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Modelling of spatio-temporal evolution of electrostatic charge transfer during the pneumatic transport of powders: General solutions and special cases

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HIGHLIGHTS

- A theoretical model for the evolution of electrostatic charge of powders is given.
- Analytical solutions for general model and simplified cases are developed.
- Charge transfer due to particle-wall impacts were described by a mechanistic model.
- A dimensionless group was established to predict the dominant tribo-charging regime.

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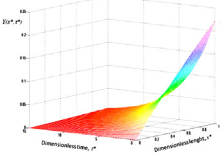
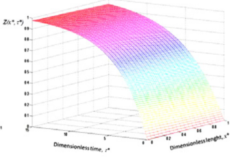
GRAPHICAL ABSTRACT



Charge of particles



Charge of the wall

ABSTRACT

Simultaneous tribo-charging of the wall and particles during pneumatic transport of powders in dilute phase is modelled. The concepts of "simple-condenser model" and "effective work function" are used to take into account the local charge transfer between the two materials during particle-wall collisions. Exact analytical solutions are provided for the model. It is shown that, the tribo-charging process is mainly governed by the ratio between the charge transfer constants of the wall and particles. The results show that for high tribo-charging conditions of wall with respect to particles, the accumulated charge of the particles tends to an asymptotic limit imposed by the charge saturation of the wall. For low charging walls, the particle charge is no more limited by the charge of the wall and increases continuously. Quantitative analyses show that the predominant regime (*i.e.* particles or wall limited) could be fairly predicted using a dimensionless group ($3\beta D/2d_p$) based on the volume fraction of the powder, β, the pipe diameter, D, and the particles mean diameter, d_p. Furthermore, a dimensionless criterion is established allowing the prediction of tribo-charging regimes and the trend of space evolution of particles charges. A comparison between the experimental and calculated data was carried out and permitted the validation of the model.

1. Introduction

Tribo-electric charging of particles is a highly important subject in powder technology. In particular, charge transfer during pneumatic conveying of powders could affect the quality of the final product (Bailey, 1984, 1993, 2001), energy loss and the efficiency of the production unit (Ally and Klinzing, 1983, 1985; Clark et al., 1952; Culgan, 1952; Larouere et al., 1984; Mitlin, 1954; Richardson and McLeman, 1960; Smeltzer et al., 1982; Wang et al., 2000) and lead to severe safety problems (Abbasi and Abbasi, 2007; Boschung and Glor, 1980; Deleuil et al., 1994; Glor, 1988, 2003; Grossel, 1988; Hoppe et al., 2000; Jaeger, 2001; Lunn, 1992;

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Nifuku and Enomoto, 2001; Nifuku and Katoh, 2003; Zhang et al., 2008). Developing reliable models is then useful for describing the tribo-charging process as well as predicting the effect of operating conditions and materials properties on the extent of charge transfer. Indeed, the lack of knowledge on this matter does not yet permit fully predictive models to be established. Much more experimental work is needed to achieve satisfying and reliable results. However, developing phenomenological models deepened by mechanistic concepts would permit a better understanding of phenomena observed in practice and provide a formal framework to better analyse the experimental data.

The aim of this work is to propose such a model to describe the spatio-temporal evolution of tribo-electric charge transfer during the pneumatic transport of particles in dilute phase.

2. Previous works

The present work puts emphasis on the phenomenological modelling of charge accumulation of materials during the pneumatic conveying operation. It is then out of the scope of this work to present an exhaustive review of the relevant literature which can be found elsewhere (Castle, 2008; Chang et al., 1995; Cross, 1987; Crowley, 1999; Matsusaka et al., 2010; Ndama et al., 2011; Saleh et al., 2011).

One of the earliest works on modelling of tribo-charging during pneumatic conveying was reported by Cole et al. (1969-70). These authors proposed a model for the prediction of the tribo-charging rate during repeated impacts of particles with the pipe′s wall. Neglecting the simultaneous charge accumulation of the wall, these authors found that charge transfer of particles follows first order kinetics. By integrating this law over the pipe′s length, they showed that the electric current generated in a given point of the pipe was a deceleration exponential function of the number of particle-wall collisions. A similar conclusion was made by Artana et al. (1997). However, the charge accumulation of the wall could only be neglected in special cases (*e.g.* if the pipe is made of conductor materials and earthed so that charges are continuously transmitted to the ground). In other cases, the wall charge could considerably affect the phenomena (*e.g.* Dragan et al., 2009a, 2009b) until the charge transfer is blocked when the wall is saturated (Inculet et al., 1997). To overcome this drawback, in a recent work Saleh et al. (2011) established a simple model of charge transfer to describe the simultaneous variation of wall′s and particles charge. The charge transfer was considered to take place at the mean charge level within the pipe. Hence, the model was not able to follow the space variations of the charge but only the time evolution of the charge of exiting particles as well as the overall charge of the wall. One of the conclusions of this work was that the charge of exiting particles decreases progressively with time due to charge accumulation on the wall′s surface whereas the accumulated charge of the wall increases according to a decelerating exponential law.

More recently, Saleh and Aghili (2012) established a more complete model that considers the spatio-temporal variations of the charge on the particles and the walls with respect to time and pipe length. This model is based on a general charge and considers a second order kinetic law for charge transfer. The hypothesis of a second order kinetic law was justified by the fact that the driving force for the charge transfer depends on chargeability of both surfaces (*i.e.* the difference between their actual charge and the charge at saturation) and the phenomenon comes to the end as soon as one of them at least is saturated. However, this hypothesis doesn′t lie in mechanistic basis and is only of qualitative significance. In addition, due to second order law, analytical solutions for the model equations could only be established for special cases whereas the general case requires numerical solutions. This paper proposes an improved form of this model making use of physical concept of “simple-condenser model” commonly used to describe the charge transfer between materials in contact (Section 3.1). Compared to the previous work of Saleh and Aghili (2012), the present paper provides two important enhancements. First, the charge transfer is considered from a mechanistic rather than a qualitative point of view. It becomes then possible to relate the macroscopic behaviour of particles to their measurable physical properties. Second, analytical solutions are established for the model which is important to point out general trends based on combination of operating conditions and particles properties.

3. The model

The system considered here is a flow of individual particles moving inside a cylindrical pipe (Fig. 1). As a consequence of repeated impacts with the wall, particles are charged progressively during their transport. Similarly, after each collision the pipe′s wall acquires an opposite charge equal to the difference between the charge of the colliding particle before and after impact. This phenomenon tends to decrease the extent of charge transfer during further collisions. Therefore, in order to properly describe the tribo-charging of particles it becomes necessary to simultaneously analyse the charge of both particles and wall with respect to the time and the space. A physical analysis of this problem can be made based on the charge conservation law. In fact, for any given differential control volume of this system, the charge balance is written as (Chang et al., 1995):

$$\frac{\partial \psi(x,t)}{\partial t} + \nabla \times \sigma(x,t) = R(x,t) \qquad (1)$$

where ψ is the charge density inside the control volume (*i.e.* the amount of charge per unit volume of the tube) and σ is the current density (*i.e.* current per unit area). The first term on the left-hand-side of this equation takes into account the charge accumulation inside the elemental volume whereas the second term corresponds to the charge variation due to flow of charged particles into, and out of, the control volume (convection). The term $R\ (x,t)$ refers to the rate of charge transfer between the particles and the wall per unit volume of the pipe. Although the wall and the particles acquire opposite charges, as a convention, all the charges will be expressed as positive quantities invoking positive and negative signs as required when such expressions are used.

To establish a model describing the charge evolution of the transport unit presented in Fig. 1 the following assumptions are made:

- very dilute phase transport is considered so that the charge transfer occurs mainly due to particle-wall collisions. Charge generation or dissipation by particle-particle collisions is then neglected.
- from a hydrodynamic point of view, steady-state conditions and plug flow are assumed for the particles and the gas streams. It implies that the tribo-charging phenomenon does not affect the hydrodynamics of the system.

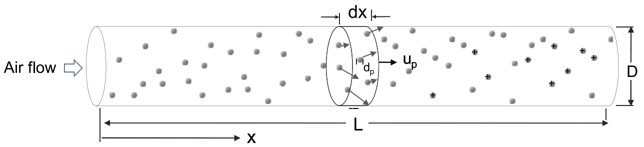

Fig. 1. A schematic representation of tribo-charging process during dilute phase pneumatic transport.