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Assessment of Electrostatic Ignition Hazard in Plastic Silos by Combining Computer Modelling of Electric Fields with Experimental Measurements

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Propagating Brush Discharges are the most energetic electrostatic discharges encountered in industrial situations. They arise when a thin insulator (<10 mm thick) acquires exceptionally high surface charge. They are capable of igniting a wide range of flammable materials. For this reason, in a section on silos and containers for flammable powders CLC/TR 60079-32-1 states: “Insulating containers should in general be avoided due to the risk of propagating brush discharges”.

In the work reported here plastic silos were being used to store wheat flour. The powder was pneumatically conveyed into the silos from tankers, thereby providing likely high levels of charge. Even though the silos had been used in this service for some time without incident, the published guidance meant the margin of safety had been questioned.

The only way of assessing the margin of safety would be to determine the electric fields inside the silo during filling. Unfortunately, direct measurements in this location are virtually impossible.

The authors have been developing the use of field modelling software in combination with experimental measurements to answer similar questions where charge generation is in liquids. Here, though, are the first results of combining measurements of electric fields outside silos with computer modelling to determine the electric field in critical locations inside.

This paper presents the principles of the approach, the experimental detail, how the field modelling software was used, and the results. The conclusion that, although these silos would not be expected to produce propagating brush discharges, the margin of safety was not large enough to warrant dismissing their occurrence altogether, is explained and justified.

Further work is proposed to improve confidence in the results even where modest or low margins of safety are indicated by this method.

1. Introduction

Pneumatic conveying is a common way of transferring powders from road tankers into silos. Pneumatic conveying of powders is a very effective way of generating electrostatic charge. Charged powder entering a silo can lead to electrostatic discharges (spark-like events) and if they are sufficiently energetic and the powder is combustible, the result can be an internal dust explosion.

Six electrostatic discharge types have been identified. In a silo made from a properly earthed conductor (e.g. stainless steel) most can be easily addressed. However, where silos are made from an insulating material a particularly energetic type of discharge cannot be so easily dismissed. An earlier assessment of existing plastic silos for storing wheat flour identified this as a potential hazard with only two options for addressing the problem: install explosion vents or replace with metal silos. Unfortunately, the first option was very difficult and the second very expensive. The operating company had used many such silos for a long time without incident. Could this be good fortune, or were charge levels actually too low for an incendive discharge?

DEKRA Process Safety had answered similar questions in liquid processing by computer modelling and it seemed likely a similar approach could help in this case. This paper presents work initiated on that basis.

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2. Electrostatic hazards and storage silos

2.1 Flammable atmospheres

During filling of a powder silo there will almost always be dispersed powder in the head space. If the powder is combustible and sufficiently fine this dispersion is likely to represent an explosive atmosphere. This is true of a wide range of powders and certainly of the wheat flour being stored in the silos under consideration here.

2.2 Electrostatic charge and discharges

Wherever electrostatic charge accumulates there is the possibility of electrostatic discharges. The type of discharge and the energy dissipated depends on the nature and situation of the charged materials.

Spark discharges occur from electrically isolated conducting materials. An electrical connection between nearby conducting objects (bonding), or more preferably connecting all conductors to earth, will ensure spark discharges cannot occur.

Brush discharges occur from charged insulating surfaces or from charged dispersed particulates, such as a dust cloud. Brush discharges are relatively low energy and, although they can ignite flammable gases and vapours, they are not able to ignite powders in the absence of flammable gases and vapours.

Lightning is an extremely energetic type of discharge, but only occurs from clouds of meteorological proportions. Hence lightning-type discharges are not considered a hazard inside process plant.

Corona is a type of discharge which occurs around a sharp point. Corona is of such low energy that it is incapable of igniting all but the most sensitive gases and vapours.

Cone discharges occur over heaps of charged powder and are therefore very relevant to powder silos.

Propagating brush discharges are very energetic discharges which can occur from highly charged thin insulators. They are therefore also relevant to silos whose walls are insulating.

Given their direct relevance to the assessment under consideration here, the last two will be discussed in a little more detail. Details of all can be found in many publications (e.g. CLC/TR 60079-32-1, 2015 & Britton, 1999).

2.3 Cone discharges

When like-charged insulating powder particles are forced together under gravity as they accumulate in a heap their potential energy increases. This manifests itself as a high electrical potential (voltage) in the centre of the heap and a high electric field (voltage gradient) across the surface of the heap. If the field exceeds the characteristic breakdown strength of the atmosphere above the heap (about 3000 $\mathrm{kVm^{-1}}$ for air at normal atmospheric pressure) this can lead to electrostatic discharges across it which can be incendive to some powders if the minimum ignition energy (MIE) is less than about 30 mJ (NFPA 77, 2019).

2.4 Propagating brush discharges

Propagating brush discharges can occur when a thin insulating layer is in contact with an earthed conductive surface and the free insulating surface is subjected to a high level of charge generation. The only requirement of the insulating layer is that it should be less than 10 mm thick and be able to sustain a potential difference of 4 kV across it. For a silo made from an insulating plastic, the wall will often be less than 10 mm thick and there must always be the possibility of an earthed conductor coming into contact with the outside while surface charge generation is occurring inside. For example, outdoor silos in the rain will effectively have an earthed conducting coating. When propagating brush discharge occur they can dissipate thousands of milijoules in a single discharge and are therefore capable of igniting a very wide range of flammable atmospheres.

3. Plastic flour silo considerations

An electrostatic hazard assessment for wheat flour in plastic silos would need to address the following:

- Spark discharges
- Cone discharges
- Propagating brush discharges.

Spark discharges can be entirely avoided if all conducting items are properly earthed and will therefore not be discussed further here.

The minimum ignition energy of wheat flour is typically 30 mJ, on which basis cone discharges could just cause an ignition. However, although initially of borderline concern, once the experimental work was begun it was quickly found that the wheat flour had an electrical resistivity of $<10^9\ \Omega\mathrm{m}$ and charge decay time of <0.1 s. For the purposes of this assessment, these values indicate the flour is not a good insulator and, provided the powder in the bottom of the silo is in contact with a good earth (such as the bottom rotary valve) it would not retain enough charge to produce cone discharges. Hence, early in the investigation cone discharges were seen as not relevant to the present situation.

Silo data indicated the walls were 7 mm thick, and therefore certainly capable of supporting propagating brush discharges if the necessary internal high charge generation mechanism were present.

The pneumatically conveyed flour enters the silos radially near the top, the conveying air being discharged through a filter. There may be impact between the incoming powder stream and the internal surfaces at the top of the silo, but once the powder starts to fall vertically inside, only a small fraction would be expected to contact the wall and that would be with a relatively low impact velocity. Hence, the necessary high charging regime could be present near the top of the silo, but would not be expected over much of the side wall.

However, another mechanism could also lead to high charge densities on the side wall. The powder entering the silo would probably carry high charge as a result of pneumatic conveying. During its fall through the silo the cloud of charged powder will lead to relatively high electric fields inside which, if the field is high enough, will lead to internal discharges. These will be brush-like discharges which, as indicated in Section 2, would not themselves be incendive to the falling powder. The discharges will transfer charge in a broadly radial direction to the inside of the silo wall where, since the wall is insulating, the charge will accumulate. This mechanism could lead to the high surface charge density required for propagating brush discharges. Hence, to be sure propagating brush discharges cannot be produced, it is necessary to demonstrate that internal discharges from the falling cloud of flour cannot occur. This was the main objective of the work described here.

4. Approach to assessing propensity for internal discharges

It can be shown that where there is a dispersed charge in a container, such as the falling cloud of flour inside the silo, the maximum electric field is at the inside wall of the container (Britton, 1999). Hence, if the field at the wall could be shown to be less than the breakdown strength of air by a suitable safety margin, it will be concluded that discharges from the dust cloud could not occur. In this case, of course, that would also indicate propagating brush discharges would not occur from the internal wall.

In principle it would be possible to assess this by installing an electric field meter at the inside wall surface in order to monitor the field during filling. In practice though, making the necessary opening in the silo wall would almost certainly be unacceptable, as would installing and operating a field meter in such a dusty environment.

However, electric fields pass through insulating materials, so it should be possible to measure an electric field outside the silo during filling. Then, with suitable field modelling software, it would be possible to determine from the external measured field the charge density of the internal dust cloud and the electric field at the wall.

Hence, by making an external electric field measurement, it should be possible to determine whether or not the internal field could lead to internal brush-type discharges which ultimately could lead to incendive propagating brush discharges. Furthermore, if discharges were shown not to be possible on the day of the experimental measurement, it would also be possible to see by how big a margin they were avoided.

5. Experimental Set-Up

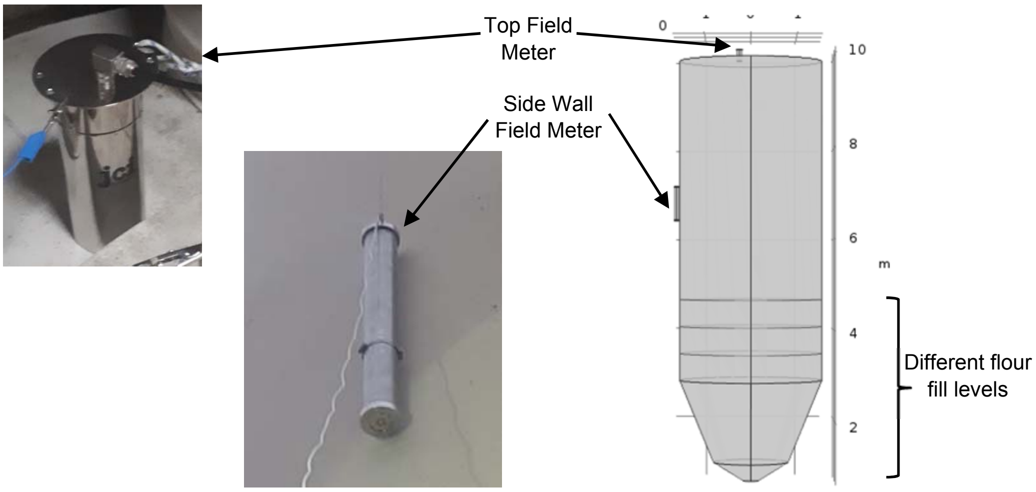

Figure 1: Field meters and their positions on the silo

Figure 1 shows a diagram of one of the silos used for the trials and the location of two field meters installed outside to record electric fields during filling. The top field meter was in a stainless steel shroud which was simply stood on the top. The side wall field meter in another shroud was hung from the top such that it rested against the silo. Both were connected to datalogging equipment for continuous monitoring during filling.

6. Results and analysis

Measurements were carried out on a number of silos but the traces for just one are shown here in Figure 2.

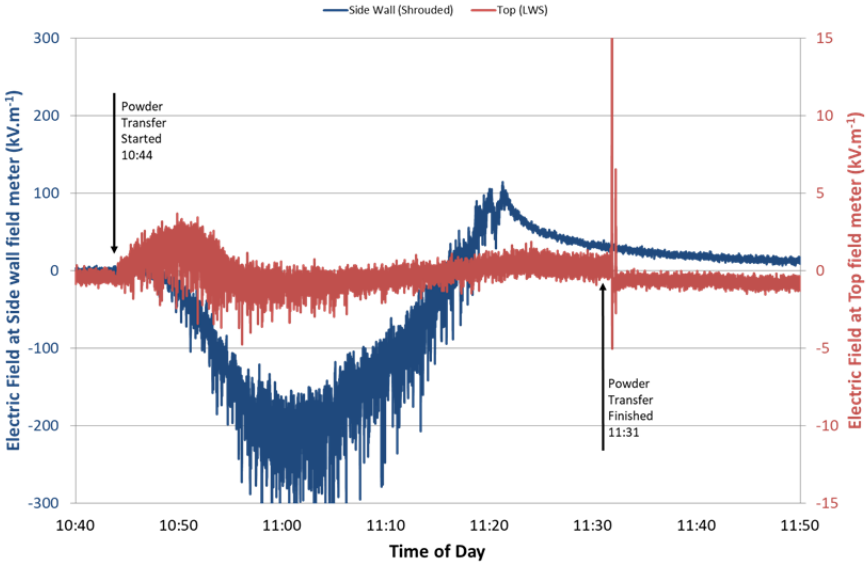

Figure 2: Example of field meter traces during silo filling

The surface resistivity of the outer surface of the silo, which clearly had a surface finish or paint applied, was also measured. It was found to be between 3×10^7 Ω for an area which looked slightly green (perhaps mossy) and 2×10^{10} Ω for an area which was quite clean. Both these extremes are in the static dissipative range in which, although not good conductors, charge on the surface would be expected to be lost quite quickly.

6.1 Qualitative considerations

Before presenting the modelling work it is helpful to give qualitative considerations to the observations.
It was expected that after a period of time during which a steady state situation became established, the powder flow rate and charge density would remain broadly constant resulting in a broadly constant charge density in the silo head space. Hence, the initial increase in measured field at the side wall might be understood in terms of establishing the steady state, for example as pneumatic conveying lines were warmed. As already mentioned, the bulked powder accumulating in the bottom of the silo will very quickly lose its charge such that it is essentially at earth potential. Hence, as the surface of the bulked powder rises towards the level of the field meter its effect would be to attenuate the field outside the wall, although that alone cannot explain the polarity reversal of the field meter trace. However, remembering the slightly conducting surface and invoking a capacitive response might help. Figure 3 shows an example of a capacitive circuit and its response to a step change.

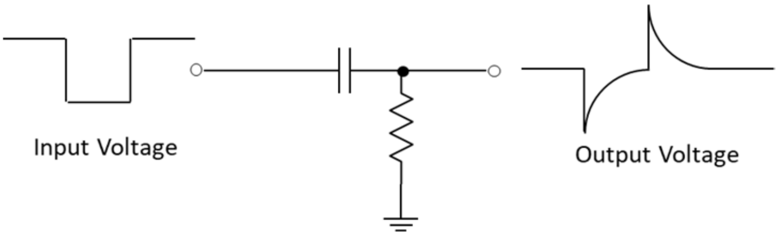

Figure 3: Capacitor response to negative and positive step changes.

If instead of the instantaneous input step changes of Figure 3, the negative-going and positive-going variations in voltage occurred much more slowly, it would be possible to get a response looking very much like the side wall field trace of Figure 2.

The overall conclusion is that, had there been no leakage of charge to earth from the outer coating, the trace's peak negative value in Figure 2 would have been more negative and the trace would have simply returned to zero when the earthed bulked powder approached the field meter level, with no positive excursion. Simplistically, the effective negative peak reflecting the space charge density in the head space would be the observed negative peak less the observed positive peak. Hence, in the next section, modelling aims to set the internal charge density such that the external field meter reads -350 kVm^{-1} (from the -250 kVm^{-1} negative peak less the 100 kVm^{-1} positive peak).

The top field meter gave an initially positive field, becoming slightly negative during much of the fill, and returning to slightly positive at the end. This was interpreted as being the result of tribocharging of the inside top surface of the silo due to impact of the incoming stream of powder. If the powder gained negative charge this would leave an effective positive surface charge on the inside top. For the purposes of modelling an average from much of the trace was used: +1.25 kVm^{-1}.

6.2 Electric field modelling

Electric field modelling for the silo was undertaken using COMSOL Multiphysics®.

The silo model was "constructed" based on available drawings and site measurements. Trial and error was then used to find a space charge density within the silo head space, and a surface charge density on the inside of the top of the silo such that the following field meter readings were indicated:

- Side wall field: -350 kVm^{-1}
- Top field: +1.25 kVm^{-1}

Other relevant variables were obtained or estimated as follows:

- Silo wall relative permittivity: 3
- Silo wall thickness: 7 mm
- Head space relative permittivity: 1

A number of models were used to represent different stages of the fill. However, Figure 4 shows the potential distribution in and around the silo to achieve the required field meter readings at around 15 minutes into the fill. This clearly shows the field distortion caused by the earthed side wall field meter and the fact that the negative potential is "contained" within the silo top by the presence of positive charge on the inside surface.

Taking results from all the models used to cover the whole period of filling, the following were determined:

- Maximum head space charge density: -4.2x10^{-7} Cm^{-3}
- Maximum top surface charge density: +6.6x10^{-7} Cm^{-2}

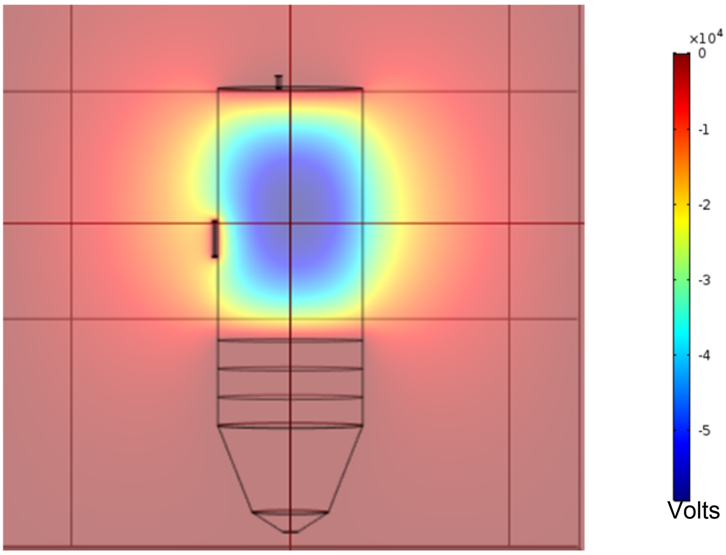

Figure 4: Graphical representation of potential distribution in and around the silo.

The model was then used to determine the maximum internal radial electric fields in order to assess the possibility of internal electrostatic discharges. Figure 5 shows the modelled radial field at the inside of the silo wall plotted against distance from the bottom. The plot shows a very pronounced peak at the position of the field meter. Of course, the field meter would not normally be on the silo wall. However, there are earthed metal ladders mounted on the wall which for reasons of simplicity were not included in the model. Hence, it was considered the field at the field meter would indeed be relevant since it would be very similar to the field near a ladder mounting.

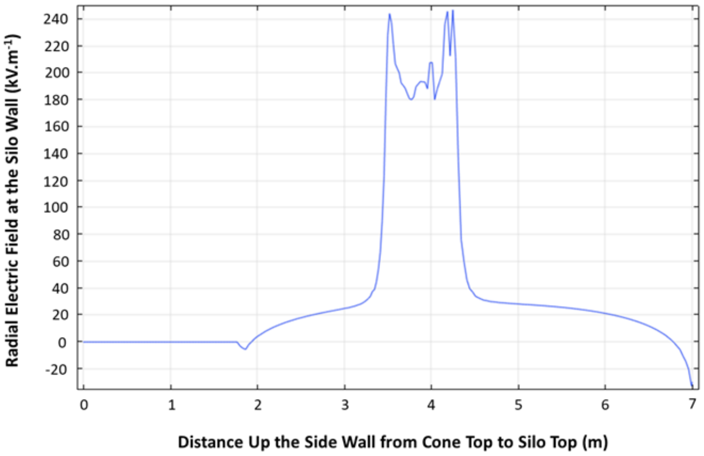

Figure 5: Radial electric field from the model

The maximum radial field taken from Figure 5 is about 240 kVm^{-1}, but including similar plots for all fill stages:

- Maximum radial field at the wall throughout the fill period: 400 kVm^{-1}

6.3 Interpretation and discussion

The breakdown strength of air (the minimum field which results in electrostatic discharges) is 3000 kVm^{-1} (CLC/TR 60079-32-1, 2015 & Britton, 1999). The maximum field found at the wall by modelling was 400 kVm^{-1}, indicating internal discharges would not be expected. However, at 13 % of the breakdown strength of air this is not considered to be a substantial margin of safety, suggesting that internal discharges, which might then lead to highly energetic propagating brush discharges, could not be entirely ruled out. Nevertheless, the fact that the field was below the breakdown strength of air could explain why no such incidents have been encountered.

Referring to the surface charge density in the top of the silo, it has been shown that propagating brush discharges do not occur for surface charge densities less than 2.5x10^{-4} Cm^{-2} (Britton, 1999 & Pavey, 2009). The indicated maximum internal surface charge density at the top of the silo was 6.6x10^{-7} Cm^{-2} which is just 0.3 % of that required for propagating brush discharges. Consequently, the possibility of a propagating brush discharge at the top of the solo due to impact of the incoming powder stream is deemed unlikely.

7. Conclusions

From the above analyses and discussions it was concluded that for the assessed resin silos used for flour storage and filled by pneumatic conveying, internal propagating brush discharges, although not considered highly likely, could not be ruled out. Subsequent trials repeated at a different time of the year confirmed this conclusion with somewhat higher results leading to a recommendation for the installation of explosion protection measures, or to undertake work aimed at defining suitable charge reduction measures.

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