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Sensitivity Analysis of Dust Explosion Consequences in a Roller Mill using FLACS-DustEx

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The current study is a continuation of the work reported by Wingerden et al. (2011). Dust explosion experiments were performed in a roller mill (capacity 36 metric tonnes coal/hour; internal volume 23.2 m^3) connected to a coal feeder located on top of the mill. Coal and wood dust clouds were generated in the mill/coal feeder combination by pneumatic injection. The concentrations investigated were however not chosen to be optimal: instead lean dust-air mixtures were investigated. The presented results are those of a sensitivity analysis using optimal dust-air mixtures. The investigation was performed with the FLACS-DustEx CFD tool: a dedicated tool for simulating the course of dust explosions in complex geometries. The following parameters were varied: type of dust, ignition source location, ignition delay time (assuming pneumatic injection) and vent opening size. The sensitivity study indicates the maximum explosion pressure that can arise in a roller mill when conditions are chosen to be optimal/worst case.

1. Introduction

Nowadays, biomass is developing into an important source of energy due to its significant potential of reduction in carbon dioxide emission compared to the fossil fuels. In the span of renewable energies, biomass is the only one with hydrocarbon basis and because of its higher volatile content resulting in a different combustion profile (Li et al., 2016). Biomass fuels such as wood pellets and straw are ground in a mill before combustion. The grinding of biomass however represents a significant dust explosion hazard. Dust explosion has the potential to result in considerable damage to the power plant and injuries or fatalities among power plant personnel. (Eckhoff, 2003; Amyotte, 2013).

A wide variety of parameters influence the explosion violence of the dust clouds. Substantial efforts have been invested in experimental investigations aiming at developing empirical relationships to design explosion venting, explosion suppression and explosion isolation (Bartknecht, 1993; Eckhoff, 2003). An increase of the level of complexity in the geometry of interest, the reliability and performance of engineering models, which rely on simplified empirical relations, will dramatically decline. This necessitates the need for applying computational fluid dynamics (CFD) as an important candidate for the design (Skjold, 2007; Skjold, 2014).

The outstanding advantage of using CFD models in the study of dust explosions is that they use fundamental principles of physics such as conservation of mass, momentum and energy for describing dust explosion propagation under laminar and turbulent flow conditions in complex geometries.

In the present study, the complex geometry of the roller mill used by van Wingerden et al. (2011) was modelled in the CFD tool FLACS-DustEx and a sensitivity analysis is performed. Van Wingerden et al. (2011) performed a series of dust explosion experiments in a roller mill (capacity 36 metric tonnes coal/hour; internal volume 23.2 m^3) connected to a coal feeder located on top of the mill. Coal and wood dust clouds were generated in the mill/coal feeder combination by pneumatic injection. The concentrations investigated were however not chosen to be optimal: instead lean dust-air mixtures were investigated. The current investigation therefore aimed at determining what could happen in the roller mill when dust cloud concentrations would have been chosen to be optimal. The investigation was performed with the FLACS-DustEx CFD tool. The presented results are those of a sensitivity analysis varying the following parameters: type of dust, ignition

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source location, ignition delay time (assuming pneumatic injection) and vent opening size. The sensitivity study indicates the maximum explosion pressure that can arise in a roller mill when conditions are chosen to be optimal/worst case.

2. Roller mill

The experiments described by van Wingerden et al. (2011) were performed in a "Loesche LM 18" roller mill consisting of a mill chamber, a classifier and “a top” with coal feeder pipe and coal dust pipes. The internal volume of the mill is formed by the lower, cylindrical part of the mill (the mill chamber, volume 8.4 m^3) and the upper conical part (containing the classifier, volume 12.0 m^3). The coal feeder pipe and the coal dust pipes mounted at the top of the mill represent an additional volume of 2.8 m^3 resulting in a total internal volume of the mill of 23.2 m^3. To simulate the effect of a coal feeder, a “dummy feeder” was installed at the top of the mill. The dummy feeder was a rectangular vessel of 5.1 m^3 capacity.

The mill table in the bottom of the mill chamber, has a diameter of 2000 mm. There is an open clearance of approximately 70 mm between the table and the surrounding wall. In the top of the mill there are three coal dust outlets of 550 mm diameter. After a 90º bend, each of these outlets end up in two pipes of smaller diameter (coal dust pipes with diameter d = 384 mm). The length of the 384 mm pipes were approximately 2 meters. In real power plants the pipes lead the fine dust produced in the mill to the burners and could be up to 60 m long. To simulate the resistance of the pipes a diaphragm was installed at the end of the pipe blocking the cross section by 80 %.

The dummy feeder (5.2 m long, 1.1 m wide and 0.9 m high) was connected to the mill via the coal feed pipe. At the top of the opposite end of the feeder, an opening (0.27 m^2) was installed to simulate the connection to a coal silo. The opening size could be varied to simulate the effect of a completely or partly filled coal silo.

Also parts of the original pair of primary air ducts were fixed to the mill foundation underneath the mill table. The ducts had a cross section of 0.85 m x 0.85 m and had a length of 6 m.

During the experiments the ignition source was always located at the most likely position for ignition in a roller mill, near the milling table, 0.65 m above the centre of the milling table. The dust clouds were produced injecting the dust from pressurised bottles. The delay time between activation of the dust dispersion and the activation of the ignition source was chosen to be 900 ms. The selected delay time was based on FLACS-DustEx simulations performed for the dust dispersion process.

3. FLACS-DustEx

FLACS-DustEx (Skjold, 2007; Skjold, 2014) is a CFD-based tool for simulating industrial dust explosions in complex geometries. The new code was developed from the CFD-tool FLACS (Arntzen, 1998). Although the validation work with FLACS-DustEx thus far has focused mainly on vented dust explosions (Skjold *et al.*, 2008), the code also contains models for the effect of suppressant on the burning velocity in dust clouds, and logical functions suitable for simulating the functionality of suppression systems and extinguishing barriers (van Wingerden *et al*, 2008).

The key challenges for any CFD code for dust explosions are the description of particle-laden turbulent flow, heterogeneous combustion, and realistic description of large-scale complex geometries. Modelling in the first version of FLACS-DustEx focused on turbulent flame propagation in dust clouds, and a simple one-fluid model (i.e. no slip velocity) describes the dust clouds.

In FLACS the combustion model for premixed turbulent gaseous combustion is using an empirical relationship describing the turbulent burning velocity S_T as a function of turbulence properties and the fundamental burning velocity:

$$S_T = 15.1 {S_L}^{0.784} {u'}^{0.412} l_I^{0.916} \tag{1}$$

where S_L is the laminar burning velocity, *u'* is the root-mean-square of the fluctuating velocity component, and l_I is the turbulent integral length scale (Arntzen, 1998). This correlation is a reformulation of an empirical relationship suggested by Bray (1990), which is a correlation between S_T/S_L, u'/S_L, and the Karlovitz stretch factor *K.*

Bradley *et al.* (1988) suggested that a similar correlation could be valid for maize starch/air mixtures. Provided suitable correlations for turbulent burning velocity exist for any dust/air mixture, in principle it could be possible to simulate flame propagation through clouds of finely dispersed dust by similar methods as those uses for gas explosions. The approach adopted in the first version of FLACS-DustEx involves extracting the lacking combustion parameters from pressure-time histories measured in constant volume explosion vessels, assuming the validity of the certain correlations for turbulent burning velocity (Skjold, 2007; Skjold, 2014). The largest available database for such data is pressure-time histories measured in the standardised 20-litre vessel.

4. Simulation set-up and investigated scenarios

This paper presents the result of a series of simulations carried out to find the effect of using optimal dust concentrations on maximum explosion pressures inside the mill and the sensitivity of a number of parameters such as the use of different types of fuel, the location of the ignition source, ignition delay time and partial blockage of available venting areas. Figure 1 shows the geometry of the roller mill in wireframe as represented in FLACS-DustEx. The Figure also shows the monitor points (MPs) (Gexcon, 2015). Their location can be summarised as follows:

- M1: underneath milling table
- M2-M3: air inlet ducts
- M4-M14: mill room and classifier
- M15: coal outlet pipes
- M16-M19: coal feeder

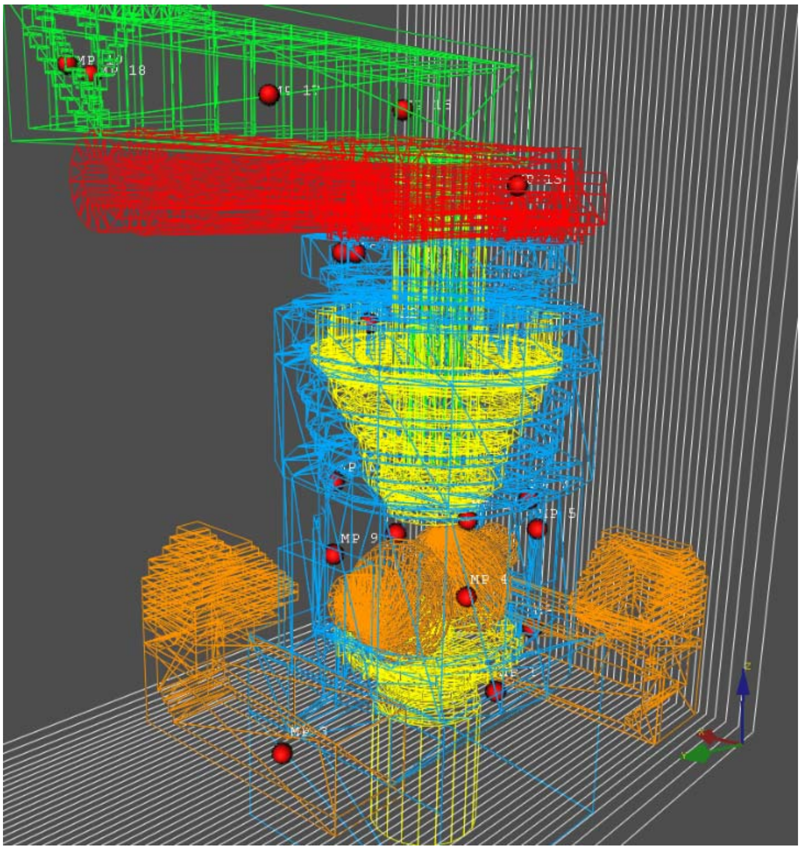

Figure 1: wireframe view of monitor points

Table 1 gives an overview of the scenarios investigated for the sensitivity analysis using FLACS-DustEx as well as the maximum overpressure obtained from each of the simulations performed.
As the table shows the following dusts were used: wood, coal and maize starch (the latter as a reference). The optimal explosion properties of the investigated dusts are:

- wood dust: P_{max} = 9.2 barg, K_{St}–value = 214 bar·m/s
- coal dust: P_{max} = 8.6 barg, K_{St}–value = 119 bar·m/s
- maize starch: P_{max} = 8.6 barg, K_{St}–value = 150 bar·m/s

The location of the ignition source was varied between the mill room (original position in experiments), classifier and coal feeder.
The ignition delay time was varied between 450 ms and 1350 ms.
To look into the effect of venting the vent opening in the coal feeder was varied between fully open to being fully closed. Similarly the effect of reducing the blocking of the coal dust outlets and increasing the blocking of the air inlets was looked into in separate simulations.

In all simulations the dust cloud was filling the entire volume: coal feeder, classifier and mill room.

Table 1: Simulated scenarios and comparison with experimental results.

Simulation no.	fuel	Ignition point	Ignition time (ms)	Coal feeder blockage (%)	Coal dust outlets blockage (%)	Primary air blockage (%)	Pmax Simulation (barg)
100000	Wood	Mill room	900	0	80	6	1.9
100001	Coal	Mill room	900	0	80	6	0.8
100002	Maize	Mill room	900	0	80	6	1.6
200000	Wood	Classifier	900	0	80	6	1.5
300000	Wood	Coal feeder	900	0	80	6	2.4
400000	Wood	Mill room	900	50	80	6	2.4
400001	Wood	Mill room	900	100	80	6	4.0
500000	Wood	Mill room	900	0	50	6	1.6
500001	Wood	Mill room	900	0	0	6	1.4
600000	Wood	Mill room	900	0	80	25	2.0
600001	Wood	Mill room	900	0	80	50	2.2
600002	Wood	Mill room	900	0	80	75	2.7
600003	Wood	Mill room	900	0	80	100	3.4
700000	Wood	Mill room	450	0	80	6	2.5
700001	Wood	Mill room	1350	0	80	6	2

5. Results

The pressure-time development for the three types of dust were studied. For the scenario investigated (see Table 1) the highest presures occur in the mill room/classifier area for each of the three dusts investigated. The respective pressure-time histories however show slightly different shapes. In the coal and maize starch explosions we see that the flame travels via the pipe connecting mill room and coal feeder into the coal feeder causing a strong secondary explosions there. As a result the pressure there temporary is higher than in the mill room causing a reversal of the flow. The flow into the mill room causes an increase of the combustion rate in the mill room for these two dusts indicated by an increase of the rate of pressure rise in the mill room. Although the effect is also seen for the wood dust the increase in pressure in the mill room is too high at the moment of maximum pressure in the coal feeder to cause a strong reversal of the flow. The highest pressures are seen for wood dust both in the coal feeder (0.9 bar) and in the mill room (1.9 bar) reflecting the higher reactivity of the dust. In all cases the pressures underneath the milling table (in the air inlet ducts) are lowest.

Figure 2 shows the pressure-time histories when varying the location of the ignition source. Three monitor points numbers were selected, monitor points number 5 and 14 to show the pressure evolution during passing from milling room to classifier and monitor point number 17 to show the pressure change in coal feeder. The strongest explosion occurs when igniting the larger volume in the mill room by a turbulent flame jet emerging from the coal feeder (bottom p-t-profile). The pressure in the mill room reaches 2.4 bar. The pressure in the mill room follows the pressure in the coal feeder due to venting into the mill room. Upon the flame emerging into the mill room the rate of pressure rise in the mill room increases considerably.

Ignition in the classifier part of the mill (middle p-t profile) allows for the flame entering the coal feeder earlier than when ignition is effected at the mill table. The higher pressure in the mill room due to the combustion there causes a strong flow into the coal feeder increasing combustion rates there and causing the pressure in the coal feeder after a short while to be higher than in the mill room. This results in a flow reversal causing the combustion rate and pressure in the mill room to increase. The maximum pressure in both the mill room and coal feeder reaches a maximum of 1.4 bar.

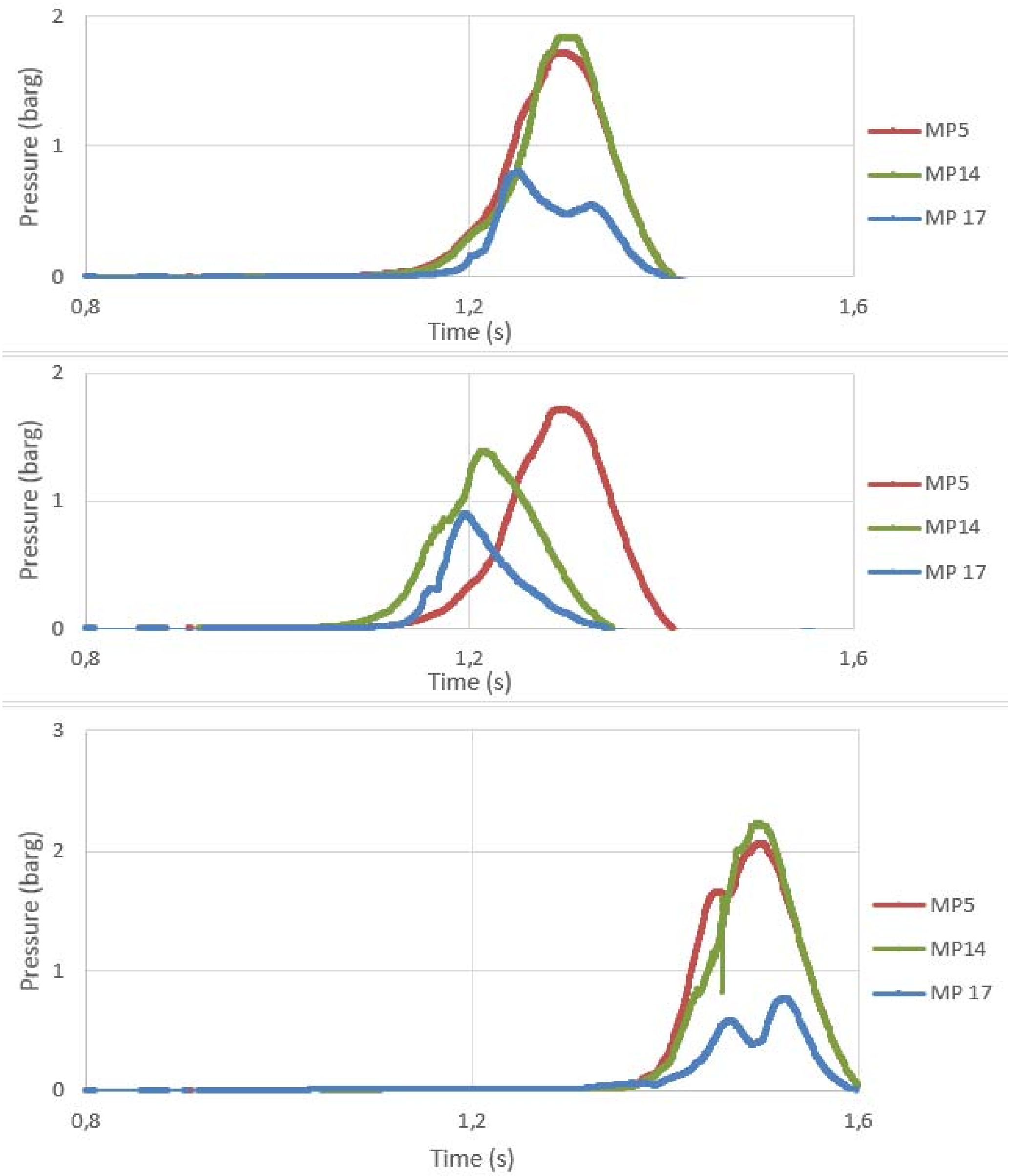

Figure 2: Simulated explosion pressures for different ignition points: mill room(top), classifier(middle) and coal feeder(bottom).

Table 1 shows the effect of reducing the delay time between start of dust injection using the pneumatic dust injection system and ignition to 450 ms (half of the 900 ms used in all other simulations and in the experiments) and increasing the delay time to 1350 ms (1.5*900 ms) on the explosion development. As expected decreasing the delay time increases the maximum pressure due to a higher turbulence intensity at the moment of ignition. An increase of the delay time implies more dissipation of turbulence generated by the injection implying lower pressure and longer duration of the explosion event.
The influence of blocking the vent opening in the coal feeder illustrated in Table 1. The vent opening (0.27 m^2) was reduced in steps blocking 0%, 50%, and 100% of the vent opening. Ignition for all these cases occurred in the milling room. The natural behaviour of increasing pressure by increasing the blocking can be inferred straight forward. The maximum achieved pressure is almost 4 bar. In these cases, we see that the pressure in the coal feeder exceeds the pressure in the mill room resulting in a flow reversal and a back flow into the mill room increasing the combustion rate there. When the pressure in the mill room subsequently exceeds the pressure in the coal feeder the combustion rate in the coal feeder increases again causing a second pressure peak there. When the vent in the coal feeder is fully blocked the pressure in the coal feeder exceeds the pressure in the mill room once more.

During the experiments reported by van Wingerden et al (2011) the coal dust outlet was blocked by 80% to represent the flow resistance by approximately 60 m of additional piping. The influence of different degrees of blocking of the coal dust outlet was investigated (see Table 1). Increasing the opening of the coal dust outlet shows that, the explosion peak happens slightly earlier due to a reduction in resistance. The maximum pressure in the mill room is decreasing due to an increase of flow of unburned material and burned material out of the mill room during the explosion event. It should also be mentioned that the static pressure in the coal dust outlet itself decreases considerably (due to a transfer of static pressure to dynamic pressure).
Table 1 represents the effect of partially blocking the primary air duct (25%, 50%, 75% and 100%). The gradually blocking of the primary vent duct causes the pressure inside the mill room to increase due to a lower degree of venting. The pressure in the primary duct increases considerably whereas the pressure in the coal feeder only increases when the primary duct is fully closed. The overall combustion rate is hardly affected as the moment of maximum pressure (in the mill room) is hardly changing.

6. Conclusions

The scenarios investigated for the sensitivity analysis using FLACS-DustEx varying dust type, ignition source location, ignition delay time and several vent openings present in the experimental roller mill showed that a maximum pressure of 4 bar is possible in the mill. This pressure was obtained when the vent opening in the coal feeder was fully blocked. In reality this would imply a situation where there is coal/or wood in the silo above the coal feeder.
The simulations showed that the interaction of combustion in both the coal feeder and the mill could cause considerable turbulence generation and thereby increase of combustion rates and overpressure generated.

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