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The spatio-temporal evolution of tribo-electric charge transfer during the pneumatic conveying of powders: Modelling and experimental validation

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ABSTRACT

This study considers the tribo-electric charging of materials during the dilute phase pneumatic conveying of powders. The main objective of the work is to develop a phenomenological model capable of describing the spatio-temporal evolution of charges of both the powders and pipe wall. The model is based on a second order kinetic for the charge transfer between the two materials (*i.e.* the elementary mechanism of charge transfer is considered to be the binary particle – wall collisions). The results show that the excess or lack of chargeability of the wall is the key parameter regarding the charge acquired by the particles. For wall chargeability levels less than that of the powder (excess ratios smaller than unity) the pipe wall becomes almost saturated over time so that the accumulated charge of the particles tends to an asymptotic limit imposed by the chargeability of the wall. For excess ratios greater than one, the particle charge is no longer limited by the charge of the wall but by the intrinsic chargeability of the particles. The accumulated charge of particles varies linearly with time and could potentially tend to saturation. In addition, for initial excess ratios greater than 3, the particle charge varies linearly with time. Finally, a comparison between the experimental and calculated data was carried out and permitted the validation of the model.

1. Introduction

Charge transfer during powder handling is a major concern for developing reliable processes involved with particular materials. Indeed, electrostatic charging of powders could cause productivity losses and affect the quality of the product, as well as more severe problems like explosions. One of the most charge generating processes in the industry is the pneumatic transport of bulk materials. It is therefore of great interest to develop relevant models to qualitatively describe the effect of the governing parameters on the tribo-charging process, and particularly on the rate of charge transfer and the maximum charge of the particles. However, very few general models have been proposed in the literature that take into account charge transfer during the pneumatic transport of bulk materials. One of the main reasons is the difficulty in expressing the elementary mechanisms involved with charge generation during the particle – wall impacts. Consequently, modelling of the tribo-charging process has so far been based on macroscopic approaches and requires knowledge of experimental data to determine the so-called adjustable or global parameters of models by back-calculation. Nevertheless, the use of this type of model is not ineffective because it permits quantitative comparisons of results on one hand, and allows a better understanding of the phenomena observed on the other hand. In addition, once validated by experimental data, the use of a model allows prediction of the behaviour of a given system in larger scales of time or transport length.

One of the pioneer works in this field was that conducted by Cole et al. (1969–70) who proposed a model for the prediction of the tribo-charging rate during the repeated impact of particles with a transport pipe. These authors assumed that the quantity of charge acquired from each impact by a single particle was proportional to the difference between the saturation (maximum) charge and the instantaneous charge of the particles before impact. The basic contribution of this investigation was to demonstrate that the electric current generated by the charge transfer in a given length of pipe was a deceleration exponential function of the number of particle-wall collisions. Although this relationship was only established theoretically in the work of Cole et al., this dependency was confirmed by several other experimental works, either on the pneumatic transport of powders (Masuda et al., 1976; Artana et al., 1997) or on repeated impacts of single particles on a target. Although the charge transfer during a single impact is found to vary linearly with the maximum

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contact area during impact (Matsusaka et al., 2000) for repeated impacts of a single particle the charge accumulation decelerates as the particle's surface becomes increasingly charged (Masuda and Iinoya, 1978; Touchard et al., 1991; Greason, 2000). It should be noted that the fact that the model of Cole et al. predicts a first order kinetic is not surprising because in this model the charge saturation of the wall is not taken into account, *i.e.* the wall's charge is assumed to be continuously transmitted to the Earth. However, in the case of an insulator or unearthed wall, the charging of the pipe will in turn affect the tribo-charging of particles. Therefore the aim of this study was to establish a model to describe the simultaneous variations of the charge on the particles and the walls with respect to time and transport length. The model was established using a conventional charge balance by treating the transferred charge as a continuum and considering a second order kinetic law for charge transfer.

In order to establish such a model, it is to be noted that during the pneumatic transport operation, electrostatic charges appear as a result of collisions between particles and the wall, or between particles of different nature (Chang et al., 1995; Cross, 1987; Crowley, 1999; Bailey, 1984, 1993, 2001; Castle, 2008; Matsusaka et al., 2010). Both materials are then charged oppositely. Matsusaka et al. (2010) recently published a comprehensive review of the state of understanding on tribocharging phenomena. Furthermore, studies on charge transfer during a single impact have been made by Matsusaka et al. (2000) and Watanabe et al. (2007). According to the literature, the driving force for the charge transfer is the difference between the so-called work function of materials coming into contact (*e.g.* Matsusaka et al., 2010). Originally, this concept was introduced (Harper, 1967) to describe the contact charging between metals for which the elementary mechanisms of charge transfer are well established. Its use for insulator materials is commonly admitted but is less straightforward due to lack of data for band structures (*e.g.* Matsusaka et al., 2010). For a single contact between two materials, the higher the difference of the work functions, the more intense the charge transfer. However, the maximum charge that can be built up on a surface is limited by two factors: the surface density of the donor/acceptor sites capable of exchanging charges and the breakdown potential of the surrounding atmosphere. The latter factor depends on the chemical nature of the materials used as well as some physical characteristics such as surface roughness, crystallinity, moisture content and the presence of impurities. From the former point of view, the maximum charge density of solids in dry air, for example, is about $2.6\times10^{-5}\,\mathrm{C\,m^{-2}}$ (Bailey, 1993, 2001; Chang et al., 1995; Cross, 1987; Crowley, 1999). Indeed, at this level of charge, the electric field in air reaches its breakdown strength (about $300\,\mathrm{MV\,m^{-1}}$). This results in air ionisation, in turn leading to the surface charge being dissipated. Note that even for highly charging materials like polymers, only the first factor is predominant in preliminary stages of the operation (short periods of time or short transport lengths).

It is to be noted that the concept of charge transfer and equilibrium charge (i.e. the charge level at which no charge transfer takes place) has been outlined in the literature and quantified for a number of materials by Watanabe et al. (2007).

2. Model development

Consider a flow of particles conveyed pneumatically through a horizontal cylindrical pipe (Fig. 1). Each particle is charged progressively due to repeated impacts with the wall as it moves forward through the pipe. At the same time, as a result of each collision the pipe wall acquires a charge of opposite sign but equal to the difference between the charge of the particle before and after impact. Generally, the amount of charge transferred is proportional to the *chargeability* of the two materials, *i.e.* the higher the charges of materials the lower the net amount of charge exchanged during a collision.

2.1. Assumptions

Let us assume the following hypotheses:

1) Air flow is carried out in a steady state regime.
2) Pipe is initially unfilled and hence the particle flow is not steady and begins at time zero from the entrance. The particles flow achieves a steady regime once the first particles leave the pipe.
3) The number density and velocity of particles at any given section of the pipe remain constant with time.

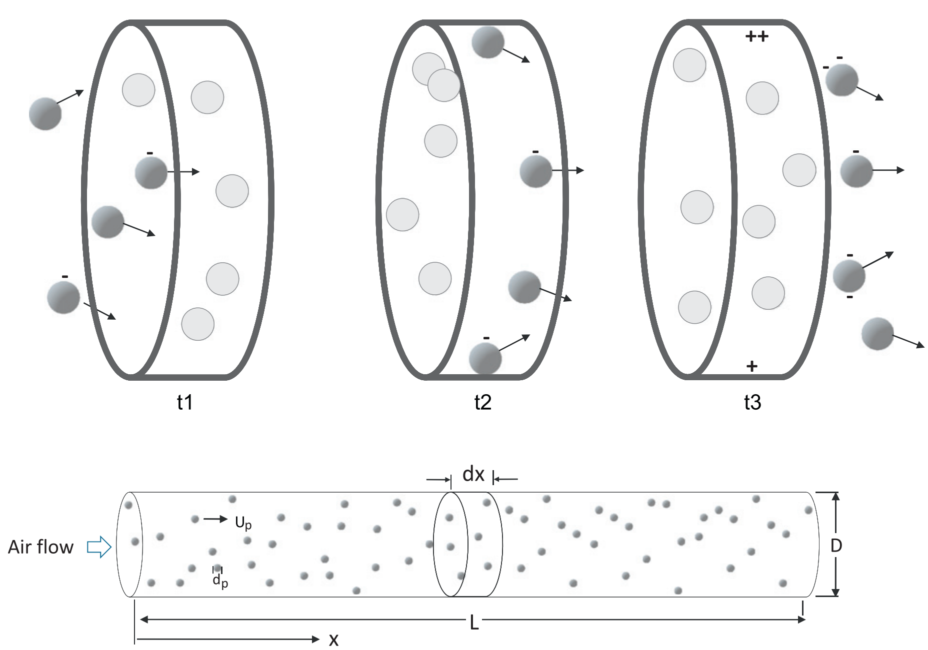

Fig. 1. Simplified scheme of dilute pneumatic transport of particles.