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Does your facility have a dust problem: Methods for evaluating dust explosion hazards

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ABSTRACT

The hazards of dust explosions prevailing in plants are dependent on a large variety of factors that include process parameters, such as pressure, temperature and flow characteristics, as well as equipment properties, such as geometry layout, the presence of moving elements, dust explosion characteristics and mitigating measures. A good dust explosion risk assessment is a thorough method involving the identification of all hazards, their probability of occurrence and the severity of potential consequences. The consequences of dust explosions are described as consequences for personnel and equipment, taking into account consequences of both primary and secondary events.

While certain standards cover all the basic elements of explosion prevention and protection, systematic risk assessments and area classifications are obligatory in Europe, as required by EU ATEX and Seveso II directives. In the United States, NFPA 654 requires that the design of the fire and explosion safety provisions shall be based on a process hazard analysis of the facility, process, and the associated fire or explosion hazards. In this paper, we will demonstrate how applying such techniques as SCRAM (short-cut risk analysis method) can help identify potentially hazardous conditions and provide valuable assistance in reducing high-risk areas. The likelihood of a dust explosion is based on the ignition probability and the probability of flammable dust clouds arising. While all possible ignition sources are reviewed, the most important ones include open flames, mechanical sparks, hot surfaces, electric equipment, smoldering combustion (self-ignition) and electrostatic sparks and discharges. The probability of dust clouds arising is closely related to both process and dust dispersion properties.

Factors determining the consequences of dust explosions include how frequently personnel are present, the equipment strength, implemented consequence-reducing measures and housekeeping, as risk assessment techniques demonstrate the importance of good housekeeping especially due to the enormous consequences of secondary dust explosions (despite their relatively low probability). The ignitibility and explosibility of the potential dust clouds also play a crucial role in determining the overall risk.

Classes describe both the likelihood of dust explosions and their consequences, ranging from low probabilities and limited local damage, to high probability of occurrence and catastrophic damage. Acceptance criteria are determined based on the likelihood and consequence of the events. The risk assessment techniques also allow for choosing adequate risk reducing measures: both preventive and protective. Techniques for mitigating identified explosions risks include the following: bursting disks and quenching tubes, explosion suppression systems, explosion isolating systems, inerting techniques and temperature control. Advanced CFD tools (DESC) can be used to not only assess dust explosion hazards, but also provide valuable insight into protective measures, including suppression and venting.

1. Introduction

Dust explosions are a continuous threat in facilities producing combustible powders and dust as final and intermediate products. Regrettable recent examples include the 2003 explosion at West Pharmaceutical Services in Kinston, North Carolina (killing 6), the 2008 explosion at Imperial Sugar Plant in Savannah, Georgia (killing 14), and one year later the explosion in a coal silo at WE Industries power plant injuring 7 in Oak Creek, Wisconsin (2009). Along with these serious accidents are many smaller industrial dust explosion accidents causing limited damage and only minor or no

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Fig. 1. Dust layer accumulation under a silo (left) and due to excessive material leaking out of process equipment (right).

injuries. Some of these smaller incidents, however, could have led to more serious consequences.

Dust explosion risks prevailing in industrial facilities are dependent on a large variety of factors that include process parameters, such as pressure and temperature, as well as equipment properties, such as the presence of moving elements, the mechanical strength of such dust handling equipment, dust explosion characteristics, and mitigating measures taken, including housekeeping and protective measures such as explosion venting or suppression.

In this document a semi-quantitative short-cut risk analysis method (SCRAM) is presented, allowing for the assessment of dust explosion risks and choosing adequate preventive and protective measures. The performance of an analysis as described here would make industry aware of the most hazardous areas in their facilities and associated consequences in case of an explosion.

The method is described and an application example presented. The example demonstrates the strength of the method and the support it offers to industry for choosing appropriate risk mitigating measures. Lastly, examples showing how advanced CFD codes like DESC can be used to assess explosion hazards and explosion venting are presented.

Fig. 2. Dust accumulation on elevated, horizontal surfaces such as ducts, beams, cable trays, etc.

2. Description of the short-cut risk analysis method

This chapter describes the methodology used to determine the risk for dust explosions in industrial facilities. The risk for a dust explosion is the product of the probability of a dust explosion occurring and the consequences of the dust explosion. The consequences can be divided into primary consequences such as failure

Fig. 3. Outdoor filter installation recycling process air back indoors.

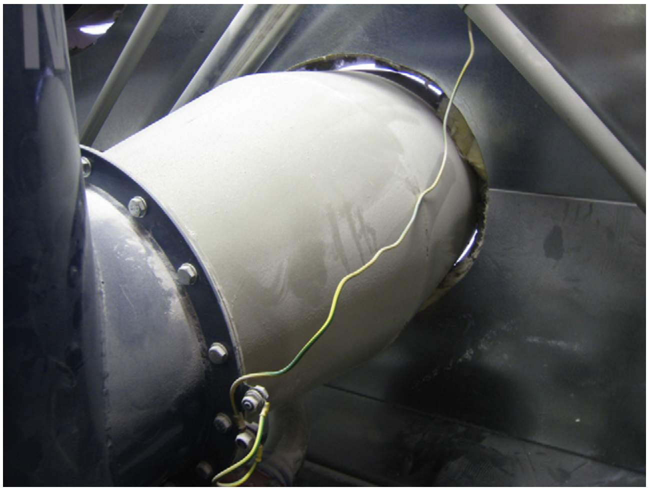

Fig. 4. Bonded and grounded piece of process equipment.

of the piece of equipment in which the dust explosion occurs and secondary consequences such as an ensuing fire and secondary explosions in connected equipment or in the working area due to whirling up and subsequent ignition of dust layers there. Fig. 1 shows examples of dust layers that have accumulated outside of equipment and elevated horizontal surfaces (shown in Fig. 2), which would be considered when evaluating secondary explosion risks.

Another process for which secondary explosions should be considered is when the air of material separators is recycled back into the facility, with a potential of escalating an explosion in the equipment back into the facility if explosible atmospheres are present or isolation is not provided. An example of an outdoor filter, which recycles the process air stream back into the facility, is shown in Fig. 3.

2.1. Estimating the probability of an explosion occurring

For a dust explosion to occur, a flammable atmosphere must be present simultaneously with a competent ignition source. The dust concentration in this atmosphere must exceed a certain threshold limit, typically 30 g/m^3, with a particle size distribution sufficiently small. Dust with particle size distributions from 10 to 40 microns and concentration ranges from 250 to 1500 g/m^3 have been shown to have the highest propensity to ignite and to produce the most severe explosions. Finer dust particles might produce explosions that are more severe if the dispersion process has enough force to break up the agglomerates and produce a dust cloud consisting of primary particles.

To be able to quantify the probability for the occurrence of an explosive atmosphere, properties of the combustible material should be considered, together with how likely it is that the combustible material will be mixed with air. The probability of a specific ignition source being able to ignite the explosive atmosphere is considered based on different criteria, such as the energy released by the ignition source, the period in which this energy is supplied, the surface temperature of the ignition source and its size. For mechanically generated sparks, collision speed, friction, contact time and physical properties of the colliding materials are included. For electrical discharges, the facilities practices for grounding and bonding need to be considered; an example of a bonded piece of equipment is shown in Fig. 4.

Whether an ignition source is capable of igniting an explosive atmosphere depends on several properties of the atmosphere, for instance the fuel concentration and the turbulence level, and the ignition properties of the explosive atmosphere (normally described by the minimum ignition energy and minimum ignition temperature).

The factors mentioned above are considered individually and form the basis for estimating how often an explosion can occur. It is not possible to give the exact frequencies for an explosion. In a risk analysis the probability for an explosive atmosphere and the probability for an ignition source are ranged from "I" to "V", where "I" has the lowest probability and "V" has the highest probability. Each "range" (I, II, III, IV and V) describes a range in "probability" or "frequency".

The probability of an explosion occurring depends on the probability of the presence of an effective ignition source and the probability of having an explosive atmosphere. The probability of an explosion will be the product of these two probabilities (as long as the two are generated independent from each other). Definitions and explanations of the values used are described below.

Fig. 5. Examples of equipment improperly vented indoors.

Consequence					
V	C	B	A	A	A
IV	D	C	B	A	A
III	E	D	C	B	A
II	E	E	D	C	B
I	E	E	E	D	C
	I	II	III	IV	V
	Probability				

Fig. 6. Risk matrix.

The probability for a secondary event depends on the probability for the primary event and is normally lower than that of the primary event.

2.2. Estimating the consequences of an explosion

The consequence for personnel (D_p) and equipment (D_e) is estimated based on the expected effect of the explosion. This is estimated based on expected damage caused by the heat, pressure or loose items after the definitions given below. The consequence for personnel and equipment from an explosion depends on the explosion pressure and the heat intensity from the explosion. Pressure build-up in enclosed units might cause the units to rupture, resulting in heat radiation from flames, dispersion of pressure waves and flying objects.

The strength of an explosion depends on several factors, such as the initial conditions of the dust cloud, including the fuel concentration, initial turbulence and the position of the ignition source. The properties of the combustible material are also important, including chemical composition. The properties of the explosive atmosphere will change over time; hence, the time of the explosion is important for the explosion propagation.

Flames propagating out from a ruptured vessel release heat that might injure personnel or cause damage to equipment. The convective heat transfer during an explosion causes the most severe burns. Burns/damage might be the result if personnel or equipment are in direct contact with the explosion flame. This can be especially true for explosions that are vented indoors. While the explosion vent may adequately protect a given piece of equipment, it may exacerbate injuries to personnel if vented in occupied areas. Fig. 5 shows examples where a bucket elevator was improperly vented indoors in the area of personnel (see ladder) as well as another piece of equipment vented indoors.

Another concern is that of secondary explosions, which under certain circumstances can be more severe than the primary explosion. Secondary explosions are caused when the primary containment system (duct, vessel, dust collector, etc.) ruptures due to the primary explosion, and the resulting venting and blast wave entrains and disperses neighboring dust layers into the air, which subsequently ignite. Generally, the severity of secondary dust explosions is related to the thickness and the area occupied by the dust layers; hence housekeeping plays a key role in reducing the hazards of secondary explosions.

2.3. Definitions

The probability or the frequency of an explosion occurring and the potential consequences are estimated from I to V, as described previously. Definitions and descriptions of the different values are given below.

Table 1
Definition of the probability and consequence for explosions under normal operation.

Probability of the formation of an explosive atmosphere		
Range D_a		*Description*
I		Very unlikely
II		Unlikely
III		Somewhat likely
IV		Likely
V		Very likely
Probability of the formation of an effective ignition source		
Range D_i		*Description*
I		Very unlikely
II		Unlikely
III		Somewhat likely
IV		Likely
V		Very likely
Probability for an explosion to occur		
Range D_x	*Description*	*Definition*
I	Very unlikely	<1/10000 per year
II	Unlikely	>1/10000 per year < 1/100 year
III	Somewhat likely	>1/100 < 1/10 per year
IV	Likely	>1/10 year < 1 per year
V	Very likely	>1 per year
Consequence for personnel and equipment		
Range D_p D_e	*Description*	*Definition*
I	Personnel	No injury.
	Equipment	Marginal damage to process units. Process shut down.
II	Personnel	Limited injury.
	Equipment	Damage to process unit (<$20,000).
III	Personnel	Personnel injury.
	Equipment	Process unit collapse, possible damage to other units (>$20,000; <$200,000).
IV	Personnel	Serious personnel injury, possible loss of life.
	Equipment	Significant damage to several process units (>$200,000; <$2,000,000).
V	Personnel	Loss of one or several lives.
	Equipment	Plant fully damaged (>$2,000,000).

2.4. Estimating the explosion risk

The explosion risk is the product of the probability of an explosion occurring and its consequences. The risk level for explosions can be estimated from the matrix given in Fig. 6 below, based on the probability and consequence described in the above section and the definitions provided in Table 1. The risk level increases from E to A.

Table 2
Risk level – definitions and recommended acceptance criteria.

	Risk level	Acceptance criteria	Need for risk reducing measures (RRM)
A	Very high	Unacceptable	RRM must be implemented
B	High	Unacceptable	RRM must be implemented
C	Medium	Medium	RRM should be implemented
D	Low	Acceptable	RRM can be implemented
E	Very low	Acceptable	RRM are not required

Table 3
Example of table summarizing the assessment of probability and consequences of a dust explosion in a process unit.

Process unit	Probability of flammable atmosphere	Probability of ignition					Probability of explosion
Example		*Equipment (electric and mechanical)*	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flames and smoldering combustion*	
	IV	II	I	I	I	I	II

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	II	III	III	E	D
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	I	V	V	C	C
Comments: ***EXAMPLE***					

2.5. Acceptance criteria

The risk level and the "recommended acceptance criteria" are selected and based on the probability for human and economical loss according to Table 1. The selected criteria are given in Table 2. It should be emphasized that these acceptance criteria are proposed levels only, and alternate criteria may also be chosen.

2.6. Risk evaluation and risk reducing measures

Comparing the determined risk, which is based on the acceptance criteria, determined from the probability and consequence of an explosion as described above, one then decides whether risk-reducing measures are necessary. Risk-reducing measures imply reducing the probability of an event (going left in the risk matrix of Fig. 6), reducing the consequences (going down in the risk matrix) or a combination of probability and consequence-reducing measures (most effective method).

In the application example given in this document, the estimated probabilities and consequences are summarized in tables(see Table 3 for an example). These tables also include estimates of ignition source probability and of the risk of secondary incidents/events.

Process unit: The process unit the analysis applies to.
Probability: The estimated explosion probability is the product of the probability for "an explosive atmosphere" and "competent ignition source" (see Table 3).
Consequence: The consequences for an event, considering both personal injuries and damage to equipment. Both primary and

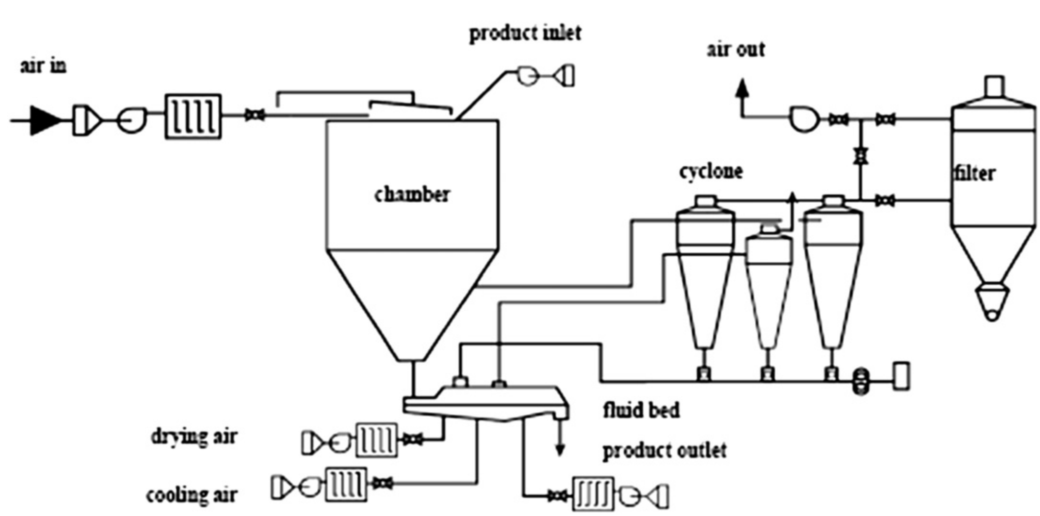

Fig. 7. Analyzed milk powder spray dryer installation.

Table 4
Explosion properties of milk powder (Beck, Glinke, & Mohlman, 1997).

Explosion property	Value
Maximum explosion pressure P_{max} (bar)	6–7
Dust explosion constant K_{St} (bar m/s)	80–130
Minimum ignition energy (MIE) (mJ)	>50
Minimum ignition temperature (MIT) (°C)	450–600
Lower explosion limit (LEL) (g/m^3)	60–150

secondary consequences are given. Definitions for explosion related probability (and consequences) are given in the above section (see Table 3).

Risk: This is the product of probability and consequence. Both the risks of primary and secondary events are estimated. See Table 2 for acceptance criteria.

Ignition source: Probabilities of occurrence of the five most common ignition sources are given (see Table 3).

3. Application example: a spray dryer installation for milk powder

To demonstrate the method an analysis is performed for a spray dryer installation used for drying milk powder (see Fig. 7). The total height of the spray dryer is 15 m, and the height of the cylindrical part is 6.3 m supported by a conical part (angle 60°). To move dried powder out of the conical part a pneumatic hammer has been provided. The temperature of the hot air to dry the milk slurry is 200 °C. The temperature of the air leaving the dryer is 90 °C. Based on air and product throughput, the average dust concentration in the dryer would be 30 g/m^3. The dried powder collected in the cone of the spray dryer is transferred into a fluidized bed for further drying or cooling. The powder taken along with the air flow out of the dryer is removed from the air by cyclones and a bag filter. Also the air from the fluidized bed is cleaned in cyclones and the bag filter. The dust collected in the cyclones is returned to the fluidized bed by pneumatic transport.

The described spray dryer installation has not been provided/equipped with any special preventive or protective measures. The installation is located inside a building. Personnel are around the installation only occasionally for inspection reasons.

3.1. Analysis

The analysis has been performed for the dryer only. To perform the risk analysis the explosion properties of milk powder need to be known. Although it is strongly preferred to have these properties determined for the milk powder in question, the present study was performed using literature data. This may lead to overly conservative preventive and protective measures resulting from the analysis, since one would normally base the analysis on the most conservative published values. On the other hand, an underestimate of the hazards may also be possible, especially for dusts where only a limited set of explosion properties is available. For milk powder, the use of literature data is acceptable since there is a rather large number of well-described data available, with little variation. The data found for milk powder are presented in Table 4 (Beck, Glinke, & Mohlman, 1997).

In addition to the properties presented in Table 4, it is known that milk powder stored in bulk might self-ignite when exposed to a higher temperature over a longer period. Tests have shown that storage at 80–90 °C for a period exceeding 20 h results in self-ignition (Le Maillard reaction).

3.1.1. Hazards identification

Under normal operating conditions the average dust concentration in the dryer is below the lower explosion concentration. Locally in the cone, however, one can expect that flammable concentrations can be reached intermittently. It has been demonstrated that an initial local explosion can whirl up dust present on the cone walls causing

Table 5
Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment.

Process unit	Probability of flammable atmosphere	Probability of ignition					Probability of explosion
		Equipment (electric and mechanical)	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flame and smoldering combustion*	
Spray dryer	V	I	I	I	I	III	III

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	III	IV	III	C	C
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	II	V	IV	B	C
Comments:					

Table 6
Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment after implementation of a CO-detection system.

<table>
<tr><th>Process unit</th><th rowspan="2">Probability of flammable atmosphere</th><th colspan="5">Probability of ignition</th><th rowspan="2">Probability of explosion</th></tr>
<tr><th rowspan="2">Spray dryer</th><th>Equipment (electric and mechanical)</th><th>Hot surfaces</th><th>Electric and electrostatic sparks and discharges</th><th>Mechanical sparks</th><th>Flame and smoldering combustion</th></tr>
<tr><td>V</td><td>I</td><td>I</td><td>I</td><td>I</td><td>II</td><td>II</td></tr>
<tr><td colspan="8">EXPOSURE TO EXPLOSION</td></tr>
<tr><td colspan="8">PRIMARY EXPLOSION</td></tr>
<tr><td colspan="2">Probability (injury/damage)</td><td colspan="3">Consequence</td><td colspan="3">Risk</td></tr>
<tr><td>Personnel</td><td>Equipment</td><td colspan="2">Personnel</td><td>Equipment</td><td colspan="2">Personnel</td><td>Equipment</td></tr>
<tr><td>II</td><td>II</td><td colspan="2">IV</td><td>III</td><td colspan="2">C</td><td>D</td></tr>
<tr><td colspan="8">SECONDARY INCIDENTS (inclusive explosions)</td></tr>
<tr><td>Personnel</td><td>Equipment</td><td colspan="2">Personnel</td><td>Equipment</td><td colspan="2">Personnel</td><td>Equipment</td></tr>
<tr><td>I</td><td>I</td><td colspan="2">V</td><td>IV</td><td colspan="2">C</td><td>D</td></tr>
<tr><td colspan="8">Comments: A CO-detection system has been included.</td></tr>
</table>

a stronger secondary explosion (Siwek et al., 2004). While all potential ignition sources were evaluated, mechanical sparks were not considered possible due to the ignition properties of the milk powder. Self-heating of the layers of milk powder was determined to be a possible ignition source. Layer accumulation is more frequent during anomalies associated with the rotating spraying wheel, distributing the milk slurry against the walls of the cylindrical part of the dryer. The hot drying air could cause the resulting milk powder cake to self-ignite. The smoldering material could then come loose and fall into the cone of the dryer, causing either ignition of a flammable dust cloud, or cause the flammable dust cloud by whirling up dust that subsequently ignites.

The probability of the latter is relatively high and, based on historical evidence, an explosion should be expected with a frequency between 10^{-1} and 10^{-2} per year (probability class III). Here it is assumed that the ignition source also causes the dust cloud (a smoldering cake of milk powder falling into the cone of the dryer).

Another ignition source could be an explosion originating in other parts of the drying installation and running back into the dryer. This ignition source, although very realistic, is not considered here because events originating in other pieces of equipment would only be included in a full risk analysis of the spray dryer installation. For the present example, it is assumed that sufficient preventive and protective measures are taken to prevent this from happening, i.e., the likelihood of this ignition source occurring is assumed to be sufficiently low.

The consequence of the explosion is most likely the failure of the dryer, potentially injuring personnel or even causing fatalities if in the vicinity of the dryer at that very moment (consequence classes III and IV respectively). Explosion tests reported by Siwek et al. (2004) show that pressures up to 1 bar are possible, under somewhat conservative conditions. Moreover there is a possibility that the explosion propagates into the fluid bed or the cyclones, and into the bag filter (secondary incident). This probability is however lower than the probability of an explosion (probability class II). The consequences are however more severe: loss of the plant (consequence class IV) and most likely loss of one or more lives (consequence class V).

The analysis is summarized in Table 5. The table also determines the risk based on the various probabilities and associated consequences.

3.1.2. *Risk evaluation*

The results of the analysis of the spray dryer are summarized in Table 5. The table shows that the risks are either medium (implying that risk reducing measures should be implemented) or high

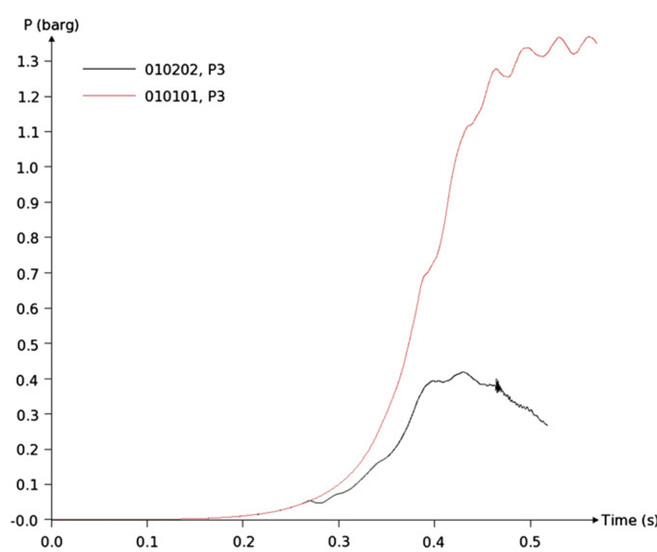

Fig. 8. Pressure in dryer with pressure relief panel (black) and without pressure relief panel (red). Note relief panel opens at approximately 0.25 s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

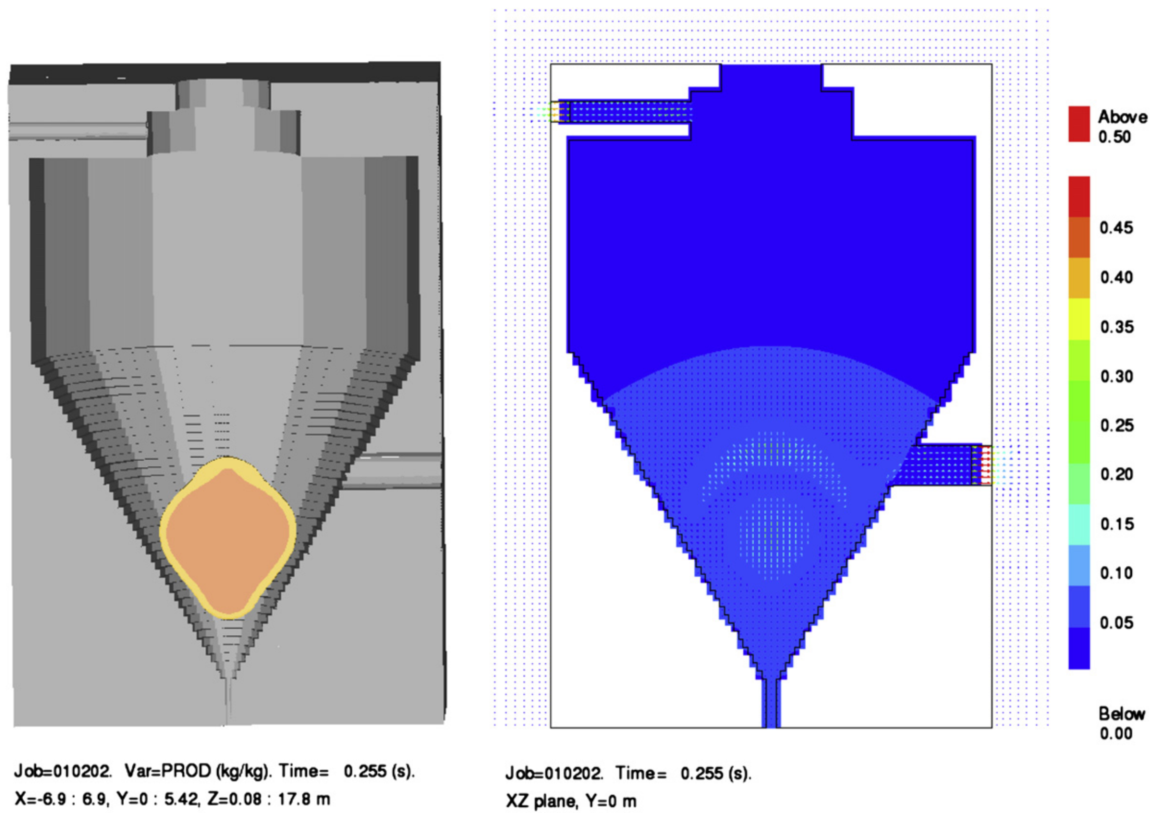

Fig. 9. Flame extent (left) and pressure [in bar] & velocity vectors (right) just before panel opens.

(implying risk reducing measures must be implemented). Hence two alternatives are investigated: one where a single preventive measure is introduced, reducing the probability of explosions, and a second where this preventive measure is combined with protective measures.

3.2. New analysis investigating the introduction of preventive measures

To reduce the probability of explosions from occurring, it is proposed to introduce a carbon monoxide-detection system. Smoldering results in the generation of carbon monoxide (CO) due to incomplete combustion. A CO-detection system could warn the operator of ongoing smoldering before a hazardous situation arises (Steenbergen, Van Houwelingen, & Straatsma, 2007). A new analysis has been performed of the explosion risks of the spray dryer including this preventive measure.

3.2.1. Hazard identification

The introduction of a CO-detection system will reduce the probability of an explosion. An early detection of smoldering combustion is assumed to reduce the probability of explosions by at least a factor of 10 implying a class II probability of explosion. The probability of equipment being damaged and personnel being affected will be reduced accordingly for both primary and secondary incidents. The consequences are however still similar. This results in risks as summarized in Table 6.

3.2.2. Risk evaluation

Table 6 shows that risks have been reduced by introducing a CO-detection system as compared to Table 5, presenting the original risks without any preventive or protective measures.

The remaining risks for personnel, which are described as medium according to the acceptance criteria proposed in Table 2, should be addressed by introducing further risk reducing measures. As described in Section 3.1, an additional analysis is presented where the preventive measure of CO-detection is combined with protective measures. A combination of explosion venting and explosion isolation by extinguishing barriers between the dryer and fluidized bed, and the dryer and the cyclones is investigated.

3.3. New analysis investigating the introduction of preventive measures in combination with protective measures

Reducing the probability of an explosion by introducing CO-detection alone still leaves personnel exposed to a medium risk. Hence additional protective measures are proposed. The effects of introducing a combination of explosion venting and explosion isolation (extinguishing barriers) have been investigated.

The probability of explosions, assuming an early detection of smoldering combustion is implemented as described in Section 3.2, is considered to be probability class II. The consequences of possible explosions are, however, reduced considerably. Assuming use of appropriate venting devices, sufficient venting surface, taking into account the effect of vent ducts (which are necessary since the spray dryer is installed inside a building) and adequate installation distances for the extinguishing barriers (containing sufficient extinguishing powder to extinguish flames), the risk of explosion in the spray dryer can be reduced considerably. For example, advanced CFD explosion models (to be discussed in detail in Section 4) can provide assistance in quantifying the reduction in explosion consequences for complex dust handling equipment.

Using the Dust Explosion Simulation Code (DESC) CFD software, an analysis was conducted to optimize the size and possible configuration of the vent on the spray dryer. The present example shows the spray dryer both with and without a pressure relief panel located on top of the dryer with an opening pressure of 50 mbar. The

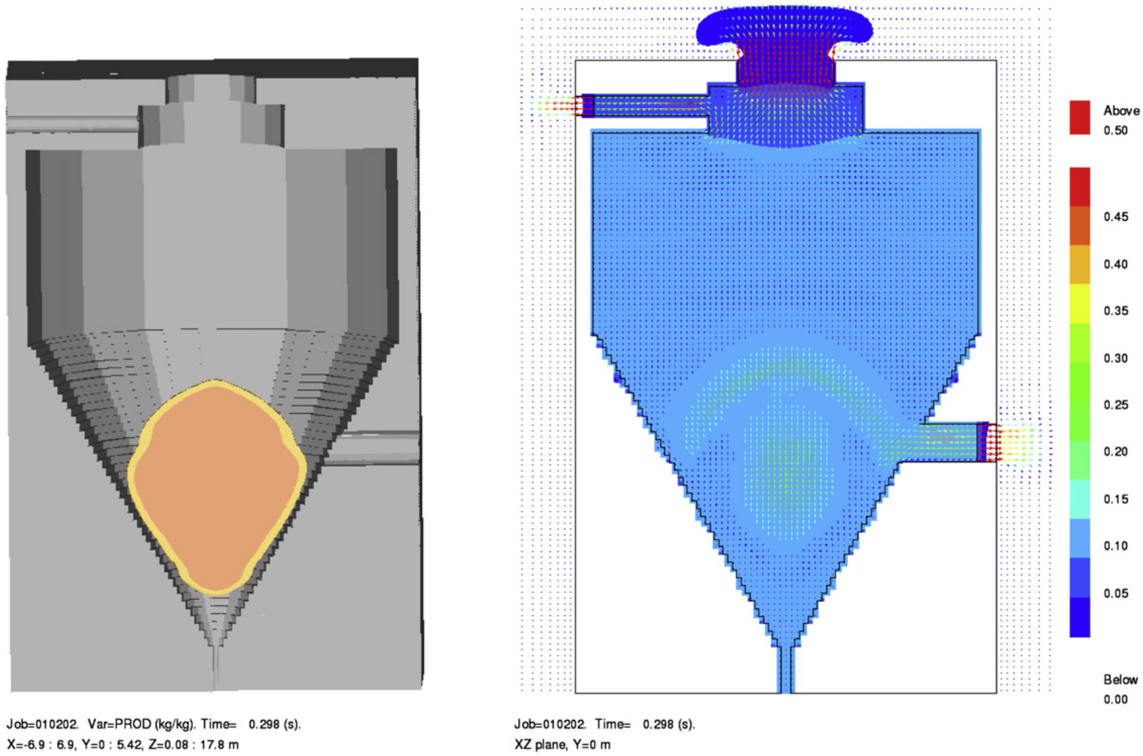

Fig. 10. Flame extent (left) and pressure [in bar] & velocity vectors (right) after panel opens.

dust cloud was assumed to only fill the lower section of the cone and the explosion properties used in the simulation were based on the literature values of a milk powder with a K_{st} value of 100 bar-m/s. In this example, one simulation was conducted without the pressure relief panel and demonstrated the explosion pressure within the dryer would be slightly in excess of 1 bar, while the second simulation showed a significant reduction in overpressure with the top panel opening at 50 mbar (see Fig. 8). This is due to the venting of the gases within the dryer as the dust cloud continues to burn (see Fig. 9 and Fig. 10), thus relieving the overpressure within the dryer.

Table 7
Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment after implementation of a CO-detection system in combination with explosion venting and explosion isolation toward fluidized bed and cyclones.

Process unit	Probability of flammable atmosphere	Probability of ignition					Probability of explosion
Spray dryer		*Equipment (electric and mechanical)*	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flame and smoldering combustion*	
	V	I	I	I	I	II	II

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	II	I	I	E	E
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	I	I	I	E	E
Comments: A CO-detection system has been included combined with explosion venting and isolation.					

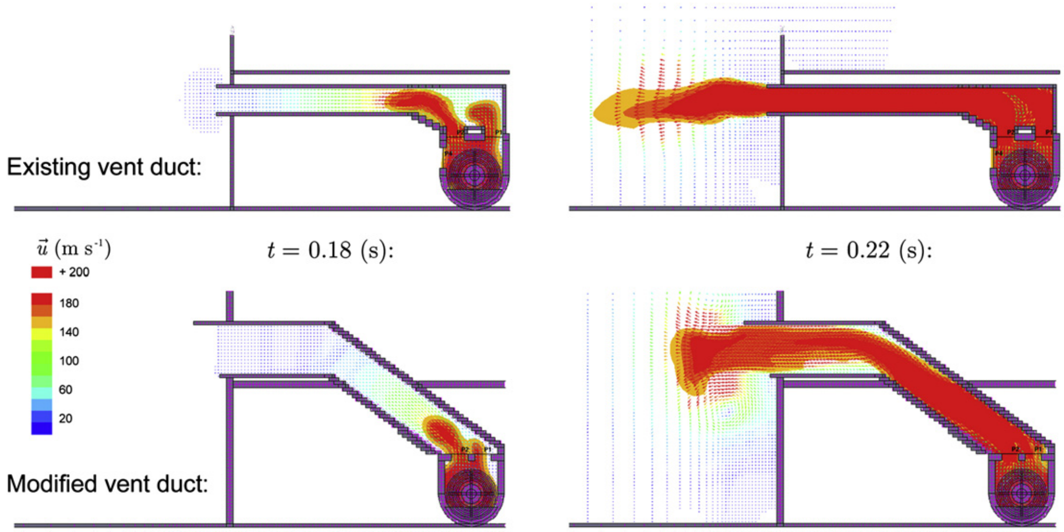

Fig. 11. Example of simulations performed with DESC investigating the effect of the shape of a vent duct on explosion loads generated in a vented dryer due to dust explosions originating inside.

The consequences of an explosion are now reduced to limited or no damage both for the primary and secondary events (consequence class I).

3.3.1. Risk evaluation

Introducing explosion protective measures as described reduces the risks both for the equipment and personnel to acceptable levels. The reduction of consequences to consequence class I (replacement of vent panels and refilling of extinguishing barriers [neglecting the costs of loss of some produced milk powder]) results in risk levels E implying that no further measures would be necessary. Results of the analysis have been presented in Table 7.

4. Dust Explosion Simulation Code (DESC)

DESC is a CFD-tool that can simulate the course of industrial dust explosions in complex geometries. DESC was developed by GexCon as part of a project supported by the European Commission. Apart from GexCon, there were 10 main participants in the project with additional contributions from three other participants. DESC can be a valuable tool for engineers designing powder-handling plants, especially when optimizing mitigation measures such as venting devices, suppression systems or explosion barriers. For the example provided in Section 3.3, various explosion vent configurations can be evaluated in a manner that takes into account equipment details such as duct lengths, as well as a given dust reactivity. Fig. 11 shows an example of how explosion vent designs, including duct configuration, were evaluated for an indoor piece of equipment.

In the approach adopted, dust explosion properties from standardized tests are used as input to the combustion model. Papers have been published on the DESC project (Skjold, Arntzen, Hansen, Storvik, & Eckhoff, 2006; Skjold et al., 2005; Skjold & Hansen, 2005) and a review of the DESC project has been published in Journal of Loss Prevention in the Process Industries (Skjold, 2007). The DESC simulations include:

- Realistic representation of industrial process plants
- Most kinds of explosive dusts used in industry
- Input from standardized tests in a 20-L sphere
- Flame propagation and rate of pressure rise
- Effect of varying the ignition position
- Prediction of external blast waves
- Dust lifting by flow or shock waves
- Identifying worst-case explosion scenarios
- Pressure-piling in interconnected vessel systems
- Extensive options for output of results, including 2D and 3D-plots
- Fast acting valves triggered by sensor points
- Vent panels triggered by internal pressure

5. Conclusions

A semi-quantitative short-cut risk analysis method (SCRAM) has been presented, allowing for the assessment of dust explosion risks and choosing adequate preventive and protective measures. The performance of such an analysis makes industry aware of the most hazardous areas in their facilities and associated consequences in case of an explosion.

The application example demonstrates the strength of the method and the support it offers to industry for choosing appropriate risk mitigating measures. In addition, an advanced tool (DESC) is discussed, which can greatly help engineers designing powder-handling plants, especially when optimizing mitigation measures such as venting devices, suppression systems or explosion barriers.

References

Beck, H., Glinke, N., & Mohlman, C. (1997). *BIA-report: combustion and explosion characteristics of dust, HVBG*. Berufsgenossenschaftliches Institut für Arbeitssicherheit. BIA 13/97.

Siwek, R., van Wingerden, K., Hansen, O. R., Sutter, G., Schwartzbach, Chr., Ginger, G., et al. (May 31–June 3, 2004). Dust explosion venting and suppression of conventional spray driers. In *Eleventh international symposium on loss prevention, Prague*.

Skjold, T. (2007). Review of the DESC project. *Journal of Loss Prevention in the Process Industries, 20*, 291–302.

Skjold, T., Arntzen, B. J., Hansen, O. J., Storvik, I. E., & Eckhoff, R. K. (2006). Simulation of dust explosions in complex geometries with experimental input from standardized tests. *Journal of Loss Prevention in the Process Industries, 19*, 210–217.

Skjold, T., Arntzen, B. J., Hansen, O. R., Taraldset, O. J., Storvik, I. E., & Eckhoff, R. K. (2005). Simulating dust explosions with the first version of DESC. *Process Safety and Environmental Protection, 83*(B2), 151–160.

Skjold, T., & Hansen, O. R. (2005). The development of DESC – a dust explosion simulation code. In *International ESMG symposium, 11–13 October 2005* (pp. 24), Nuremberg, Germany.

Steenbergen, A. E., Van Houwelingen, G., & Straatsma, J. (2007). System for early detection of fire in a spray drier. *International Journal of Dairy Technology, 44*(no. 3), 76–79.