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A generalized model for the electric field in silos/containers

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The electrical field strength may be used to assess the ignition risk by cone discharges. The field may be measured in situ or calculated based on validated models (TRGS 727, 2016). In this paper results of a generalized model are presented, which allow the determination of the electrical field strength based on the estimation of the charge density and the relative permittivity on one hand and well-known parameters like powder resistivity (i.e. charge relaxation time), bulk density, filling rate and the dimension of the silo.

* 1. Introduction

Since the discovery and first characterization, cone discharges have been an essential element of any ignition source analysis within explosion protection concepts (Abdel-Salam et al., 2015; Choi et al., 2022). The relevant decision trees for the assessment of the hazard caused by cone discharges are given in (TRGS 727, 2016) and (IEC 60079-32-1, 2013). This paper focuses on the assessment of bulk materials with medium (1 MΩ·m < ρ ≤ 10 GΩ·m) or high (ρ > 10 GΩ·m) resistivity, filled in containers with a volume greater than 0.25 m³ by gravity or a container filled pneumatically, regardless of the volume.

The following parameters have to be considered:

* Powder resistivity
* Flow rate
* Volume of the powder
* Particle size
* Minimum ignition energy
* Diameter and volume of the containment
* Electrical field strength

If the energy from a cone discharge exceeds the Minimum Ignition Energy (MIE) of the powder being handled, and the powder is either filled into a silo by gravity with a volume greater than 0.25 m³ or into container pneumatically, regardless of volume, the possibility to exclude cone discharges could be considered, by assessing the electrostatic field within the silo. The electric field (ES) along the surface of the solid in the silo has be considered. If ES<500kV/m there is no ignition risk by cone discharges (TRGS 727, 2016).

The determination of ES is difficult and expensive. The standards therefore allow the use model calculations, to answer this question. With the broader availability of software for the necessary Finite Element Calculations like COMSOL Multiphysics® or HIPHI®, the model approach became increasingly used in this relation. Glor has shown the usefulness and feasibility of such calculations for many problems in static electricity. Recently it was shown that the consideration of the charge relaxation may lead to less conservative but still safe assessments (Glor, 2023). This paper presents a generalization of the calculations provided in (Glor, 2023).

* 1. Generalized model without charge relaxation
		1. Electrostatic field in an infinitely long charged container

A charged container is considered infinitely long when the ratio Hf/R is infinite

Assumptions:

* The charge is uniformly distributed throughout the volume of the cylinder
* The electrostatic field is radial due to the symmetry of the problem.

The electrical field along the wall of cylindrical containers with infinite Hf/R ratio can be calculated using the Gaussian surface integral:

|  |  |
| --- | --- |
|  | (1) |

Therefore, for an infinitesimally small volume, as shown in Figure 1, the ES is as follow:



Figure 1: infinitesimally small Gaussian surface

|  |  |
| --- | --- |
|  | (2) |

|  |  |
| --- | --- |
|  | (3) |

Thus, can easily be calculated without modelling.

* + 1. Electrostatic field in a finite long charged silo – without charge relaxation

For real silos with finite filling height and without taking charge relaxation (i.e with an infinite resistivity), the ES is not constant along the silo wall (Glor, 2023). A conservative approach is to consider the maximum value of the electrostatic field, ESmax, which appears about in the middle of the filled part of the container, and not above the powder heap as required following current standards TRGS 727 (2016) and IEC 60079-32-1 (2013). ESmax is larger than ES(z=Hf), as shown in Figure 2. It should be noticed, that the highest field strengths are obtained not along the vertical wall but in the centre of the bottom silo, if there is no charge relaxation.



Figure 2: The geometrical factors β and φ, for an 8m high silo filled up to Hf=6m with powder. The full line is for infinite resistivity, the dotted line is for a charged layer thickness Hc=1m. The contours are shown for a cross section along the axis of the container

A dimensionless geometrical factor β can be calculated numerically which represents the reduction of ESmax as a result of the limited ratio Hf/R:

|  |  |
| --- | --- |
|  | (4) |

Over fifty modelling simulations were conducted to determine the conditions related to the container and the quantity of powder introduced, to achieve an optimal fit of β. The fit was made with the Python software.



Figure 3: β fit with the software python

|  |  |
| --- | --- |
|  | (5) |

As shown in Figure 3, β increases with increasing ratio Hf/R and approaches 1, the value for infinite Hf/R, for about Hf/R=5.

The conditions under which the β fit is valid are:

|  |  |
| --- | --- |
|  | (6) |

* + 1. Electrostatic field in a finite long charged silo – with charge relaxation

Even highly insulating powders have a finite resistivity, which allows for charge relaxation. The relation between the charge relaxation time τrelax, in which the actual charge density decreases to 1/e of the initial charge density and the resistivity ρ is:

|  |  |
| --- | --- |
|  | (7) |

Charge relaxation competes with charge accumulation on the added solid. By applying the Gauss's local theorem and the charge conservation formula, the following equation could be obtain:

|  |  |
| --- | --- |
|  | (8) |

Given that the mass flow rate is assumed to be constant, the following relation holds

|  |  |
| --- | --- |
|  | (9) |

The charge density can be expressed as a function of the filling height instead of time.

|  |  |
| --- | --- |
|  | (10) |

This can further be modified by introducing the charged layer thickness Hc:

|  |  |
| --- | --- |
|  | (11) |
|  | (12) |

From Equation 12 it could be notice that the maximum electric field along the wall ESmax does not depend on the filling height if Hc < Hf/3.

This can also be observed graphically by modeling the electrostatic field for different silo heights while maintaining the same charged layer thickness, as shown in Figure 4.



Figure 4: Graphical illustration of the charged layer Hc

As done for Equation 4, the dimensionless geometrical factor φ can be calculated numerically, representing the reduction in ESmax due to charge relaxation.

|  |  |
| --- | --- |
|  | (13) |

Over fifty modelling simulations were conducted to determine the conditions related to the container, the quantity of powder introduced, and the charge relaxation to achieve an optimal fit of φ. The fit was made with the Python software.



Figure 5: φ fit with the software python

|  |  |
| --- | --- |
|  | (14) |

The conditions under which the φ fit is valid are:

|  |  |
| --- | --- |
|  | (15) |

* 1. Result discussion

The two formulas provided above enable the calculation of the maximum electric field along the wall of a silo without the need for finite element modelling. This applies to both a powder with infinite resistivity and a case where charge relaxation is considered. To determine the electrostatic field on the silo wall, it is recommended to use the geometrical factor for a powder with charge relaxation if the container dimensions and powder quantity meet the condition (H-Hf)/R ≥ 1 and the charge layer thickness meet the condition Hf/Hc ≥ 3. If this condition is not met, it is advised to use the geometrical factor for a powder with infinite resistivity, provided that (H-Hf)/R > 0.25.The formula for infinite resistivity is however of limited practical value, because the resulting electrical field for any realistic combination of parameters would still be in the critical range, i.e. above 500 kV/m. On the other hand, the concept of the charged layer shows the significant effect of the powder resistivity on the electrical field ESmax and open the chance to actively control ESmax with the dosage rate.

Since the condition for the neglection of cone discharges in ESmax < 500kV we obtain from 13:

|  |  |
| --- | --- |
|  | (16) |

Which results for typical values of e (2) and d (600 kg/m3) in

|  |  |
| --- | --- |
|  | (16) |

The table below summarizes the values of φcrit for different values of container radius and charge density.

Table 1: Limit values for j to fulfill the condition ESmax < 500 kV/m for typical values of e and d.

|  |  |
| --- | --- |
| Charge density (nC/kg) | Radius R (m) |
| 0.25 | 0.5 | 1 | 1.5 | 2 |
| 1.0 | > 1 | > 1 | > 1 | > 1 | > 1 |
| 1.0‧101 | > 1 | > 1 | > 1 | > 1 | > 1 |
| 1.0‧102 | > 1 | 6.0‧10-1 | 3.0‧10-1 | 2.0‧10-1 | 1.5‧10-1 |
| 1.0‧103 | 1.2‧10-1 | 6.0‧10-2 | 3.0‧10-2 | 2.0‧10-2 | 1.5‧10-2 |
| 1.0‧104 | 1.2‧10-2 | 6.0‧10-3 | 3.0‧10-3 | 2.0‧10-3 | 1.5‧10-3 |
| 1.0‧105 | 1.2‧10-3 | 6.0‧10-4 | 3.0‧10-4 | 2.0‧10-4 | 1.5‧10-4 |
| 1.0‧106 | 1.2‧10-4 | 6.0‧10-5 | 3.0‧10-5 | 2.0‧10-5 | 1.5‧10-5 |

Since φ cannot exceed 1, as this would imply that the electrostatic field is greater than the electrostatic field of an infinite cylinder, it indicates that even without charge relaxation (i.e., with infinite Hc) ESmax remains < 500 kV/m.

In the reddish zone of Table 1, the required values for φ and, consequently, Hc, are so minimal that achieving them in a controlled and practical manner is not feasible. Conversely, in the yellow zone, the risk of cone discharge can be effectively managed by regulating Hc, and thus φ, through precise control of the dosing rate.

Practical example:

The following example illustrates the use of Table 1 and the limitations of the dosing rate to avoid a cone discharge: a silo with a radius of R = 1.5 m and a height of H = 5 m is filled with a powder that has a volume resistivity of ρ = 1.0‧1011 Ωm and an initial charge density of qm0 = 1.0‧102 nC/kg. The powder is filled to a height Hf = 3 m.

The condition 1 of Equation 15 is fulfilled. Based on Table 1, the risk of a cone-type discharge cannot be ruled out. Consequently, Hc must be numerically determined with Equations 16 and 13. Once Hc is determined, the dosing rate can be derived accordingly. It is then essential to verify that Condition 2 of Equation 15 is still satisfied. The numerical application indicates that Hc must be less than 0.1379 and so the dosing rate must be below 0.33 t/s. In this case, condition 2 of equation 13 is satisfied.

* 1. Conclusion

The generalized calculation of ESmax presented in this paper is based on the following input parameters for Container and Process (radius, filling height, filling rate) and for powder (bulk density, resistivity, relative permittivity, charge density). Most parameters are straight forward to determine; however, a critical challenge lies in accurately determining qm0​, the specific charge density. This parameter can vary significantly, from 10 pC/kg to 1 mC/kg. While current standards provide general ranges, less conservative, case-specific values can be obtained through on-site measurements. These measurements can involve using an electrostatic voltmeter to assess the introduced charge or measuring the charging current.

The model offers a practical alternative to finite element simulations, providing an accessible and robust method for risk assessment in industrial applications. By addressing the interplay between critical physical parameters, the study enhances understanding of cone discharges and delivers actionable guidelines for ensuring operational safety in silos.

Nomenclature

β – geometrical factor for a powder with an infinite

resistivity, -

δ – bulk density, kg/m3

ε – dielectric constant of the powder, -

ε0 – vacuum permittivity, F/m

ρ – powder volume resistivity, Ωm

φ – geometrical factor for a powder with charge relaxation, -

φcrit – geometrical factor for a powder with charge relaxation typical values of e and d, -

τrelax – relaxation time, s

H– container height, m

Hc – the charged layer thickness, m

Hf – final powder height, m

Hf→∞ – infinite height of a container, m

ES(Hf🡪∞) – electrostatic field on the wall of the infinite container, V/m

ESMax – maximum electrostatic field on the wall of a container, V/m

ESmax, crit – condition for the electrostatic field to generate a cone discharges, 500 kV/m

m – mass introduced at time t in the container, respectively at height z, m

m’ – mass flow rate, kg/s

qm0 – initial mass charge density on the powder, C/kg

qm –mass charge density on the powder at the time t respectively at height z, C/kg

R – container radius, m

vfill – velocity of the level rise in the silo during the filling, m/s

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