

Charge accumulation and dissipation in micrometer sized powders.

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Abstract

When moving, dry particles tend to acquire electric charge due to collisions between themselves and other solid surfaces, in a process called tribocharging. Provided there is enough number of collisions in a short amount of time, the charge accumulated can be high enough to constitute an electrostatic hazard. However, when the particles finally come at rest, the electric charge tends to dissipate, even if the particles are made of insulating material. In fact, in general the time it takes for the charge to dissipate is much shorter than what it would be expected from the electrical conductivity of the material of the particles. In this work, we present a model that describes the discharge of a powder layer formed by the settling of charged particles based on the assumption that the settled powder has an effective conductivity. We compare the model with the results of an experiment in which particles are charged and collected in a Faraday cage. The value of the conductivity that the model requires to match the experimental results is compared with the electrical conductivity of the bulk powder measured directly.

1 Introduction

Dry powder handling operations are usually accompanied by electric charge built-up due to triboelectrification. Pneumatic transport is specially prone to triboelectrification as the particles carried by the gas experience many collisions with other solid surfaces, each collision contributing to the built up of charge in the particles. Once the particles settle to form a packed powder, the concentration of charge can create electric fields large enough to trigger electrical discharges. The likelihood of electrical discharges depends on the charge accumulated in the settled powder at any given time, which depends on the balance between the electric charge accreted by the incoming particles in the heap and the dissipation of electric charge to the surroundings. In this work, we study the temporal evolution of charged particles dispersed in a gas stream, resembling pneumatic transport which, after being charged, are allowed to settle by gravity.

| Material | d_p (μm) | Material | d_p (μm) |
|-------------------|-------------------------|--------------------|-------------------------|
| Sipernat D10 | 3.4 | 5-50 glass beads | 33.9 |
| TiO ₂ | 3.7 | 70-110 glass beads | 92.0 |
| Sand | 4.0 | 90-150 glass beads | 125.4 |
| Sipernat 320DS | 6.6 | Pmma beads | 200 |
| Cornstarch | 7.3 | sugar | 720 |
| Coated cornstarch | 7.3 | semoline | 796 |
| Regolith | 9.7 | | |

Table 17: Materials used in the experiments presented in this report. With the exception of PMMA beads, whose size is provided by the manufacturer, their mean particle size d_p (surface-mean diameter) was measured in a Mastersizer 2000 using the Sirocco 2000 air dispersion unit (air dispersing pressure 1 bar).

2 Materials

The materials used in the experiments are listed in Table 17 in ascending average particle diameter. Different samples of the same material were stored at different controlled relative humidities in chambers with 10%, 30% and 60% R.H. Samples were contained in these chambers for months and were taken out only to perform experiments, after which they were placed again in the controlled ambients.

3 Experimental set-up

We have built two experimental set-ups. In one of them a sample powder is dispersed in a gas stream, charged by collisions against solid surfaces and the charge acquired by the particles is measured. In the second set-up, we have measured the electrical conductivity of a powder layer. The set-up used to charge powder samples is composed of three units: the disperser, the tribocharger and the collection unit. A picture of the set-up showing the tribocharger and collection unit is shown in Fig. 1. The disperser makes use of a venturi device which entrains powder particles in a gas stream prior to the injection in the tribocharger system. The sample is fed into the venturi through a low pressure port, with a mass rate that should be as constant as possible, and with total masses of tens of grams at least.

We have made experimental runs with two tribochargers: a nylon cyclone tribocharger with a cone shape on its bottom part (350 mm in length, 74 mm internal diameter) and a steel pipe (length 540 mm and internal diameter 21 mm). Collisions of particles against the tribocharger inner walls generate the electrical charge build up on the particles surfaces. In the experiments with steel pipe as the tribocharger, a programmable electrometer (Keithley 6512) working in the ammeter mode connects ground to the tribocharger, thus measuring the electric current involved in the charge transfer process between powder and steel pipe. The electric charge Q_d transferred to the particles while they are dispersed into the gas stream is obtained by numerical integration of the registered current.

After exiting the tribocharger, charged powders fall by gravity into a cylindrical

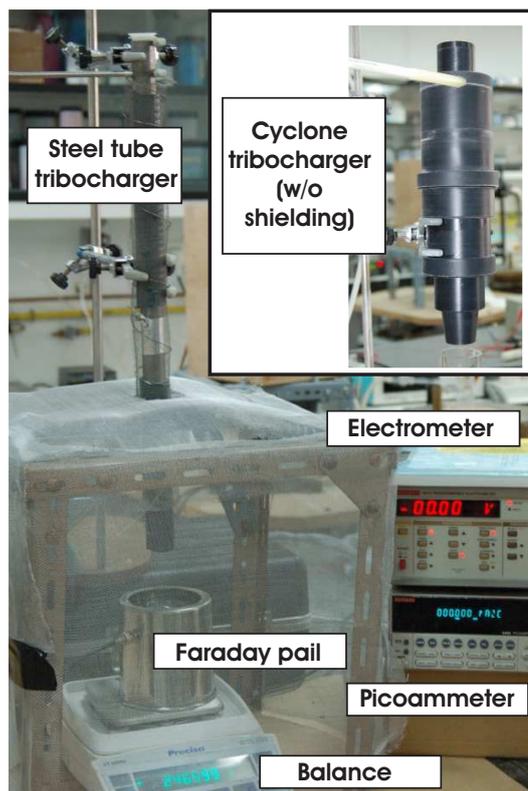


Figure 1: The experimental setup for measuring triboelectrification levels, with the steel tube tribocharger in place and the nylon cyclone tribocharger in the inset, shown without electric shielding. The Faraday pail resting on the balance collects the powder coming from the tribocharger. The electric current flowing into the Faraday pail is measured by the picoammeter and recorded by a PC. When the steel pipe is used as tribocharger, the electrometer depicted in the figure is connected to it and its data is also registered by the PC. The metallic mesh around all the setup is grounded to reduce electric noise from the rest of the lab. The dispersion units do not appear in the figure.

cell made of insulating material (a methacrylate tube), closed at its bottom with a metallic filter to help separate the particles from the gas. The filter inside cell is electrically insulated to the outside of the cell. The cell is located inside a Faraday pail consisting of an inner and an outer cage made of conductive material, the former being connected to ground through a picoammeter (Keithley 6485). The picoammeter measures the current flowing from ground to the inner cage of the Faraday pail as the collecting cell is filled by the material exiting the tribocharger. Integration of this current yields the charge $Q_s(t)$ in the settled powder as a function of time. The Faraday pail system rests on a mass balance that measures the collected powder mass $m(t)$ as a function of time. More details of this experimental set up are given in ref. [1].

The experimental set-up to measure the effective electrical conductivity of bulk powders σ consists on a cell of rectangular cross section (internal dimensions 48×24 mm) in which a layer of powder rests on a porous metallic plate ($5\mu\text{m}$ pore size).

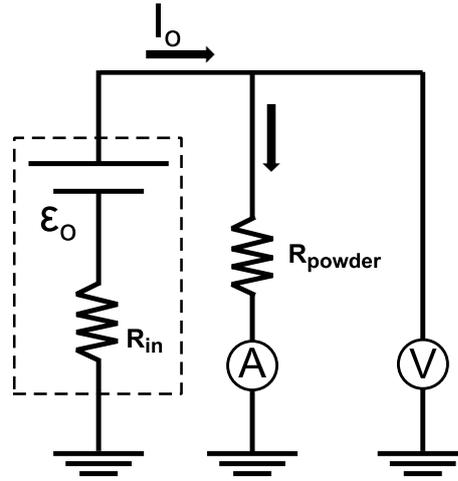


Figure 2: Electric diagram of the experimental arrangement to measure powder electrical conductivity. The granular material in the cell has an electric resistance R_{powder} . The HV source is enclosed in dotted line. Ammeter and voltage probe are pictured as A and V.

The cell has transparent methacrylate walls. The sample of powder in the cell is compressed by a punch of rectangular cross-section (dimensions 10% smaller than the inner dimensions of the cell), also made of transparent methacrylate walls, except for the face of the punch pressing the powder, which is made of the same porous metallic plate as the cell filter. With this arrangement, a flow of gas can be set to pass through the powder and exit the layer of powder through the filter on the punch. The reason to allow gas to pass through the powder is that other authors working in similar experiments [2, 3] have found that the humidity of the gas changes the electrical conductivity of the powders. For each of the materials used in the experiments, we have tested one sample with a flow of dry nitrogen and another with a flow of humid air that had passed bubbling through a beaker holding hot water. In both cases, the flow of gas is maintained during 60 minutes before inserting the punch to start the measurement of the powder conductivity. Before inserting the punch, the relative humidity inside the cell was measured with a hygrometer. When using dry nitrogen, the relative humidity inside the cell was found to be 14% RH, while when using humid air it was 80 % RH. Since the consolidation stress acting on the powder can also affect the powder conductivity, the punch can be loaded using weights. Two weights have been used in each experiment: for the smaller weight, the combined weight of the punch and the weight is 218 g, while for the larger weight is 3218 g. The resulting consolidation stresses acting on the layer of powder in the cell are 1.9 and 27.3 kPa, respectively.

Both filters also serve as electrodes: the filter on the cell is connected to a high DC voltage source (Spellman RHR20) while the filter on the punch is connected to ground through a picoammeter (Keithley 6485) to measure the current intensity through the sample. A multimeter equipped with a high voltage probe measured the voltage drop between the live electrode in the cell and ground. With minor modifications undergone through the several experiments, the equivalent circuit of

the set-up is shown in Figure 2. Powder conductivity is tested measuring the current through the powder I as a function of the voltage drop V across the cell, ideally lying on a straight line. Readings from the ammeter are taken as soon as a voltage V is set adjusting the high the voltage source, since the number of mobile charge carriers within the powder normally decreases with time, and so it does the current passing through the cell [3].

The slope of the best fit straight line through the $I - V$ plot is the electrical conductance G of the cell loaded with powder, which is the sum of the electrical conductance due to the powder G_p and the electrical conductance due to the walls of the cell G_w ($G = G_p + G_w$). Only if $G_p \gg G_w$ are the results meaningful. This fact makes it necessary to measure the conductance of the empty cell at the two relative humidities used in our experiments. The results for a gap of 9 mm between the electrodes for 14% RH and a gap between the electrodes of 15 mm for 80 % RH are 4.1×10^{-4} nS/m and 1.6×10^{-3} nS/m, respectively. Both the conductance of the powder G_p and the conductance of the empty cell G_w depend on the gap h between the electrodes, because this gap represents the distance the charge carriers must travel between the two electrodes. The electrical conductance of the cell is assumed to be inversely proportional to the gap h between the electrodes.

From the powder conductance $G_p = G - G_w$, the powder conductivity is determined as:

$$\sigma = G_p \frac{h}{wd} \quad (1)$$

where w and d are the dimensions of the cross section of the cell. In practice, the current that flows through the cell walls limits our measurement of the conductivity of a powder to values larger than about 3×10^{-3} nS/m at 14 %RH and about 2×10^{-2} nS/m at 80 %RH

4 Results.

The charge acquired by the particles in the tribocharger while they are dispersed in the gas stream q_d can only be evaluated for the steel tube tribocharger, for which the total charge Q_d given to the powder can be measured. Assuming the sample is monodisperse and that all particles have the same charge to mass ratio, the individual particle charge is $q_d = Q_d(m_p/m)$ where m_p is the particle mass. Fig. 3 shows the value of q_d as a function of the particle radius r_p (half the surface mean diameter listed in Table 17) for the experiments using the steel tribocharger. Since there is always some powder that remains stuck to the inner walls of the tribocharger, using the collected mass m somewhat overestimates the value of q_d . The typical mass loss ranges from 19% to 69% of the total mass of dispersed powder for 5-50 μm glass beads and 1% to 20% in 90-150 μm . In general, the mass loss decreases with larger particles and higher storage humidity. Such overestimation in charged mass contributes to the experimental error in q_d in figures 3. In this figure a grey coloured bar by each group of symbols indicate the uncertainty in q_d , when mass losses between 19% and 69% are considered for the 5-50 μm glass beads, and

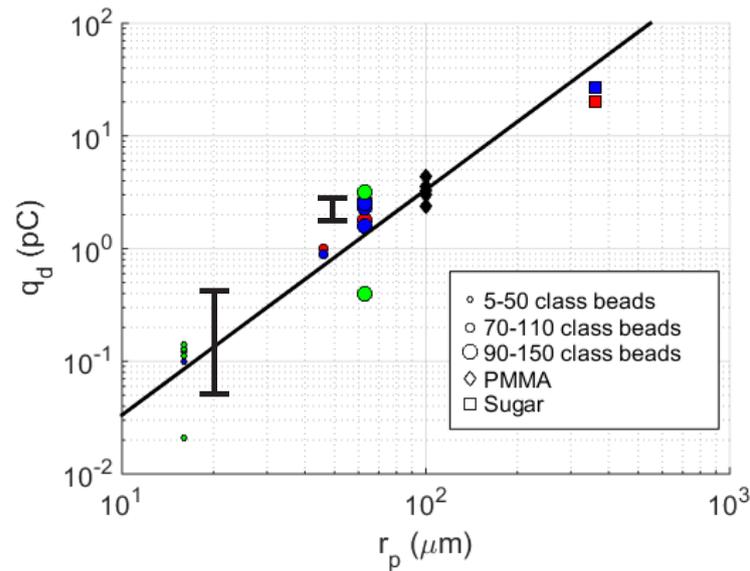


Figure 3: Results of absolute values of transferred charge q_d from the steel pipe tribocharger to particles of different materials. The line marks the theoretical values for maximum charge of particles limited by planar corona discharge. The dispersing gas and storage conditions of the material at each experimental point are given according to the following color code: Black: storage RH not controlled, dispersed in compressed air. Blue: stored at 56% RH, dispersed in compressed air. Red: stored at 30% RH, dispersed in compressed air. Green: stored in dry N₂, dispersed in dry N₂. Error bars indicate the typical uncertainty for each size range. For the larger particles particles, error bar and symbol are approx. the same size.

20% for the 90-150 μm glass beads. The bar corresponding to a mass loss of 1% is neglected since its effect is not visually noticeable.

In Fig. 3 we have drawn a line for the maximum particle charge $q_{d,max}$, assuming the value of $q_{d,max}$ is given by the condition that the electric field on the particle surface equals the breakdown field for corona discharge as suggested in Ref. [4], that is:

$$q_{d,max} = 4\pi\epsilon_0 r_p^2 E_c, \quad (2)$$

where we assume the breakdown field is equal to $E_c = 3 \times 10^6$ V/m irrespective of particle size and ϵ_0 is the electric permittivity of the gas surrounding the particle, which we assume is equal to the permittivity of vacuum ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m). All the experimental data lie very close to the corona discharge line, which means that, when dispersed, particles charge up to their maximum attainable value.

If the powder particles did not discharge during collection of the sample into a settled powder, the charge Q_s in a settled sample would equal the total charge Q_d transferred to its particles in the steel tube tribocharger. However, this is not so: in experimental runs $Q_s < Q_d$. The average electric charge per particle in the collected sample can be calculated from $q_s = Q_s m_p / m$. For the experiments with the steel tube tribocharger q_s can be compared with the electric charge per particle when the sample was dispersed in the gas stream q_d to evaluate the amount of

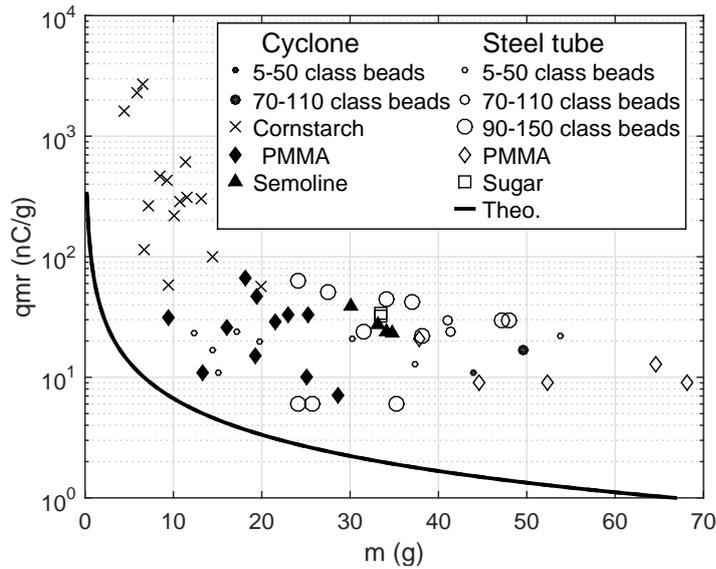


Figure 4: Specific charge qmr (charge to mass ratio) of the collected sample as a function of the collected mass m . Data for all the experimental runs are included. The void symbols represent data from experiments using the steel tube tribocharger. Data with filled symbols represent data from the experiments using the nylon cyclone tribocharger. The solid line represents the result of the model presented in discussion for 5-50 μm glass beads.

charge lost during settling: in most cases q_s is between 1/100 to 1/10 of the charge q_d acquired from the tribocharger. Fig. 4 illustrates the specific charge qmr of the collected powder against the collected mass m for all the available experiments, that is, using the steel tube and the nylon cyclone tribochargers. For a given material, the specific charge qmr tends to decrease when more mass is collected. Although the data points presented in Fig.4 have a large scatter, there is a visible tendency of decreasing specific charge qmr with sample mass m . More details of the results obtained with this set up are given in ref. [1].

Some of the missing charge may be in the layer of powder that remains stuck on the inner walls of the tribocharger. However, this layer forms in the initial seconds of each experimental run which lasts for a few minutes. Once the layer of stuck powder is formed, all the electric charge flowing to the tribocharger has no option but to be carried away by the particles, so this argument does not explain the decreasing trend of specific charge qmr with collected mass m .

The remain option is that the charge in the collected bulk powder is somehow lost while the powder is being collected. As the particles settle to form a bulk powder, there is a increase in the spatial concentration of the electric charge and we must expect the electric field on the bulk powder to increase to very high levels, high enough to cause ionization of the surrounding air. Ions of opposite polarity of the charge in the bulk powder would be attracted to the powder surface, neutralizing its charge with time. The charge inside the bulk powder must also have some mobility, to be able to reach the powder heap surface and be neutralized. So a model the

of charge accumulation and dissipation must account for: (1) Charge accumulation due to the inflow of charged settling particles; (2) charge dissipation on the bulk powder surface due to attraction of ions of opposite polarity from the surrounding air and possible transfer to the conductive surfaces of the Faraday pail, and (3) charge redistribution inside the powder, which can be represented as an effective conductivity.

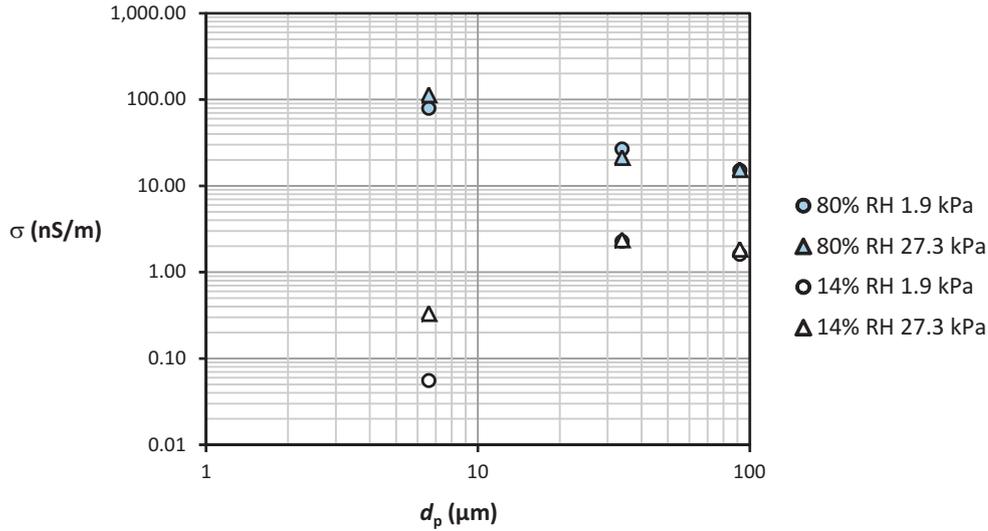
Regarding the conductivity of powders, we have tested four materials: 70-100 μm glass beads, 5-50 μm glass beads, sipernat 320DS (a hydrophilic micron-sized silica) a sipernat D10 (a hydrophobic micron-sized silica). The conductivity of these powders is represented in Fig. 5 and its accompanying Table. The electrical conductivity of Sipernat D10 was so small that their $I - V$ plot did not differ significantly from that of an empty cell in the same conditions of relative humidity and electrode gap and therefore no value is quoted.

While the consolidation stress acting on the powder has little effect on the conductivity, the relative humidity has a very large effect, changing the conductivity by one to two orders of magnitude. Although three data is too little a sample to judge trends, the electrical conductivity decreases as the particles gets smaller when the interstitial gas is dry, but increases as the particles get smaller for wet air. Both trends can be explained if the mobility of the electrical charge in a bulk powder is caused by the presence of physisorbed water layers on the surface of the particles. The electrical conductivity raises with the humidity because the thickness of the physisorbed water layer increases with increasing relative humidity. And the increase may be more marked for smaller particles because the pores between the particles are smaller and capillary condensation favors the growth of the water layer. Besides, this mechanism would explain why the Sipernat D10, which is hydrophobic, is much less conductive than the hydrophilic Sipernat 320DS. The decrease of the conductivity for smaller particles for 14% RH would be explained if, at this level of humidity, charge carriers had to pass from one particle to the other at existing particle contacts. Powders with smaller particle sizes have lower solid fractions and lower average number of contacts between particles than larger sized powders.

5 Discussion.

To make a model we assume that as particles settle there is a corona discharge from the surface of the settled sample to the surrounding air and that the remaining charge is determined by the condition that the electric field at the surface of the sample must equal the electric field for corona discharge in air, which we take for simplicity as $E_c = 3 \times 10^6$ V/m. Since the calculation of the electric field created by a cylindrical heap of powder is not straightforward, the sample is assumed to be an infinite layer in the XY plane that grows in the positive Z direction by uniform addition of particles to its surface. The layer rests on a conductive plate representing the metallic filter of the collecting cell. The mass flow rate of new particles per unit area is F_m , so if the mass density of the powder layer is ρ_m , the height H of the powder layer grows as:

$$H = \frac{F_m t}{\rho_m} \tag{3}$$



| Material | Effective conductivity σ (nS/m) | | | |
|--------------------------------|--|-----------------|----------------|----------------|
| | 14% RH | | 80% RH | |
| | 1.9 kPa | 27.3 kPa | 1.9 kPa | 27.3 kPa |
| 7-70 μm glass beads | 1.61 ± 0.06 | 1.85 ± 0.06 | 15.1 ± 1.0 | 15.4 ± 1.1 |
| 5-50 μm glass beads | 2.28 ± 0.14 | 2.37 ± 0.13 | 26.7 ± 0.7 | 21 ± 12 |
| Sipernat 320DS | 0.056 ± 0.022 | 0.33 ± 0.02 | 79.0 ± 2.5 | 113 ± 12 |

Figure 5: Effective electrical conductivities of glass beads 70-110 μm and 5-50 μm and hydrophylic sipernat 320 DS as a function of consolidation pressure and relative humidity of the gas flowing through the cell.

until at $t = t_o$ the sample collection stops and the powder layer attains its final depth H_f . The powder layer has an electrical conductivity σ that represents the ability of the electric charge inside the powder layer to move. The temporal evolution of the charge per unit volume $\rho(z, t)$, the electric displacement $D(\vec{z}, t)$ inside the layer as well as the surface charge density on the conductive plate $\sigma_p(t)$ are given by the solution of the set of equations:

$$\begin{aligned}
 \nabla \cdot \vec{D} &= \rho + \sigma_p \delta(z) \\
 \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{j} &= \rho_o \delta(t - z \frac{\rho_m}{F_m}) \\
 \frac{d\sigma_p}{dt} &= -j_z(0, t) = -\frac{\sigma}{\epsilon} D_z(0, t)
 \end{aligned} \tag{4}$$

where $\delta(t - z\rho_m/F_m)$ is the Dirac's delta function and ρ_o represents the charge per unit volume on a newly deposited layer of powder. Due to the geometry of the problem, spatial derivatives are given by $\nabla = \vec{u}_z \partial / (\partial z)$, the electric displacement by $\vec{D} = D_z \vec{u}_z$ and the current density by $\vec{j} = \sigma D_z / \epsilon \vec{u}_z$. As the powder loses its charge, the charge per unit volume $\rho(z, t)$ decreases from the value ρ_o : part of the charge is lost to the surrounding air by corona discharge and part migrates to the metallic filter. As initial conditions we take that the initial height of the powder layer is zero and that the plate representing the filter is discharged.

The solution of Eq. 4 for $t \leq t_o$ is:

$$\begin{aligned}\rho(z, t) &= \rho_o \exp \left[-\frac{\sigma}{\epsilon} \left(t - \frac{\rho_m}{F_m} z \right) \right] \Theta \left(t - \frac{\rho_m}{F_m} z \right) \\ D_z(z, t) &= \rho_o \frac{\epsilon F_m}{\sigma \rho_m} \left\{ \exp \left[-\frac{\sigma}{\epsilon} \left(t - \frac{\rho_m}{F_m} z \right) \right] - \exp \left(-\frac{\sigma}{2\epsilon} t \right) \right\} \\ \sigma_p(t) &= \rho_o \frac{\epsilon F_m}{\sigma \rho_m} \left[1 + \exp \left(-\frac{\sigma}{\epsilon} t \right) - 2 \exp \left(-\frac{\sigma}{2\epsilon} t \right) \right]\end{aligned}\quad (5)$$

The total charge per unit area in the layer of powder for $t \leq t_o$ is given by:

$$\frac{Q}{A} = \int_0^{H(t)} dz \rho(z, t) \Rightarrow \frac{Q}{A} = \rho_o \frac{\epsilon F_m}{\sigma \rho_m} \left[1 - \exp \left(-\frac{\sigma}{\epsilon} t \right) \right]\quad (6)$$

While the powder layer is growing $t \gg \epsilon/\sigma$ the electric displacement on the surface of the powder layer tends to the value:

$$D_z(H, t) \rightarrow \rho_o \frac{\epsilon F_m}{\sigma \rho_m} = D_{z,lim}\quad (7)$$

The electric field outside the powder layer is given by $E_z = D_z(H, t)/\epsilon_o$. If we identify the value of the electric field obtained from Eq. 7 with the electric field $E_c = 30$ kV/cm for corona discharge on air, we get:

$$E_c = \rho_o \frac{\epsilon}{\epsilon_o} \frac{1}{\sigma} \frac{F_m}{\rho_m}\quad (8)$$

From this equation we can also evaluate the effective conductivity of the powder σ if we assume that the charge per unit volume of a newly deposited layer ρ_o is formed by particles charged up to the limit set by Eq. 2. In this case:

$$\rho_o = \frac{3\epsilon_o E_c}{r_p} \rightarrow \sigma = \frac{3\epsilon F_m}{r_p \rho_m}\quad (9)$$

In our experiments, the mass flow rate into the collecting cell was 0.2 g/s, while the diameter of the collecting cell was 4 cm. In total, the mass flow rate per unit area is 0.16 kg/(m²s). In using Eq.9, we assume the solid fraction of the settled material is $\phi = 0.6$, the density of bulk glass is 2.5 g/cm³, $r_p = 17.0$ μ m for the 5-50 μ m glass beads and $r_p = 46.0$ μ m for the 70-110 μ m glass beads. The dielectric permittivity of both powders is $\epsilon = 2.95\epsilon_o$ assuming the dielectric constant of bulk glass is 5 and that the dielectric constant of glass powder can be found using Bruggeman mixing rule [5]. Under these assumptions Eq. 9 predicts an effective conductivity of $\sigma = 0.29$ nS/m for 5-50 μ m glass beads and $\sigma = 0.10$ nS/m for 70-110 glass beads, one order of magnitude less than the value measured directly (see Fig. 5).

The theoretical model outlined here predicts that the total charge per unit area in the collected layer of powder layer is given by:

$$\frac{Q}{A} + \sigma_p = 2\rho_o \frac{\epsilon F_m}{\sigma \rho_m} \left[1 - \exp \left(-\frac{\sigma}{2\epsilon} t \right) \right]\quad (10)$$

If the values obtained for ρ_o , σ and ϵ are substituted in Eq. 10 we can obtain a prediction of the specific charge qmr as a function of the collected mass $m(t)$. The resulting curve for 5-50 μm glass beads is plotted in Fig. 4, where it can be compared with the experimental data. The model seems to give the correct trend in the data of specific charge against collected mass, although the values of the specific charge are about an order of magnitude smaller than the experimental values if a value of $\sigma = 0.29$ nS/m is used. Larger values of the effective conductivity increase the discrepancy between the predictions of the model and the experimental results.

6 Conclusions.

From the experiments presented in this manuscript it can be concluded that the rate of charge dissipation in a settled bulk powder would depend on the effective conductivity of the powder. Large accumulations of electric charge would appear in those situations in which the charge on the bulk powder is replenished by the arrival of charged particles at a rate faster than the rate of charge dissipation. If the uncharged particles leave the bulk powder for some reason, there would be an equilibrium between inflow of charge and its dissipation leading to a stable value of the charge to mass ratio. If the uncharged particles remain in the bulk powder, as it is the case for example of heap formation, the charge to mass ratio of the powder will decrease with time even as new charged particles are constantly arriving. However, although as a whole the powder discharges, those regions of the bulk powder formed by newly arrived particles would still hold large concentrations of electric charge, giving rise to localized regions of high electric fields.

Acknowledgements

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