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Numerical study of the influence of the powder and pipe properties on electrical charging during pneumatic conveying

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ABSTRACT

During pneumatic transport, powders often experience the build-up of electrostatic charge due to collisions of the particles with the pipe. Since this can lead to hazardous spark discharges with unwanted implications, such as accidental explosions, there is a strong interest in exploring various options to limit this electrification process. In this paper we present the results of numerical simulations that we performed in order to evaluate the influence of the material properties of the powder and pipe, respectively, on this process. In our study, the turbulent flow of the carrier gaseous phase was treated numerically via Large Eddy Simulations while the particles were tracked individually in Lagrangian framework. Four-way coupling between the powder and the gaseous phase was also assumed. Our numerical simulations predicted that the particle Poisson ratio and Young's modulus, its electrical resistivity, as well as the permittivity represent promising measures to control the charge of the powder. More specifically, an increase of each of these quantities by 50% may lead to a decrease of the powder charge of up to 40%.

1. Introduction

Powders often gain electrostatic charge during pneumatic transport, which can lead to hazardous spark discharges. In the past, such discharges have been the cause of numerous dust explosions. On the other hand, dust explosions are especially dangerous since the resulting heat radiation lasts much longer than in typical gaseous explosions [9]. For this reason, a significant research effort has been devoted to the understanding of the physics underlying the charging process of powders. Moreover, in modern technological applications, such as lithography and visual displays, there is a strong need to find methods to influence the charging process in a desired way.

In the literature there are several experimental studies (e.g. [7,35,38]) as well as numerical investigations (e.g. [24,41,45]) that examined the effect of the conveying conditions on the powder electrification. Through that, consensus concerning the high sensitivity of the powder charge on their transport velocity was reached. The rapid development of the field of Computational Fluid Dynamics (CFD) made computer simulations a reliable tool to model this kind of complex flows. Also, in a recent study of ours, the charge exchange of a particle with a pipe wall and the subsequent electrostatic field was successfully predicted via numerical simulations [13]. In the same study, we also modeled the charge build-up of polymethyl methacrylate (PMMA) powder during pneumatic conveying. This was achieved by implementing dynamic models describing the charge exchange between particles and the pipe and in-between particles. The turbulent flow inside the pipe was treated numerically via the technique of Large Eddy Simulation (LES) according to which the large turbulent structures are directly resolved whereas the structures smaller than the grid resolutions are suitably modeled. The same methodology was employed in a subsequent study [12] to evaluate the influence of the design parameters of a pneumatic system on the powder charge. Therein, the conveying gas velocity was confirmed to be the most important factor to enhance the electrification process. On the other hand, the powder mass flow rate and the pipe diameter were predicted to have a minor effect.

Nonetheless, there is a consensus that, besides these aforementioned design parameters, the mechanical and electrical properties of the particle and pipe materials can also significantly affect the charging process. However, up to now, only a few and sporadic investigations have been devoted to this issue. The influence of the type of material on the contact potential difference due to different work functions was already quantified in an early work by Harper [22]. His investigations involved a chromium sphere in contact with another metal sphere of a different kind. This study was later extended by Davies [4] and Murata and Kittaka [34] to charge

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exchanges during contact between a metal and an insulator. Later developments [1,25,27] took into account the dependency of the charge exchange between two insulators on the materials involved.

Based on this information, Matsusaka et al. [31] proposed to maintain the charge of powder during pneumatic transport at a low level by combining pipes of different materials. To test their idea, they connected alternately one-meter long pieces of steal and brass pipes. With this configuration, the particles gained positive charge during collisions with the steal pipe but negative charge with the brass pipe. As a result, the specific charge of the powder remained within certain limits. Instead, in a subsequent study, Matsusaka et al. [30] considered a pipe made of combinations of two different materials. By doing so, the charge on the particles reached its limiting value without the fluctuations that necessarily appear when using pipes of different materials connected in series.

The possibility of reducing the powder charge via the addition of anti-static powders, such as Larostat-519, was explored by Wang et al. [44]. Subsequently, Zhu et al. [50] reported that the charging of a non-conductive pipe is significantly reduced by adding a small amount (0.5% by weight) of this agent. They put forward that Larostat-519 forms a thin layer on the particle surface and on the pipe walls, resulting in a reduction of the contact potential. Interestingly, in an earlier study without this agent Zhu et al. [51] had observed a particular flow pattern which they referred to as *annular capsule* flow. However, in their subsequent study in which they added the agent, Zhu et al. [50] reported that this pattern disappears when the afore-mentioned agent is added. This suggests that powder charging has an influence of the flow patterns that are developed during pneumatic conveying.

All of the above studies were focused on modifying the electrical properties of the system consisting of the two-phase mixture and the pipe walls. More recently, Sow et al. [40] measured the charge transfer between spheres of different materials and latex rubber sheets, which were subjected to mechanical strain. They observed that strain can reverse the direction of the charge transfer which they attributed to an alternation of the physico-chemical properties of the material surface. Furthermore, they reported a decrease of the transferred amount of charge when strain is applied. They attributed this behavior to the decrease in the material elasticity under strain. This produces a reduction to the contact area between a spherical particle and the sheet which, in turn, causes the decrease in charge transfer.

In the literature there only a few studies available that deal with the influence of the electrical and mechanical properties of the powder and the pipe on the charge build-up process. While an exhaustive study of this subject is not available yet, the research presented herein aims to filling this gap by means of numerical investigations. More specifically, the mechanical properties under study are the Poisson ratio and Young's modulus of both the pipe and the particle material. Further, the electric properties involve the resistivity of the particle and the permittivity of the system.

The paper is organized as follows. The mathematical model and its validation are elaborated in Sections 2 and 3. Afterward (Section 4), the investigated properties are detailed. In the end, the results are discussed (Section 5) and final conclusions are given (Section 6).

2. Mathematical model

According to our approach, the description of the flow of the carrier gas is based on the Navier-Stokes equations with constant diffusivities, whereas the motion of each particle is tracked individually according to the Discrete Element Method (DEM). The governing equations for the gaseous phase are solved in Eulerian framework whereas those of the powder are solved in a Lagrangian framework. The suitability of this approach to treat pneumatic conveying processes has been demonstrated and discussed in detail by Zhu et al. [49] and Zhou et al. [48]. Further, as regards the motion of powder, we assume four-way coupling [6]; in other words, we take into account momentum exchange between the gas and the particles via aerodynamic drag and also momentum exchange due to particle collisions. The complete mathematical model used in the study is given in detail by Grosshans and Papalexandris [13] and is outlined below. Special attention of our description is paid on the presence of the material properties in the equations that describe the charge exchange process.

By spatially filtering the Navier-Stokes equations, we obtain the equations that are used in LES. According to this technique, the large-scale turbulent structures of the flow field, which have a leading effect on the particle dispersion, are directly resolved on the grid. The momentum fluxes caused by the action of the small, unresolved turbulent structures are modeled as additional stresses according to the Smagorinsky model. The Smagorinsky constant is calculated by the dynamic approach of Germano et al. [8] using the least-square technique and averaging in the streamwise direction as proposed by Lilly [26]. In order to reduce the requirements on the grid in the near-wall region the wall model by Grötzbach [20] is introduced.

The governing equations for the gaseous phase are discretized via finite differences. As regards spatial discretization, the convective terms are approximated up to fifth-order and the diffusive and pressure terms up to fourth-order of accuracy. On the other hand, time integration of the governing equations is performed via an implicit second-order backward scheme. The reader is referred to Gullbrand et al. [21] for further details concerning the numerical implementation.

Each individual particle is assumed to be isolated, rigid and spherical. The acceleration of each particle is given in the Lagrangian framework by

$$\frac{d\boldsymbol{u}_\mathrm{p}}{dt} = \boldsymbol{f}_\mathrm{ad} + \boldsymbol{f}_\mathrm{el} + \boldsymbol{f}_\mathrm{g} + \boldsymbol{f}_\mathrm{col}\,, \tag{1}$$

where $\boldsymbol{f}_\mathrm{ad}$, $\boldsymbol{f}_\mathrm{el}$, $\boldsymbol{f}_\mathrm{g}$ and $\boldsymbol{f}_\mathrm{col}$ denote the acceleration due to the aerodynamic, electric field, gravitational and collisional forces, respectively. The collision forces include both, inter-particle and particle-wall collisions. The acceleration of a particle due to the electric field forces, $\boldsymbol{f}_\mathrm{el}$, is calculated by

$$\boldsymbol{f}_\mathrm{el} = \frac{Q\,\boldsymbol{E}}{m_\mathrm{p}} \tag{2}$$

where Q and m_p are the charge and the mass of the particle, respectively. The electric field strength, $\boldsymbol{E}$, is the gradient of the electric potential, ϕ,

$$\boldsymbol{E} = -\nabla\phi\,. \tag{3}$$

This, in turn, is described by the Poisson equation,

$$\nabla^2\phi = -\frac{\rho_\mathrm{el}}{\varepsilon_0}\,. \tag{4}$$

which is also solved numerically via finite differences. In the above equation ε_0 is the permittivity of the gaseous phase and its value is set at $\varepsilon_0 = 8.854\cdot10^{-12}\ \mathrm{F\,m^{-1}}$. The electric charge density, denoted by ρ_el, is calculated by taking into account the individual positions and charges of the present particles.

Charge exchange, as well as momentum exchange, takes place when a particle collides either with the wall of the pipe or with another particle. With regard to momentum exchange, and for the sake of simplicity, we consider that binary particle collisions are fully elastic. In other words we assume that, during binary collisions, the