PROBABILISTIC RISK ASSESSMENT IN COMBINATION WITH CFD MODELLING OF BIOMASS DUST EXPLOSIONS WITHIN LARGE BULK STORAGE VOLUMES

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The number of power-generation projects adopting co-firing with biomass is increasing. Such projects often require very large storage areas, prescribing silos/storage capacities in excess of 10,000 m^3 and in some cases exceeding 100,000 m^3.

International standards for explosion relief design (*e.g.* EN 14491:2006, NFPA 68) have largely been developed for conventional process vessel volumes of less than 10,000 m^3. Empirical calculations are typically used to determine the suitable vent areas required to achieve explosion protection in the event of an internal incipient explosion. Such methods are often not suitable for these massive bulk biomass stores and if used may impose excessively conservative explosion protection requirements with significant economic penalties.

Using a probabilistic analysis approach of potential dust cloud dispersion, dust cloud size within the storage volume assisted by modelling of an incipient explosion using differing turbulence length scale following flow modelling and varying ignition locations using validated dust explosion CFD codes provides a more realistic design approach to establish a suitable basis of safety using significantly less explosion relief area than would be suggested by empirical calculations. More focus and economical weight can then be applied to more proactive preventative measures to reduce the probability of flammable atmospheres and or effective ignition sources whilst demonstrating ALARP in relation to explosion safety.

The paper demonstrates potential reduced explosion protection requirements for an example study in which vent relief design calculations are performed both empirically and using CFD modelling to protect a silo in excess of 100,000 m^3 for a typical Biomass dust explosion risk.

A semi-quantitative probabilistic assessment of the risk using qualitative values for probability and consequence will also be discussed which can be used for the combined analysis of a whole processing facility; this method is known as SCRAM (Short Cut Risk Assessment Method).

INTRODUCTION

Biomass can be one of the most cost-effective forms of renewable energy. As such, the number of power-generation projects adopting biomass is increasing significantly. AEA (2011) estimate that by 2020 biomass could meet 20% of the UK energy demand, with this figure more than doubling by 2030.

Biomass power-generation schemes often require very large storage areas. Silos can have capacities exceeding 60,000 tonnes and 100,000 m^3.

Due to the organic dust generated on filling and emptying such silos, the risk of an explosible dust cloud forming within the enclosed volume is very likely. Dust explosion risks prevailing in industrial facilities are dependent on a large variety of factors that include process parameters, such as pressure and temperature; equipment properties, such as the presence of moving elements, the mechanical strength of such equipment and the presence of effective dust handling equipment (known as local extract ventilation or LEV); the dust explosion characteristics (does it require a little energy or a lot of energy to ignite, does it propagate flame rapidly); and mitigating measures taken including ignition detection and suppression and constructive protective measures such as explosion relief venting combined with effective explosion isolation to mitigate the propagation of an explosion through other parts of the process.

To properly assess such risks a rigorous systematic method is required. One such method is the semi-quantitative short-cut risk analysis method (SCRAM). SCRAM allows for a thorough assessment of primary and secondary explosion risks to personnel (as required by law ATEX137/DSEAR) and for the plant/business (exposure to large losses/insurance underwriting) for each section of a combined process. Hence making the plant owner aware of the most hazardous areas in their facilities and allowing an acceptable risk to be established.

As part of the risk assessment the consequence of a dust explosion needs to be determined – *i.e.* the maximum overpressure possible within the silo compared to its strength. International standards for dust explosion protection determining over pressures in enclosures protected with explosion relief panels (*e.g.* EN 14491:2006, NFPA 68) are based on empirical data. Hence, the methods presented to determine the suitable area for explosion relief are only applicable over a given region of the parameter space. In particular, they are only proven for vessels with volumes less than 10,000 m^3 and are generally not suitable for massive bulk-biomass stores. If used, these methods often impose excessively conservative explosion protection requirements with the associated economic penalties. As an alternative to the empirical formulations presented in the standards, computational fluid dynamics (CFD) codes may be used. The Dust Explosion Simulation Code (DESC, see Skjold, 2007) is a CFD tool developed to simulate dust explosions.

Herein, SCRAM and DESC are briefly summarised. A case study of a typical biomass silo is then presented illustrating their use. The results of the DESC simulations are also compared to those predicted by the methods presented in the standard EN 14491:2006.

OVERVIEW OF METHODS

SCRAM

The risk of a dust explosion is the product of the probability of a dust explosion occurring and the consequences of the dust explosion. The consequences are divided into primary consequences such as failure 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.

The probability of an explosion occurring depends on the probability of an effective ignition source and the probability of an explosive atmosphere. The probability of an explosion will be the product of these two probabilities (as long as the two are generated independently from each other). SCRAM categorises the probability into five classes ranged from '*I*' to '*V*', where '*I*' has the lowest probability ('very unlikely') and '*V*' has the highest probability ('very likely').

Similarly, the consequences of a dust explosion to both personnel and equipment are categorised into classes ranging from '*I*' ('Marginal damage to process units. Process shut down. No injuries') to '*V*' ('Plant fully damaged. Loss of one or several lives').

Table 1 shows the breakdown of these categories.

The probability of an explosion and the consequence are combined using a risk matrix (Figure 1) to determine a risk level ranging from 'Very High (*A*)' to 'Very Low (*E*)'.

DESC

DESC (Dust Explosion Simulation Code, see Skjold, 2007) is a CFD simulation tool that predicts the potential consequences of industrial dust explosions. DESC is based on the CFD-code FLame ACceleration Simulator (FLACS). A three-dimensional grid is made for the preferred simulation volume forming small grid cells (control volumes). Based on the geometry, fuel (dust type) and other key parameters, DESC calculates (for example) the pressure, temperature and dust concentration in each control volume at each time step (solving the equations of mass balance within a Cartesian grid covering the whole process vessel domain inside and outside). Hence, DESC can be used to determine the maximum pressures realised for any size and shape of silo containing any size and shape of dust cloud and the pressures, flame velocities, densities, drag forces on steel members and the far field pressures on external point sources can thus be evaluated in detail.

CASE STUDY

A case study is presented to illustrate the use of SCRAM and use of DESC to determine the required explosion relief venting for massive bulk biomass stores. The results of DESC are compared to those predicted by the standard EN 14491:2006.

We consider a large silo (with volume 101,000 m^3) representing a typical biomass store. The silo is designed to store wood pellets and is filled via a carousel chute from the top and emptied from the base. It is able to withstand overpressures up to 0.3 barg. Figure 2 shows the silo considered.

To reduce effective ignition probability at the base of the silo caused by a thermite reaction (nonferrous/light metals falling to the base of the silo with high velocity and striking a rusty surface) an impact zone covering the centre of the floor has been defined and no mild steel parts will be allowed within this area, all parts within this area will be constructed of stainless steel. All equipment within designated zoned areas will be ATEX approved according to the correct equipment category and temperature class thus reducing the probability of effective ignition from mechanical and electrical equipment.

All feed chutes delivering product into the silo are installed with ignition detection and mist suppression systems to reduce the probability of smouldering material being transferred into bulk storage.

Each silo has 3D pile temperature monitoring and CO gas-monitoring systems installed to detect the onset of smouldering ignition at the earliest stage. Nitrogen purge (first response), CO_2 fire suppression (second response) and water deluge (final response) systems are installed which can be deployed upon detection of an event (smouldering) or established fire within the store.

It is known that if wet biomass is stored for long periods it will start to decompose and generate exothermic activity leading to heat gain within the stored pile quicker than heat can be lost to the surroundings, thus leading to smouldering combustion and ultimately flaming combustion when the smouldering reaches the pile surface as the gases due to pyrolysis mix with the surrounding oxygen and combust. Various procedures can be adopted such as stock rotation to prevent heat build-up and emergency extraction of product if exothermic activities are identified. Although a fire within these large silos is a probable event during the lifetime and explosion is still considered a low probability with potential high consequence.

To reduce the maximum pressure realised during an explosion event provision is made for an array of 4 m high explosion relief vents (set to open when the pressure increases above $p_{stat} = 0.1$ bar) to be installed around the circumference of the silo near its top. DESC explosion modelling has been performed to evaluate a conservative (worst)

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Table 1. Definition of probability and consequence classes in SCRAM

Probability of the formation of an explosive atmosphere				
Range, D_a	**Description**			
1	Very unlikely			
2	Unlikely			
3	Somewhat likely			
4	Likely			
5	Very likely			
Probability of the formation of an effective ignition source				
Range D_i	**Description**			
1	Very unlikely			
2	Unlikely			
3	Somewhat likely			
4	Likely			
5	Very likely			
Probability for an explosion to occur				
Range D_e	**Description**	**Definition**	**Probability for incident during 1 hour**	
1	Very unlikely	<1/ 10000 per year	1.14E-8	0.000000114 % per hour
2	Unlikely	>1/10000 per year<1/100 year	1.14E-6	0.0000114 % per hour
3	Somewhat likely	>1/100<1/10 per year	1.14E-5	0.00014 % per hour
4	Likely	>1/10 year<1 per year	1.14E-4	0.0114 % per hour
5	Very likely	>1 per year	>1.14E-4	>0.0114 % per hour
Consequence for personnel and equipment				
Range D_p D_e	**Description**	**Definition**		
1	Personnel	No injury.		
	Equipment	Marginal damage to process units. Process shut down.		
2	Personnel	Limited injury.		
	Equipment	Damage to process unit (<£10, 000).		
3	Personnel	Personnel injury.		
	Equipment	Process unit collapse and possible damage to corresponding units (>£10, 000; < £100, 000).		
4	Personnel	Serious personnel injury, possible loss of life.		
	Equipment	Significant damage to several process units (>£100, 000; <£1, 000 000).		
5	Personnel	Loss of one or several lives.		
	Equipment	Plant fully damaged (>£1, 000 000).		

Consequence					
5	C	B	A	A	A
4	D	C	B	A	A
3	E	D	C	B	A
2	E	E	D	C	B
1	E	E	E	D	C
	1	**2**	**3**	**4**	**5**
	Probability				

Figure 1. Risk matrix

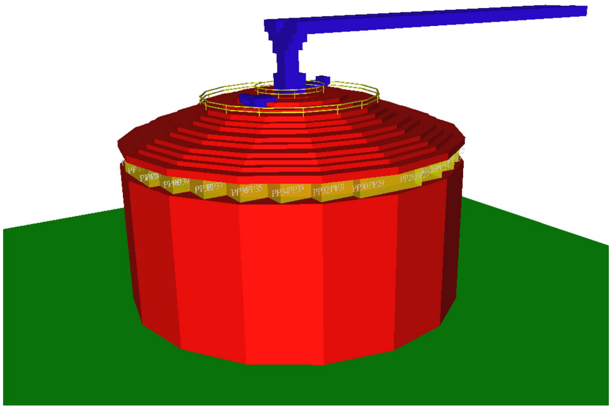

Figure 2. The ‘typical’ biomass silo considered herein. The silo is filled from a single point in the top (coloured blue) and includes explosion relief venting around its circumference (coloured yellow)

case probabilistic incipient explosion originating within the silo from an ignition source at the base. This has evaluated the efficacy of explosion-relief burst membranes to provide sufficient vent area to allow the rapid combustion from a deflagration to continue to expand externally thus achieving the required reduced explosion pressure ($p_{red} = 0.3$ barg) within the silo.

SCRAM

The first stage of SCRAM is to determine the probability of an explosion. As the silo is designed to store wood pellets the probability of a wood dust cloud and hence a flammable atmosphere is ‘likely’. It is reduced from ‘very likely’ as the silo is to be carefully filled using a chute.

A range of measures as discussed above are in place to reduce the probability of various ignitions sources, hence the probability of the formation of an effective ignition source is rated at ‘somewhat likely’.

This results in the probability of an explosion (the product of probability of explosive atmosphere and product of effective ignition source) being ‘somewhat likely’ (*i.e.* 0.01 – 0.1 year^{-1}).

The second stage of SCRAM is to determine the consequence of an explosion event. As the area around the explosion vents and the silo inside is restricted access

Table 2. Summary of risk assessment for silo considered herein

Process Unit	**Probability of flammable atmosphere**	**Probability of Ignition**					**Probability of explosion**
Biomass Storage Silos		*Equipment (Electric and mechanical)*	*Hot surfaces*	*Electric and Electrostatic sparks and Discharges*	*Mechanical sparks*	*Flames*	
	4	1	1	1	1	3	3

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
2	3	2	3	E	C
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
1	2	2	4	E	C

Comments

- Explosible dust clouds are only expected in smaller local areas within the silo, hence the whole volume will unlikely to be filled with a homogenous dust cloud.
- Smouldering ignition leading to a fire within the silo is considered likely during the life of the silo.
- Personnel will be prohibited from the area above each silo during a filling activity.
- Explosion protection is provided by proprietary explosion relief.
- In the event of an explosion, the explosion relief panels would need to be replaced and the cost of this would be in excess of £10,000 and possibly less than £100,000 thus a grade 3, resulting in a medium risk rating for equipment.
- In the event of a post explosion fire within the silo the damage caused could result in a cost in excess of £100,000 hence a consequence grade of 4 which produces a risk grade of C.

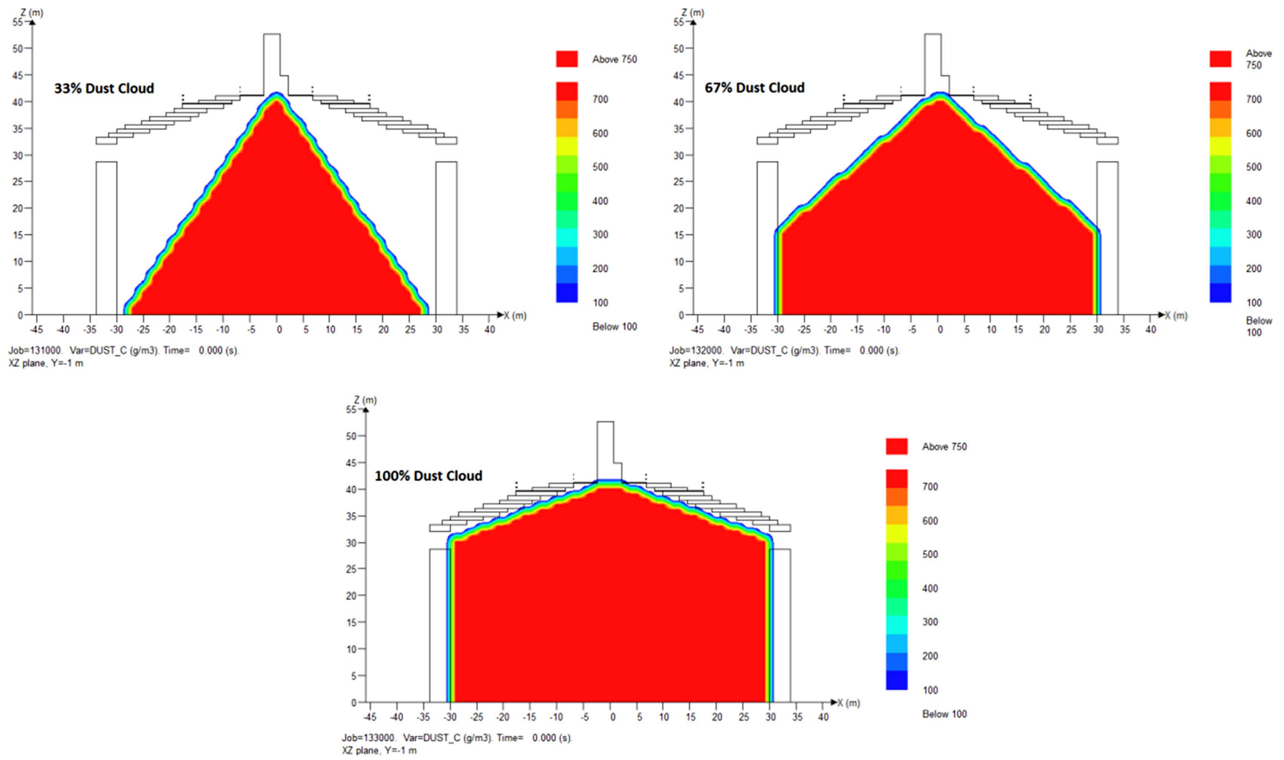

Figure 3. The initial dust clouds considered.

(unmanned), the probability of personal being effected by the primary event can be assumed to be less than the probability of an explosion itself. The probability of the silo being effected by the primary event is the same as the event occurring. Explosion protection is installed to the silo; hence during the primary explosion event no damage should occur to the silo itself and personal injury would be limited. Instead the costs would be associated with replacing the explosion relief panels and potential plant shutdown. This is expected to be in the range £10,000 – £100,000. Should the event be allowed to escalate to a secondary event albeit with a lower probability of the primary event, a fire may be expected). This could result in a higher economic cost due to the shear scales of these large bulk stores and the combined cost to fight the fire, replace the explosion panel being in excess of £100,000 a grade 4 equipment consequence (*i.e.* £100,000 – £1,000,000).

Table 2 shows a summary of the SCRAM assessment for the case described and shows a low risk (E) to personnel and medium risk to equipment (C) for the silo design as proposed.

DESC

To determine the effective relief venting area required analysis was conducted using DESC. A range of scenarios are considered to determine the realistic overpressure expected during an explosion event. The scenarios are characterised by the dust cloud, turbulence and ignition location.

Dust Cloud

A wood dust cloud will be created on filling and emptying of the silo. Typical values were used to characterise the explosive properties of the dust (*i.e.* K_{st} = 142 bar m s^{-1} and p_{max} = 8.9 bar). It was assumed the concentration of the dust cloud was 750 g m^{-3} representing a worst case scenario.

The wood dust cloud will fill a given fraction of the internal volume of the silo. Three filling fractions were considered 33%, 67% and 100%. Figure 3 shows schematics of the initial dust clouds considered.

Note that the methods presented in EN 14491:2006 do not allow for the variation of parameters such as cloud size, turbulence level and ignition location. Instead they are designed to calculate vent areas for a general scenario that is appropriate to a wide range of applications – *i.e.* an enclosure completely filled with a turbulent dust cloud of optimum concentration.

Table 3. Parameters characterising the turbulence levels considered

Turbulence Level	Characteristic Velocity (m/s)	Turbulent Length Scale (m)	Turbulent Intensity
Low	1	0.04	0.02
High	1	0.25	1

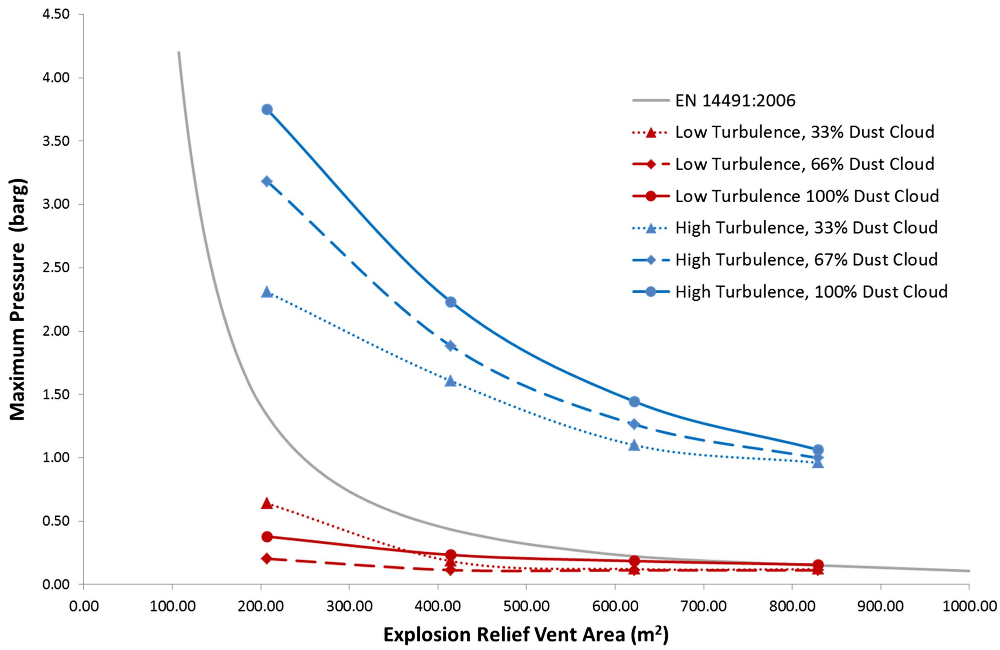

Figure 4. Maximum pressure realised for each of the scenarios considered

Turbulence

The initial level of turbulence is a critical factor in the evolution of an explosion – higher levels of turbulence may result in a higher degree of flame folding and faster flame acceleration leading to higher overpressures. The initial level of turbulence will be determined by the method of filling the silo. Dropping the wood pellets from multiple points at the top of the silo will likely result in a highly turbulent atmosphere. Conversely, placing the wood pellets in the silo without dropping them (via a carousel chute for example) will result in an atmosphere with significantly lower turbulence. To capture these filling methods, two initial levels of turbulence were considered throughout the silo – high turbulence and low turbulence. Table 3 lists the key parameters characterising the respective turbulence levels.

Note that EN 14491:2006 does not allow for differing levels of turbulence.

Ignition Location

Maximum pressures are realised when the explosion is able to propagate over the largest possible distance (i.e. the longest path for flame to propagate before it reaches the explosion vents and can expand freely outside the volume). Hence, to represent a worst case, the cloud was ignited in the centre at the base of the silo.

Note that EN 14491:2006 does not allow the ignition location to be specified.

Results

Figure 4 plots the maximum pressure realised within the silo for each of the scenarios considered. The maximum pressure varies significantly dependent on the initial turbulence levels – very high levels of turbulence can result in pressures an order of magnitude higher than in low turbulence scenarios.

Some of the latest biomass stores are designed with controlled filling methods such as carousel chutes to reduce the breakdown of material during filling. This means that one would expect any dust cloud formed to be relatively small (local to the delivery onto the pile) and the turbulence levels in the internal vessel domain to remain low.

Compared to the low turbulence scenario simulated with DESC, EN 14491:2006 significantly over-predicts the explosion relief vent area required. For the allowable maximum pressure ($p_{red} = 0.3$ barg), EN 14491:2006 requires a vent area of 521 m^2. The most conservative DESC simulation suggests that a vent area of 350 m^2 would be sufficient (see Figure 5). Hence, EN 14491:2006 over-predicts the required vent area by around 1.5 times. For the case study considered herein, this could represent an additional cost of proprietary explosion vent panels alone of over £50,000 (estimated £300/m^2 vent area), taking into consideration installation costs and future maintenance this figure could easily be £150,000 difference. Note that, for this case study, the most conservative scenario is counter-intuitively the 33% dust cloud[1]. This highlights the importance of considering a wide range of scenarios in the analysis.

At the detailed design stage, the above study could be expanded for value-engineering purposes to predict the consequence of a dust explosion for a wider range of scenarios. For example, multiple ignition locations might be

[1]This may be because the larger dust clouds are compressed once an explosion events starts and concentrations of dust increase to levels that are sub-optimum for explosion propagation.

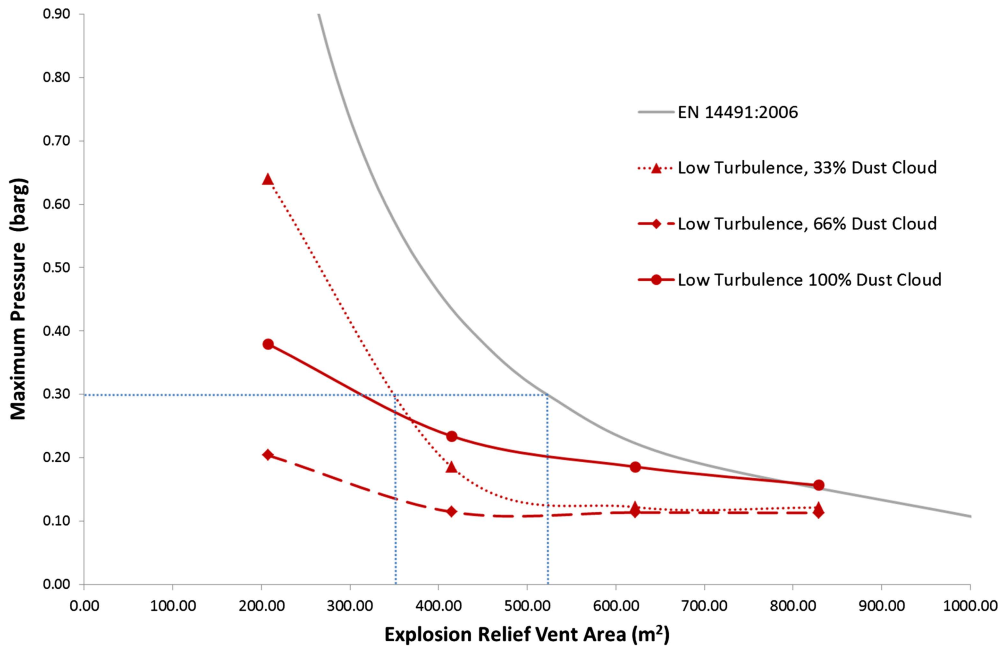

Figure 5. Maximum pressure realised for each of the scenarios considered

considered. The filling of the silo might be explicitly modelled in DESC to determine the likely dust cloud size and concentration and the resulting turbulence levels. By considering a representative sample of all the possible scenarios, the probability that the overpressure in the silo will exceed its design value can be estimated and suitable explosion protection can be determined on an economical basis with the justification recorded within the SCRAM assessment thus achieving a robust basis of safety while demonstrating ALARP (As Low As Reasonably Practicable).

CONCLUSIONS

Methods associated with assessing the risk of explosions with a large biomass silo (SCRAM) and the designing of the explosion relief venting (DESC) have been discussed. A case study has been presented to illustrate these methods.

The case study presented herein highlights that, while the international standards such as EN 14491:2006 may provide indicative first estimates for the relief venting of large biomass stores, advanced techniques, such as DESC Computational Fluid Dynamic modelling, can provide explosion protection designs much more appropriate for the application of interest.

By using more refined analysis techniques, one may show that the vent area required to adequately protect a silo is significantly smaller than that predicted by EN 14491:2006, for example. This can provide significant economic benefits.

Reducing the explosion relief vent area to a minimum while maintaining effective protection also has advantages over the working life time of the silo. A reduced explosion relief vent area corresponds to a reduced chance of a mechanical failure of the panels and a reduced maintenance cost. The probability of water ingress (which as discussed above is a real threat to bulk biomass stores) into the silo is also reduced.

Savings made through this type of value engineering can be redistributed to afford other constructional prevention methods within the process, which ultimately continue to drive the overall residual risk lower within the essence of improving the safety of personnel and protecting the plant and business.

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