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Evaluation of the parameters influencing electrostatic charging of powder in a pipe flow

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A B S T R A C T

Triboelectric charging of powders during pneumatic transport can lead to hazardous spark discharges. In this study, the charging process was studied numerically by means of large eddy simulations. A range of design parameters was then analyzed statistically applying the Design of Experiments methodology. It is shown that the electric charge of the powder can be significantly decreased by reducing the conveying air velocity. Furthermore, the usage of pipes of a larger diameter and the application of higher solid mass flow rates also reduce the powder charge.

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1. Introduction

Pneumatic transport of powders is commonly used in numerous process industries. During transport, the particles experience frequent collisions with the pipe. If the particle and the pipe are made of different materials, then the individual particles gain electric charge during these collisions. This can reduce the performance of the piping system due to deposition of charged particles at the pipe wall (Adhiwidjaja et al., 2000; Guardiola et al., 1996). The build-up of electrostatic charge can even lead to hazardous spark discharges.

This, in turn, might cause dangerous explosion events. Several exemplary cases of dust explosions during the filling of silos storing fine chemicals and plastic products are discussed by Glor (2001). In that work, and in the case of plastic products a change made in the process leading to a greater product throughput was identified as having increased the electrostatic charge. Also, Nifuku and Katoh (2003) reported that 198 dust explosions caused by static electrification occurred in Japan between the years 1955 and 1994. Further, Glor (2003) pointed out that dust explosions are even more hazardous than gas explosions since the resulting heat radiation lasts much longer. Therefore, a significant research effort has been focused towards a better understanding of the physics underlying the charging process of powders, respectively its prevention.

For example, ionizers have been developed and tested by Mogami et al. (2010) and Choi et al. (2016) to reduce the powder charge. By using either their newly developed feedback control system or bipolar ionizer they were able to decrease the electrostatic field strength in the loading pipe of charged polypropylene powder close to zero. On the other hand, Klippel et al. (2014) approached the problem by knowledge concerning the local dust concentration during the filling of a vessel. A combined experimental and numerical approach was chosen to predict parts of the vessel where the lower explosion limit is reached and exceeded. This could help to improve dust explosion protection. General guidelines for the design and operating practices for safe conveying of particulate solids are given by Grossel (2012). These include for instance the recommendations to minimize the dust leakage in order to prevent a combustible atmosphere outside the system, to use conductive pipe materials and principles of proper grounding.

Even though the above discussed measures ensure process safety, one might try to reduce the actual charge build-up during conveying by means of design. However, when designing a pneumatic conveying system, some parameters are fixed with respect to the purpose of the system. For example, while the electrical and mechanical properties of the particles play a major role for the

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powder electrification, the designer of the piping system has very little influence on them.

On the other hand, other parameters might be variable and can be determined by the designer. It is therefore of strong interest to adjust these parameters in order to reduce the powder charge. For this reason, Nifuku and Katoh (2003) measured experimentally the powder electrification in pipes for different conveying air velocities. In particular, they reported an increase in the charge for higher air velocities, at least until saturation is reached. The same conclusions can be drawn from experimental results presented by Watano et al. (2003) even though this tendency is less clear in the numerical data included therein. However, it should be noted that the numerical calculations of Watano et al. (2003) were conducted by applying an a priori defined velocity profile of the gaseous phase.

Further, Fath et al. (2013) measured the influence of the solid mass flow rate on the powder charge experimentally. For all reported materials, which include polysterene, melamine and lewapol, an inversely proportional relationship between the charge and the throughput was observed. The experimental results by Watano et al. (2003) also suggest such a relationship, albeit less noticeable. However, the simulations reported in that article did not predict an inverse proportionality between charge and throughput.

Besides the aforementioned numerical studies, Kolniak and Kuczynski (1989) and Tanoue et al. (1999) computed the electrostatic charging of powder by solving the Reynolds Averaged Navier-Stokes (RANS) equations for the carrier fluid. However, the RANS approach can only predict the (time) average velocities and cannot resolve any of the turbulent structures that are developed in the flow. Therefore, the RANS methodology provides limited information about the interaction between the flow turbulence and the particle charging. Moreover, the influence of operation parameters was not discussed in the above works. In contrast, time resolved simulations were performed by Lim et al. (2012) to investigate the trajectories of charged particles within a charged pipe. Nevertheless, the charges were assumed to be constant and the actual charging process was not the scope of this analysis.

When studying the influence of certain conditions, researchers often vary only one parameter and elaborate its effect on the results. Since the number of required experiments scales with the dimensions of the parameter space, this approach can lead to an unaffordable effort. However, a possibility to reduce the number of required simulations and to analyze the results is offered by the Design of Experiments (DoE) methodology. In general, DoE aims to reveal the relation between influential factors and responses, i.e. depending variables. At the same time the number of required experiments are reduced to a minimum. For details of the underlying theory of DoE, the reader is referred to the review articles of Leardi (2009) and Dejaegher and Heyden (2011) or to the book of Kleppmann (2013).

DoE has been extensively used before to assess the dependence of various physical or technical phenomena on variable parameters. Bravo-Linares et al. (2013) explored the influence of the type and quantity of naturally occurring bacteria on biodegradation of spilled oil in coastal zone areas. Elfstrand et al. (2007) evaluated the recrystallization of waxy maize starch during manufacturing of starch microspheres depending on the process temperature and the incubation time. Even if DoE traditionally relates to laboratory testing, the terminology also includes numerical experiments. For instance a combined experimental and numerical approach was chosen by Grosshans et al. (2016). In the latter, the significance of the process temperature, initial droplet diameter and solute content on the characteristics of particle produced in drying apparatus was analyzed via DoE.

Since Computational Fluid Dynamics (CFD) proved to be a reliable tool for flow situations, in the context of the present study, we performed Large Eddy Simulations (LES) in conjunction with DoE. In LES the large turbulent scales are resolved while the small universal scales are modeled. We assessed the sensitivity of electrostatic powder charging for a wide range of conveying conditions. The chosen conditions are those which can be altered by the designer for a given material system, including different conveying air velocities, solid mass loadings and pipe radii. Detailed numerical models, which have been implemented previously by Grosshans and Papalexandris (2016), were used to evaluate the charge exchange between the pipe and individual particles during wall collisions.

This paper provides a guideline to reduce the expected electrostatic powder charging when designing pneumatic systems. By applying the DoE methodology not only the influence of single parameters but also their interactions are explored. Exploiting the detailed level of information provided by LES, clear conclusions concerning the underlying physical mechanisms are drawn.

The article is organized as follows. The second section is devoted to the description of the mathematical model upon which the simulations are based. The third section describes the conditions studied in the present DoE, and, finally, the fourth section contains the presentation and discussion of the results.

2. Mathematical model

The mathematical model used in the study has been described in detail by Grosshans and Papalexandris (2016) and is outlined in the following.

2.1. Gaseous phase

The continuous gaseous phase is described in Eulerian framework by the Navier-Stokes equations with constant diffusivities and coupled to the particulate phase by two-way coupling (Elgobashi, 1994). The volume occupied by the solid is negligible compared to the volume occupied by the gas. Thus, the volume fraction of the gaseous phase is assumed to be unity, i.e. the flow is dilute. The mass and momentum balance laws are given by

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho_g}\nabla p + \nu_g \nabla^2 \mathbf{u} + \mathbf{f}_s \tag{1b}$$

where $\mathbf{u}$, p, ρ_g and ν_g are the gas velocity, pressure, density and kinematic viscosity, respectively. A source term, $\mathbf{f}_s$, accounting for the momentum transfer from the particulate to the gaseous phase is also introduced.

By spatially filtering Eqs. (1a) and (1b), the governing equations of LES are obtained. The subgrid unresolved stresses are modeled by the dynamic Smagorinsky model. Further, the Smagorinsky constant is calculated by the dynamic approach of Germano et al. (1991) using the least-square technique and averaging in streamwise direction as proposed by Lilly (1992). As it is often the case in LES, the near-wall flow structures are modeled instead of resolved. This is done in order to avoid the usage of very fine grids that are required for the resolution of the regions near the wall, thereby significantly reducing the computational cost of the simulations. More specifically, we apply the near-wall model of Grötzbach (1987), assuming that the mean velocity profile follows the logarithmic law.

The above governing equations are discretized by the Finite Difference Method (FDM). The convective terms are approximated

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