap valve must be a few times (3-4x) larger than the P_{red} measured in the vessel. It is important to understand that the pressure pilling at the valve is due to the accumulation of two distinct phenomena. The first is the acoustic part of the pressure wave that is also measured when the pipe is left open, which signal shows a shape similar to the overpressure signal in the vessel, delayed and slightly damped. When the valve is closed, it is reflected. For this reason, one can expect a factor up to 2 between the vessel pressure and P_{f1}. The second part is due to the sudden deceleration and stopping of the dust-gas column in front of the valve, whose inertia is converted into pressure, thus leading to another increase of P_{f1}. In this specific example, the configuration is some sort of a worst-case scenario in which both the acoustic part of the pressure wave and the dynamic stopping of the gas column are superposed. In any case, this factor of two to three between the pressure in the front of the flap and the driving pressure in the vessel indicates roughly the conservation of the energy in the pipe, which means that there is barely any pressure build up due to the combustion in the pipe. This might not remain true for more reactive dusts. When the vessel is not supporting sufficiently the flame propagation in the pipe (i.e. the explosion in the vessel is (almost) finished when the flap closes), which can happen at other scales (in particular at large scale or when the volume of the duct is to large in comparison to the vessel volume), or when the ignition location is changed (ignition close to the vent) both contributions may be decoupled in time. Such a situation may lead to dangerous misinterpretation of the flap valve capabilities. Thus, a major difficulty in the testing procedure is to identify and test configurations in which the explosion is still ongoing in the vessel when the flame reaches the end of the pipe. Under those conditions, the flame in the pipes is not moving in a medium at rest but is continuously pushed by the explosion in the vessel. However, the opposite situation must also be tested, to ensure the closing of the flap is achieved even when the flame propagation is slow, and the pressure effects are weak.

Also, during a certain period, this pressure difference P_f becomes negative, which can lead to the re-opening of the flap, in the absence of a locking system. The flap can therefore reopen by two mechanisms: the rebound once arrived in its abutment and a suction effect when P_f is negative. In the absence of a locking system it is thus necessary to ensure the flame remains far enough from the valve to prevent any risk of transmission. In these specific conditions, flame transmission relies on the blockage of the flow and is not a problem of Maximum Experimental Safe Gap (MESG) anymore. Indeed, in these specific conditions, a pressure higher than that in the vessel can be generated in front of the valve, leading to a reversal of the flow in the pipe. If this reversed flow velocity is equal to, or larger than, the flame velocity, the flame cannot travel towards the valve anymore. However, this observation may not remain true for all dust types and should be verified, in particular for the most reactive ones such as metal dusts in which case the physical mechanisms responsible for flame propagation can be different.

In Fig. 5, the flame position and velocity extracted from the cinematographic records are compared with the pressure signals. The flame trajectory is compared first with the pressure signals in the vessel and the pressure difference between each side of the flap. The flame propagating in the pipeline is driven by the explosion in the vessel. In this example, it reaches 7 m before stopping, going back and stopping at about 6 m from the vessel. In the section between the vessel and the flap valve, the pressure difference between the upstream (the vessel, P_v sensor) and the front of the valve

(P_{f1} sensor) is expected to fully determine the velocity of the flow. It is thus compared with the measured flame velocity of the right side of Fig. 5. One can notice that the flame velocity initially follows the same evolution as the pressure in the vessel: it increases gradually and then stagnates at the opening of the vent, around 100 m/s. When the pressure difference $P_v - P_{f1}$ becomes negative, the flame moves back towards the vessel. From t = 160 ms this difference is again positive and the flame velocity re-increases then converges to 0 when the pressures are balanced, at t = 180 ms. This confirms that the trajectory of the flame is dominated by the flow in the pipeline. These fundamental mechanisms must be considered in the realization of the dimensioning model of the final system.

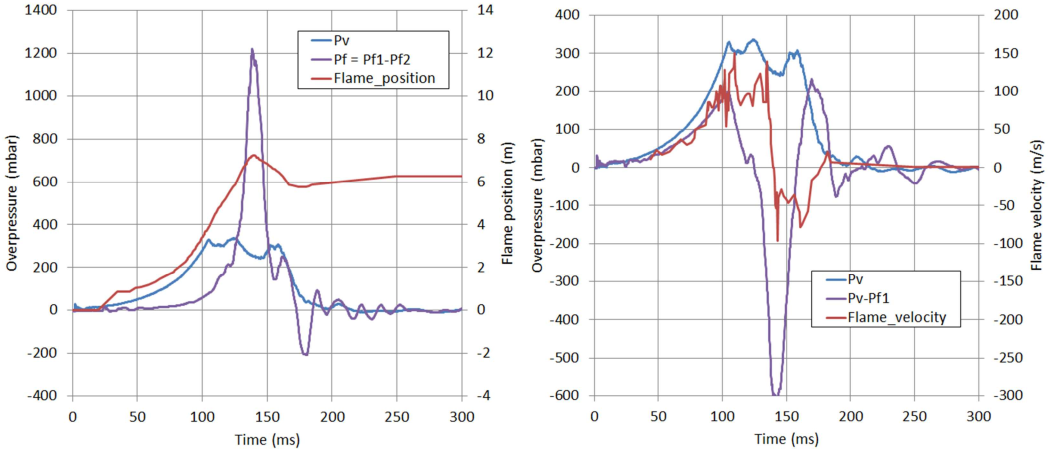

Fig. 5. Flame position (left side) and velocity (right side) compared with selected pressure records.

DIMENSIONING

Phenomenological modelling can be used in an extension to the parametric experimental study to investigate the limits of the valve. We first look at the distance $L_{\min}$, which corresponds to the minimum distance for which the system will be able to isolate the flame, preventing its transmission downstream of the pipe. To isolate a flame, the valve must be closed before its arrival. For the investigated valve without a locking system, successful isolation occurs if the flame stops at about 3 diameters of pipe before the valve. Note that it might not remain true for other devices, this limit should be verified experimentally. To trigger the closure of the flap, it is necessary that the overpressure in the vessel reaches a minimum value, sufficient to reverse the flow in the duct (typically on the order of 10 mbar). This condition is fulfilled after a noted time t_{exp}. The information of this reversal reaches the valve after a time t_{sound}, corresponding to the delay for the acoustic wave to travel the distance in the pipe between the vessel and the valve. Note that the time t_{act} described in Table 2 corresponds to the sum $t_{exp} + t_{sound}$. Then, the flap makes its complete run from the open state to the closed state, which takes time t_{flap}. The total time of closure of the system t_{tot} is obtained by summation of t_{exp}, t_{sound} and t_{flap}. This delay t_{tot} will be compared with t_f, that required for the flame to reach the position of the valve x_{flap} minus a certain safety length close to 3 diameters of pipe (in the current case). Alternatively, the second installation limit is the distance $L_{\max}$, from which the valve becomes unable to withstand the pressure forces generated by the explosion in the pipe and eventually let through the flame. $L_{\max}$ is directly related to the resistance of the valve. To determine $L_{\min}$ and $L_{\max}$, it is necessary to describe: the behaviour of the valve subjected to a pressure wave, the explosion in the vessel, the propagation of the flame in the pipeline. Note that the solution of the problem, the distance between the valve and the vessel, will be needed to compute t_{sound} and t_f. The problem is implicit and must be solved iteratively.

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 (1987):

$$\frac{1}{P}\frac{dP}{dt} = \gamma \cdot \frac{Q_{produced} - Q_{lost}}{V}, \qquad (1)$$

where P, V and γ are the vessel 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. Such a model clearly indicates that the effect of the explosion is directly linked to the reacting products, which will determine the rate of the gaseous production and the environment through the action of the vessel volume and vents in the denominator and the Q_{lost} parameter. Q_{lost} can be estimated with the generalized Bernoulli's laws. Consequently,. the time t_{exp} will be shorter if the vessel or vent volume is smaller. A shorter t_{exp} implies a shorter delay for the flame to reach the valve thus a larger $L_{\min}$. For this reason, limits in terms of minimum vessel volume, vent area, and maximum $P_{\max}$ and K_{St} (that play a role in $Q_{produced}$) are specified in the flap valve certificates.

To estimate the flame propagation delay, t_f, one can rely on the experimental observation that the flame flow is driven by the vessel overpressure. Phenomenological models based on Bernoulli's law can be found in [7].

Finally, the closing delay of a valve t_{flap} is also of critical importance. In the absence of an explosion, independent of the flap valve diameter, the trajectory of the inner flap can be well predicted with a simple model of a damped pendulum. The valve considered in the current example is based on the use of a counterweight to allow shorter closing delays. A similar model can be used for valves equipped with a spring. When there is an exploding dust-air flow pushing on the valve, the closing delay is reduced. It can be quite satisfyingly calculated adding a pressure force contribution to the earlier equation. The pressure signal can itself be approximated by a Gaussian, leading to the equation:

$$r\ddot{\theta} = -g \cdot \sin\theta - \frac{k}{m} \cdot \dot{\theta} - P_{v,max} \cdot exp\left(-\frac{(t - t_{sound})^2}{2 \cdot \sigma^2}\right) \cdot \cos\theta \cdot \frac{\pi \cdot D^2}{4 \cdot m}, \qquad (2)$$

where m is the mass (kg), r is the radius between the axis and the flap barycentre (m), k is the damping factor, and θ is the flap angle with the horizontal and the standard deviation of the normal law σ to be adjusted to fit with the explosion duration (σ roughly equal to 1/4 to 1/3 of the explosion duration). An experimental measurement without an explosion can be used to determine k for each valve.

With this model the determination of $L_{\min}$ is possible for a given configuration (fuel reactivity, ignition location, vessel, and vent and valve dimensions) but the determination of $L_{\max}$ is more challenging as it requires the pressure in the duct to be computed as a function of flame propagation. An alternative to costly modelling or experiments can be the use of the formulas listed in the EN standards for vent duct applications. NFPA68 also provides a chart describing pressure increase in a duct with a closed end, in which a dust-air flame of K_{St} 100, 200, or 300 propagates. This approach does not consider the presence of a vent and is expected to be conservative. From these data, it is also possible to estimate the duct length that should be investigated experimentally for a given flap valve diameter of a given pressure resistance.

CONCLUSIONS

Three different models of passive flap valve, of three diameters (DN150, 300 and 800) were tested with wheat flour and cornstarch dust explosions, in the scope of ATEX certification, on a 1 m^3 vessel (valves of DN150, DN300) and a 10 m^3 vessel. Recommendations for the testing of such devices are described in the normative document EN16447, which was chosen as an initial baseline to conduct the experiments. Practical and scientific limits of the standard are exposed, such as the impossibility to conducting large scale testing with the use of fans at a reasonable cost, or in controlled conditions. Some recommendations for the testing are also given. It appears to be fundamental to go farther than the configurations presented in the EN16447 and identify practically which configurations should be investigated. In particular, ignition location is of critical importance. Depending on the vent and pipe locations on the vessel the worst case scenario may correspond to an ignition close to the pipe or at the farthest point from it. Specific attention is also given to the explosion duration in the vessel: our test setup was arranged, where possible, to keep the explosion pressure in the vessel close to its maximum value when the flap valve is closed. This implies that for a given duct diameter, the explosion volume must be sufficiently large and the vent area sufficiently small to maintain the P_{red}. Finally, a phenomenological analysis of the test results reveals, for such devices, the critical importance of their pressure resistance (which should be of the order of 4 times the P_{red} in the vessel and also determines the maximum installation distance $L_{\max}$) as well as their closing delay (that can be estimated with equation (2), which determines their minimal installation distance ($L_{\min}$). Both phenomena being decoupled, is is possible to have $L_{\min} > L_{\max}$. This corresponds to a non-functioning device. It is interesting to point out that the determination of the possible installation distances for a given valve depend on the time t_f for the flame to reach the valve position. Thus, the problem is implicit and must be solved iteratively.

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