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# Flameless venting: achievements and difficulties

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## Abstract

Flameless venting is a sort of dual mitigation technique allowing, in principle, to vent a process vessel inside a building where people are working without transmitting a flame outside the protected vessel. Existing devices are an assembly of a vent panel and a metal filter so that the exploding cloud is forced to go through the filter. Within the frame of ATEX Directive, those systems need to be certified. To do so a standard (NF EN 16009) has been issued describing which criteria need to be verified / measured. Among them, the "efficiency" factor as defined earlier for standard vents. This implies that flameless venting systems are basically considered as vents. But is it really so? The practical experience of INERIS in testing such systems is presented in this paper. Schematically, with a flameless vent the pressure is discharged but not the flame so that combustion is proceeding to a much longer extent inside the vessel than with a classical vent. Therefore the physics of the explosion is different. This question is discussed on the basis of experimental results and some implications on the practical use and certification process are drawn.

Keywords: *dust explosions, vented explosions, flameless venting, flame propagation, mitigation*

## 1. Introduction

Over the last decades, a significant number of experimental studies demonstrated that the dust explosion venting technique can be applied to a wide range of industrial situations and that it is possible to establish reasonable dimensioning rules to estimate the required vent areas. A number of guidelines or standards were developed to help the designers in France (AFNOR), in the USA (NFPA), in United Kingdom (BSI), in Germany (VDI). It was observed that the results provided by these methods differed significantly (Roux, 2000). In an effort to harmonize the practices and to cover more situations, additional work was performed during the last ten years which resulted in upgraded versions of VDI3673, EN14491 and NFPA68 documents which tend to become international references. In parallel, since the last decade of the twentieth century a specific venting technology emerged to comply with the need of indoor installations: the flameless vents. Flameless venting is a sort of dual mitigation technique allowing, in principle, to vent a process vessel inside a building where people are working without transmitting a flame outside the protected vessel. Existing devices are an assembly of a vent panel and a metal filter so that the exploding cloud is forced to go through the filter. Within the frame of ATEX Directive, those systems need to be certified. To do so, a standard (EN16009) was issued describing which criteria need to be verified / measured. Among them, the "efficiency" factor as defined earlier for standard vents. As a reminder, it is stated in EN16009 that the flameless device efficiency can be influenced by the characteristics of the dusts (coarse, fibrous, melting and any other parameters that may lead to the device blockage) or by overheating, and indicated that comparative studies must be performed. However the normative document does not consider any differences between the efficiency of a standard vent panel or the efficiency of a flameless system: it is the ratio between the effective venting area and the physical vent area.

This implies that flameless venting systems are implicitly considered as functioning like vents. But is it really so? With a flameless vent the pressure is discharged but not the flame so that combustion is proceeding to a much longer extent inside the vessel than with a classical vent. Consequently, the physics of the explosion is different. The purpose of the present work is to analyze the behavior of flameless venting with respect to venting efficiency. In the following, available data from the literature is recalled but additional data are also presented. A discussion follows.

## 2. Available data (published)

### *2.1 Devices*

Holbrow (2006) performed an inventory work on the flameless devices available on the European market. Most flameless devices are composed of (**Fig. 1**) a venting device, a expansion chamber, and a flame quenching / dust retaining element, which will be referred in the following as a "dust explosion filter". The latter is usually a superposition of different metal meshes. The role of the expansion chamber is to allow a total and free opening of the venting device but also to provide enough area for the "dust explosion filter". The venting device is very often a standard explosion panel, but it may also be a bursting disc, or a spring loaded valve. Three arrangements seem more frequent:

- With the disc type of design, the venting device is a circular spring loaded valve mounted against the strong top flange. As a consequence the dust cloud and flame can only be vented radially through the "dust explosion filter" and the aspect ratio of the device is smaller than 1.
- With the cylindrical design, the venting device is a bursting disc covered with a cylindrical expansion chamber in which the aspect ratio (L/D) is larger than one. The wall of the expansion chamber is the "dust explosion filter";
- In the box type of arrangement, the venting device is a vent panel covered with a sort of prismatic expansion chamber. The dust explosion filter usually occupies the largest side of the expansion chamber ;

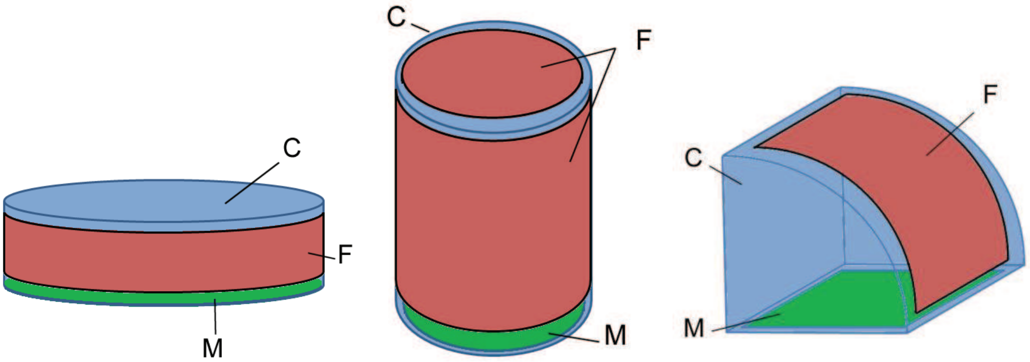

***Fig. 1:*** *Three principal types of flameless vents. From left to right: disc, cylinder and box type flameless (M: venting device; C: chamber; F: filter)*

During the dust explosion, the venting device opens. First the unburnt cloud, later the burnt products, enters the expansion chamber and is pushed through the dust explosion filter. A very large amount of particles (the fuel, agglomerates and solid post-combustion products) is trapped and the flame/burnt products are cooled down by the metal meshes. According to Barton (2002), this second mechanism is important because when the burning mixture temperature drops below the minimal ignition temperature of the dust (Barton, 2002), subsequent flame propagation is impeded. In practice however, the dust cloud flowing out from the dust explosion filter is very faint and may be too lean to burn anyway so that the first mechanism is certainly as important as the second. So, any flameless device is a series of two consecutive barriers: the venting device and the dust explosion filter, which acts very differently on the explosion (the first one on the pressure and the second one on the flame).

However in the NFPA68 and EN16009 standards the flameless device is completely viewed as a venting device with some additional limitations (as compared to standard vent panels).

These limitations include the impossibility to use the flameless technology for applications involving toxic materials or fibrous / melting dusts (if not duly tested). Further, the flameless venting system is said to have a lower efficiency as compared to the venting device alone and needs to be measured. This second limitation is obvious because of expected additional head losses in the dust explosion filter and the first one too because flameless devices are intended to be used indoor. Coarse, fibrous or melting dusts are expected to easily clog the meshes severely limiting the venting capability of the flameless device. An example was reported by Holbrow (2006) about a sugar dust explosion that occurred in 2004 in a bucket elevator at the Sugar Australia Glebe Island Terminal in Australia. Despite the relatively low Kst of the dust (133 bar.m/s, measured in a laboratory) and a venting area judged adequate, it was found out the flameless dust explosion filter located at the bottom of the elevator was clogged and the venting capability was severely impaired.

### *2.2 Efficiency*

The efficiency coefficient is defined as the ratio between the effective venting area and the physical vent area of the venting device.

*STUVEX* provides datasheets for a disc type flameless device (“*DSQ”*) and a cylindrical one, (“*INDOORVENT*”). DSQ system shows efficiencies between 55 and 67 %, increasing with the “desired $P_{red}$”. INDOORVENT systems show efficiencies between 76 and 85 %, varying (not regularly) with the device diameter. Unfortunately no link can be established between these efficiencies and the process conditions.

IEP provides datasheets about a cylinder type and a box type of flameless venting device. The efficiencies range between 83 and 93 % for the cylinder type, and 59 to 64 % for the box type despite having similar hydraulic diameters. This means that a better efficiency is obtained with the cylinder type flameless than with the box type, which could be explained due to the larger “dust explosion filter” area for the cylindrical design.

Bartknecht and Vogl (1994) investigated flameless pressure relief of dust explosions using a bursting disc (static opening overpressure $P_{stat}$ = 0.1 bar) and ribbon type dust explosion filter. As described in EN16009, ribbon type quenching elements are made of alternating layers of thin, corrugated metal ribbons and flat metal ribbons of the same width, which are wound together on a mandrel to form a many-layered cylinder of the desired diameter. Tests were performed with a 1 $m^3$ and with a 60 $m^3$ vessel. It is not clear which dusts were used but it was reported that the device was successful up to a reduced explosion pressure ($P_{red}$) of 3 bar. Above that value, the barrier effect dropped. In any case, they observed, as it would be expected, that the flame arrestor elements caused a restriction to flow and the effective relief area was diminished.

In 1998, Stevenson presented global results about the Q-Rhor flameless device which is now produced by REMBE. The Q-Rhor is a cylinder flameless device. Stevenson indicates an efficiency factor between 70 to 90 %, depending on the size of the device and the nature of the dust explosion filter. These data show that the flameless device cannot be considered as an extension of a standard venting device.

Going and Chatrathi (2003) published test records obtained using a cylindrical flameless venting device, (FlamQuech II device) produced by FIKE. Three test chambers were used (0.5, 2 and 4 $m^3$), several device diameters (8, 14, 20, 24 and 36 inches) and three different dusts (cornstarch, anthraquinone and coal) in addition to propane gas. Efficiencies vary between 72 and 100 %. No relationship could be established between the efficiency coefficient and the process conditions: $P_{red}$, $K_{St}$, device sizes, etc. For the same dust, increasing $K_{st}$ leads to an increase of $P_{red}$. Also an increase of $P_{stat}$ leads to an increased $P_{red}$. Later, in 2013, Snoeys claimed that a “representative” efficiency coefficient of box type version of the flameless venting device FlameQuench II Square) would amount to 60 %.

In the same period of time, Holbrow (2013) tested a box type flameless venting device produced by FIKE (possibly the same model as that presented by Snoeys, 2013) on 0.5 and 2 $m^3$ vessels using two dusts with a similar $K_{St}$ coefficient but with very different particle size distributions: corn flour ($K_{St}$ = 147 bar.m/s, 100 %> 63 µm) and wheat flour ($K_{St}$ =138 bar.m/s, PSD: 63 µm < 90 % < 180 µm). With wheat flour, $P_{red}$ with the flameless venting devices did not exceed those measured with the “naked” vent panels. With corn flour, the measured $P_{red}$ with the flameless venting devices are much larger with the “naked” vent panels. These results were unexpected and pointed out that two organic flours of similar explosion parameters ($K_{St}$, $P_{max}$) may nevertheless behave very differently as far as flameless venting is concerned.

Recently Chao and Dorofeev (2015) proposed a methodology to calculate the overall efficiency of a flameless system by multiplying the efficiency coefficient of the venting device standing alone by an estimated efficiency of the dust explosion filter standing alone. Equations are proposed to estimate these parameters based on three different models from FM Global, NFPA 68 and VDI 3673. The equations take into consideration the usual parameters for the dusts and the vents such as the physical vent area or the $K_{St}$ but no specific attention is laid on the type of dust nor its concentration. Cornstarch dust was used at two different $K_{St}$ (adjusted varying the ignition delay) to simulate ST1 and ST2 dusts. The overall efficiency is found to be poorly dependant on this parameter as it is 77 % for the ST1 case and 76 % for the ST2 case.

So many open questions remain and the experience of INERIS is presented below.

## 3. INERIS experiments

Flameless venting has been investigated over the past five years. Five type of flameless venting devices from different producers were tested.

### *3.1 Experimental setup*

All of the devices were tested using a 10 $m^3$ tank with an inner diameter of 1.8 m, a length of 3.9 m and a L/D ratio of 2.18 (**Fig. 2**). In the present example, the ignition point (made of two 5 kJ chemical igniters) is located in the middle of the axis of the chamber. But in other cases, the ignition point was set at the back of the tank, near the dispersion nozzle.

***Fig. 2:*** *Pictures of INERIS 10 $m^3$ tank*

The dust dispersion system is a pressurized fluidized particle bed technique (**Fig. 3**). The device uses a cylinder in which air is blown from the bottom, through a particle layer, to have it behave as a fluid. When the fluidized particle bed is obtained, the dust is released into the vessel. The ignition delay is adjusted depending on the dust type and its concentration, to ensure satisfying turbulence and concentration conditions in the vessel.

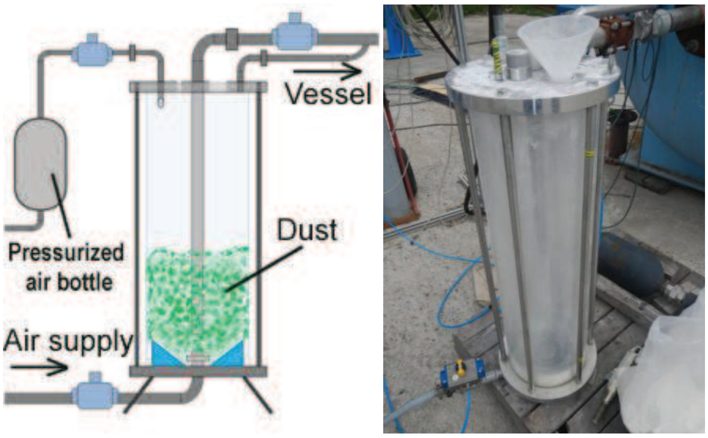

***Fig. 3:*** *Scheme and picture of the dispersion device based on the fluidization technique*

As known to the reader, the $K_{St}$ of the explosion depends on the dispersion and ignition conditions, not only on the dust. Because of this, the $K_{st}$ can be varied to a certain extent independently from the nature of the dust. But since the physico chemistry of the dust seems of importance, two very different dusts were used (Table 1). Wheat flour is much coarser. $K_{st}$ and $P_{max}$ (maximum explosion overpressures) were systematically measured in closed vessel conditions. For wheat flour, $K_{st}$ varied between 80 and 160 bar.m/s, depending on the ignition point location and concentration in the cloud. For cornstarch, it varied between 120 and 210 bar.m/s. The maximum overpressure ranged for both dusts between 6.5 and 9 bar.

*Table 1: Particle size distributions for the two dusts tested**

| Dust | D(v, 0.1) (μm) | D(v, 0.5) (μm) | D(v, 0.9) (μm) |
|---|---|---|---|
| Wheat flour | 17.20 | 70.57 | 145.35 |
| Cornstarch | 10.74 | 23.78 | 49.64 |

*D(v,x) is the characteristic particle diameter such that x % in volume (or mass) of the sample is finer.

Five types of flameless venting devices were tested: one of disc type of design (DISC1), and four box-types (BOX1, BOX2, BOX3 and BOX4). The experimental configurations are presented in Table 2. In some cases, an additional vent (simple plastic foil opening at about 100 mbar) was provided in addition to the flameless venting device to limit $P_{red}$.

*Table 2: Experimental configurations*

| Flameless device | dusts | ignition | Additional vent | Location |
|---|---|---|---|---|
| DISC1 | Wheat flour and cornstarch | Centre | 400 mm | Side flange |
| BOX1 | Wheat flour and cornstarch | Back | None | Main flange (entrance) |
| BOX2 | Wheat flour and cornstarch | Back or centre ($300\ g/m^3$ tests) | None | Main flange (entrance) and side flange when 2 devices were tested |
| BOX3 | Cornstarch | Back | None | Main flange (entrance) |
| BOX4 | Wheat flour | Back | None | Main flange (entrance), 3 devices |

Between BOX2 and BOX3, only the filter part is different, the rest of the system being the same. Besides the general description of "BOX shaped Flameless devices", there is no common point between the other devices: they are built by different manufacturers and based on different technology. Five pressure gauges (Kistler piezoelectric gauges) were used: 2 inside the vessel (one at the back near the dispersion system and another one close to the flameless venting device), 1 on the dispersion system (to control the injection process), and 1 outside at 5 m in front of each vent (or flameless vent). Thermocouples were also used to control the temperature outside the vessel (on the pressure gauge and over the surface of the flameless device). A high speed camera (Photron APX) was used (2000 frames per second in a 1024x1024 pixels window), and a standard HD camera. Also, when relevant, a small pyrotechnic igniter in parallel with the chemical igniters is placed outside acting as an indicator of the timing of the explosion process on the videos. The vent opening is normally visible (emission of particles) on the videos.

### *3.2 Results*

#### *3.2.1 DISC1*

DISC1 (physical vent hydraulic diameter Dh = 540 mm) was installed on the main end flange together with a 400 mm vent (plastic foils opening at 100 mbar) located on a side flange to limit $P_{red}$. The data in Table 3 correspond to the efficiency for the flameless devices alone. Although the reactivity and dust concentration are relatively similar, the venting efficiencies (thus $P_{red}$) are very different suggesting (confirming) a massive incidence of the physico chemical nature of the particles.

*Table 3: Tests performed with DISC1*

| Test # | DISC1-1 | DISC1-2 |
|---|---|---|
| Dust type | Wheat flour | Corn starch |
| Mass (kg) | 7 | 7 |
| $K_{St}$ (bar.m/s) | 85 | 120 |
| $P_{max}$ (bar) | 9 | 8.5 |
| Valve opening pressure (mbar) | 150 | 90 |
| Dh (m) | 0.54 | 0.54 |
| $P_{red}$ | 320 | 1965 |
| Efficiency | 70 | 29 |
| Comment | | No reconditioned (re-usable device) |

#### *3.2.2 BOX1*

Aside the standard efficiency testing, two additional tests were performed. One (test BOX1-4) immediately after test BOX1-2 using a charge (not dispersed) of black powder to estimate the blockage ratio due to the clogging of the dust left from the preceding test and another one (test BOX1-5) in similar conditions than BOX1-3 to estimate the consequence of this clogging (Table 4) in dust explosion conditions. This last test in particular perfectly illustrates the very large influence of the quantity of particles flowing through the dust explosion filter.

Apparently a very significant incidence of $P_{stat}$ is noticed. This is also true for standard vent panels but in a lesser extent.

*Table 4: Tests performed with BOX1 flameless device.*

| Test # | BOX1-1 | BOX1-2 | BOX1-3 | BOX1-4 | BOX1-5 |
|---|---|---|---|---|---|
| Dust type | Cornstarch | Wheat flour | Wheat flour | Black Powder | Wheat flour |
| Mass (kg) | 7 | 7 | 7 | 1 | 7 |
| $K_{St}$ (bar.m/s) | 350 | 180 | 180 | - | 150 |
| $P_{max}$ (bar) | 8.5 | 9 | 9 | - | 9 |
| $P_{stat}$ (mbar) | 100 | 100 | 200 | no vent | no vent |
| Dh (m) | 1 | 1 | 1 | 1 | 1 |
| $P_{red}$ (mbar) | 1540 | 280 | 1610 | 270 | 1940 |
| Efficiency | 48 | 95 | 50 | - | 34 |
| Comments | - | - | - | Not reconditioned since BOX1-2 | Not reconditioned since BOX1-3; ejection of the device (20 m) |

### *3.2.3 BOX2*

The BOX2 is build by another manufacturer. Three sizes of the BOX2 device were investigated, with two different dusts, and three levels of concentration (Table 5). For tests 6 to 8, the ignition was performed at the center of the vessel.

*Table 5: Tests performed with BOX2 flameless device.*

| Flameless # | BOX2-1 | BOX2-2 | BOX2-3 | BOX2-4 | BOX2-5 | BOX2-6 | BOX2-7 | BOX2-8 |
|---|---|---|---|---|---|---|---|---|
| Dust type | Wheat flour | Wheat flour | Corn-starch | Corn-starch | Corn-starch | Corn-starch | Corn-starch | Corn-starch |
| Mass (kg) | 10 | 5 | 5 | 10 | 10 | 3 | 3 | 3 |
| $K_{St}$ (bar.m/s) | 140 | 160 | 210 | 200 | 200 | 175 | 175 | 175 |
| $P_{max}$ (bar) | 7.5 | 6.5 | 8.5 | 9 | 9 | 6.5 | 6.5 | 6.5 |
| $P_{stat}$ (mbar) | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Dh (m) | 0.716 | 0.716 | 0.716 | 0.716 | 0.716 | 0.716 | 0.455 | 0.61 |
| Number of devices | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| $P_{red}$ | 1283 | 780 | 340 | 800 | 2350 | 485 | 2200 | 940 |
| Efficiency | 27 | 36 | 64 | 36 | 37 | 87 | 59 | 62 |

All other parameters being equal, the larger the amount of dust in the vessel, the lower is the efficiency (test 3-4, tests 5-6). With wheat flour the efficiency is much lower: tests 2 and 4 led to similar $P_{red}$, despite half of the mass of particles was used in the case of the wheat flour (**Fig. 4**).

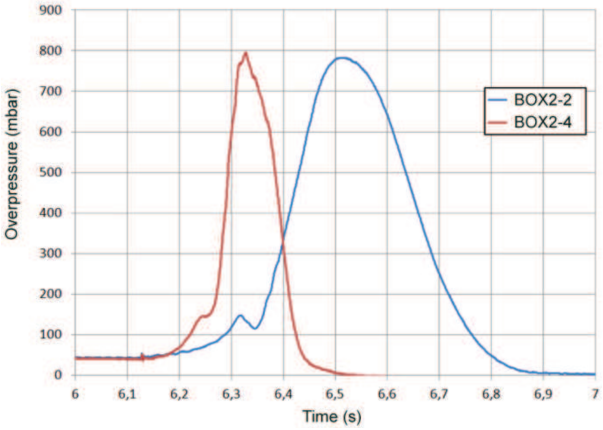

***Fig. 4:*** *Pressure records for tests BOX2-2 and BOX2-4*

As expected the pressure rise is much slower for wheat flour (blue curve in **Fig. 4**) but the same value for $P_{red}$ is reached. This can be understood considering the depressurization phase (after $P_{red}$).The discharge of the vessel is driven by the pressure difference between the inside of the vessel and the outside of the flameless device and by the effective free area through the filter. The faster pressure decay rate in test 4 for the cornstarch explosion reveals the effective free area is larger than during the wheat flour explosion. So wheat flour particles tend to clog more rapidly than cornstarch. It was noticed that the smaller mesh cell is 80 µm large. Considering Table 1, it is clear that a significant proportion (may be 50%) of the wheat flour particles will not go through whereas most of the cornstarch particle will. This suggests that the difference in the particle size distribution between wheat flour and cornstarch could be a reason for the lower efficiency measured with cornstarch.

### *3.2.4 BOX3*

The BOX3 prototype is a modified version of the BOX2 system (same system at the same manufacturer) in which only the filter was changed (Table 6). This other type of filter is build differently and was described as having larger orifices (unfortunately, no further details are available on this aspect). The comparison between BOX2 and BOX3 in same experimental configuration is shown on **Fig. 5**.

*Table 6: Tests performed with BOX3 flameless device.*

| Test # | BOX3-1 |
|---|---|
| Dust type | Cornstarch |
| Mass (kg) | 5 |
| $K_{St}$ (bar.m/s) | 210 |
| $P_{max}$ (bar) | 8.5 |
| $P_{stat}$ (mbar) | 100 |
| Dh (m) | 0.716 |
| Number of devices | 2 |
| $P_{red}$ | 200 |
| Efficiency | 89 |

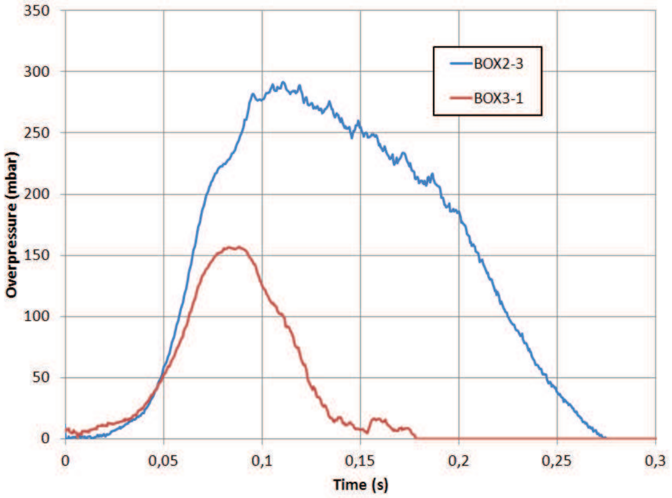

***Fig. 5:*** *BOX2-3 and BOX3-1 pressure records: 500 g/m$^3$ of cornstarch, same flameless devices but different filters*

The initial rates of pressure rises are similar testifying the same kind of explosion. However the pressure discharge is much more efficient for BOX3.

### *3.2.5 BOX4*

In this case the devices are smaller and 3 of them were used simultaneously. Again the technology is different from BOX1 or BOX2/3. During this test a complete failure of the flameless vents was observed, despite relatively low dust reactivity. The dust was ignited at the center of the vessel in this case.

*Table 7: Tests performed with BOX4 flameless device.*

| Test # | BOX4-1 |
|---|---|
| Dust type | Wheat flour |
| Mass (kg) | 7 |
| $K_{St}$ (bar.m/s) | 120 |
| $P_{max}$ (bar) | 8 |
| $P_{stat}$ (mbar) | 100 |
| Dh (m) | 0,455 |
| $P_{red}$ (mbar) | 1600 |
| Efficiency | 15 |

Interestingly, exactly the same device was tested successfully on another test site. But these experiments were performed using additional vents on the explosion chamber whereas at INERIS no additional vent was used. Presumably the testing conditions have an influence. When an additional vent is used, a large proportion of the dust cloud goes directly outside without flowing through the dust explosion filter so that the clogging effect is significantly reduced.

## 4. Discussion

### *4.1 Potential phenomenology*

Present data are in line with published information. For instance, the presence of the filter on the flameless vent is able to retain dusts and quench the flames but alters the flow and leads to higher $P_{red}$ / lower efficiency coefficients. Also a disc shaped flameless device presents a reduced filtering area than the box type systems and shows much lower efficiencies.

Additionally some of these results underlined some specific points:

- the filter restrains the flow and has a significant effect on the explosion discharge,
- large amounts of particles do block the flameless filters during the discharge,
- a partially blocked filter may allow extreme pressure build up in the vessel, even when the dust explosion is slow (weak flame velocity),
- adding a standard vent on the same explosion vessel as that on which the flameless device is placed, may completely change the flow in an uncontrolled manner and can lead to dramatic misinterpretation of the performances of the flameless venting device.

This demonstrates that the present physical mechanisms are more complicated than a simple discharge of a pressurized volume of gas throughout a porous media. The effect of the flameless device on the explosion is very complicated because it relies on the competition of two very different phenomena:

1) The “filtering” effect of the flameless device: solid particles are expected to seal a part of the holes in the flameless filter, slowing down the flow in this system.
2) The extra gas volume produced by the combustion (as compared to normal venting): most of the particles remain trapped inside the chamber all along the discharge process which constitutes a large difference as compared to normal venting. The burning or pyrolysis of those particles would produce extra volume of gases and maintain a rather high level of pressure. The decrease of the pressure should occur when the flame would have propagated throughout the whole volume of the vessel and extinguished.

A direct consequence of this is that the flameless device may not behave as a vent, and the vent dimensioning rules may not be applied without due consideration. For the same reason, the definition of the vent efficiency transposed to the case of the flameless device system may not be representative of its real functioning without further information on the process conditions. For instance, large concentrations of weakly reactive powders (thus low $K_{St}$ values) may lead to hazardous situations whenever a flameless device were to be used. Particles will be stuck in the grids and limit the discharge surface of the flameless device while the rest of the burning particles will generate significant pressure rise at a later time, which would lead to an uncontrolled pressure rise in the tank. Consequently when the dust concentration reaches a certain level, the flameless system may not behave as standard vents anymore, this is a critical parameter of the system. However estimating the dust concentration in an industrial process in accidental conditions is a challenging task and only a limited number of flameless producers indicate publically concentration limits for their systems.

### *4.2 Tentative modeling*

All these experiments demonstrated that besides the actual explosion, the limiting phenomenon is the flow of burning mixture through the flameless device. To get a better understanding of the problem it has been decided to study this dense particle flow. The simplest characterization of a flow in fluid mechanics is made with the Reynolds numbers which takes the form: $Re = \frac{U \cdot L}{\nu}$, with ν the kinematic viscosity of the fluid, U the maximal velocity relatively to the fluid, L a characteristic length and ρ the fluid density. It corresponds to the ratio of the inertial forces over the viscous forces. The ν parameter is difficult to estimate and probably on the order of $10^{-4}$-$10^{-5}$ $m^2/s$. Because of a lack of data, in first approximation it is assumed to be constant and equal to $10^{-4}$ $m^2/s$. U can be linked to the $P_{red}$, again with a simple approximation based on Bernoulli laws: $U = \sqrt{\frac{2 \cdot P_{red}}{\rho}}$ with ρ the fluid density, that is the dust concentration plus the air density. Knowing the theoretical homogeneous dust concentration, it is possible to obtain an average value of ρ. At last the characteristic dimension here would be the hydraulic diameter of the flameless system Dh.

The flameless Reynolds numbers were compared with the flameless efficiency in the case of the BOX2 tests as more experimental data was available:

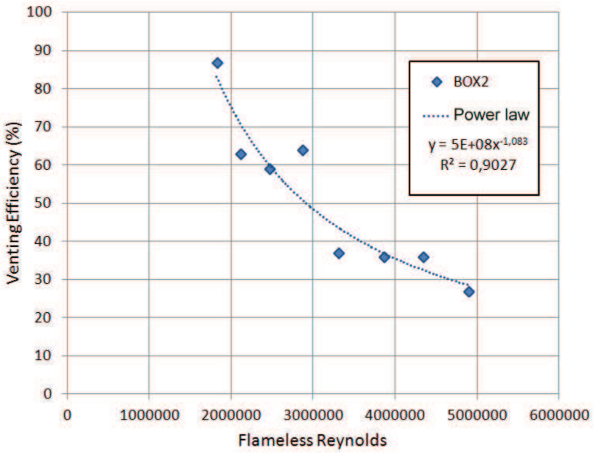

***Fig. 6**: Flameless Reynolds versus venting efficiency for BOX2*

There is a decent agreement between the fundamental flow parameters and the flameless efficiency. But what does this imply? First this model will not tell whether the flame passes through the grids or not and it cannot be used directly to dimension a protection solution as it does not consider the fundamental differences between two types of dusts. However it describes how the specific BOX2 system works, suggesting that predicting the flow could be helpful to estimate the associated efficiency. Indeed, for a given flameless system, based on a set of experimental data, it is possible to obtain the system response to a given flow under the form of a simple correlation as presented in **Fig. 6**.

The same exercise was performed on all of the data available from INERIS test as well as that acquired in the scientific literature (when sufficient data was available):

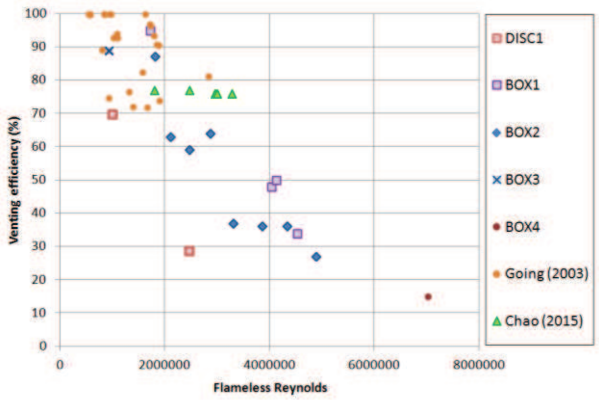

***Fig.*** *7: Flameless Reynolds versus venting efficiency for other flameless systems*

The general trends appear to be respected. Deeper work is needed on the flow characterization to complete this model but it sheds light on fundamental phenomena at stake during the flameless venting.

## 5. Conclusions

The major result of this study is that the flameless device does not behave as a standard vent.

Besides the problem of the unloading of the explosion in the tank, there is a highly complicated fluid mechanics problem of a fluid-particle flow passing through a porous media (the flameless device grids arrangement in the filter) with the passing surface being progressively reduced. As a consequence the capability of the system to discharge the explosion is linked to:

- the dust combustion itself: at which rate it will produce gases ($K_{St}$) and in which quantity (Explosion volume) ,
- the mass fraction of solid particles and also probably the granulometry of the dust that may progressively close the pores in the filter and
- the filter which is limiting the exhaust of the burnt gases.

Because of this, we can consider that an explosion occurring over a longer duration (low Kst but large quantities of matter reacting) may be more damaging than the quick explosion of a more sensible mixture producing gases with barely any solid burnt particles. The direct consequence of this is that a lower $K_{St}$ dust may decrease the required vent area. This is not taken into account with the current formulas of certification norms such as the EN14491 on the dust explosion venting protective systems. Further study is needed on the dust explosion pressure unloading through flameless venting. The model developed in the last part of the present work shows a strong influence of the air-particle flow on the final efficiency of a flameless system.

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