J Biochem Tech (2019) Special Issue (2): 126-132
ISSN: 0974-2328

Simulation of Particle Pneumatic Conveying Process: Electrostatic Charge and Hazard Evaluation

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Received: 08 January 2019 / Received in revised form: 27 April 2019, Accepted: 03 May 2019, Published online: 25 May 2019

Abstract

One of the main issues related to particle technology is disasters and troubles due to the possibility of generating charged particles as a result of collisions between particles and equipment wall. Indeed, the electrostatic discharge can occur in the system leading to explosion or fire. In order to prevent these hazards, modeling and simulation of the conveying pneumatic particle are required. This paper deals with the simulation of particle pneumatic conveying process inside an inclined tube. By using a particular approach that assumes the electrification of particles inside the tube depends directly upon the vertical collision velocity against the tube wall, the model is developed. Simulation of the particle movements inside the tube, distribution of electrostatic charges over the particle surfaces as well as the possibility of fire as a result of discharging the electrostatic energy are investigated. The possibility of fire is investigated by comparing the amount of electrostatic energy with minimum ignition energy (MIE) of the particles. The capabilities of the developed model are tested and confirmed by different analysis including the effect of particle diameter, the volumetric flow of the air and the tube wall material. Finally, several solutions are proposed to manage the risk of fire and explosion.

Keywords: Electrostatics, Pneumatic conveying, Simulation, Powder technology, Particle charge.

Introduction

The technology of pneumatic conveying was developed in the middle of the 19th century. Since then, various researches have been done for analyzing the behavior of conveying particles in the tube or other geometric shapes.

One of the main issues related to powder (or particle) technology is disasters and troubles due to the possibility of generating charged particles as a result of collisions between particle and equipment wall. Indeed, when the charged particles are transported, the electrostatic discharge can be occurred which sometimes leads to fire and catastrophic events resulting in facility damage and production losses.

In order to prevent these hazards, modeling and simulation of the conveying pneumatic process are required. Modeling and simulation lead to understanding the process, which in turn leads to proper and safe design to minimize the occurrence of fire and explosions.

In the first attempts in this field, the mechanism of electrification of polymer particles by the impact on metal plates has been reported (Masui and Murata, 1983). Satoru Watano et al. (2003) used a two-dimensional discrete element method (DEM) to analyze the particle movement in a pneumatic conveying process under various operating conditions. Lim (2006) studied the pneumatic transport of granular materials through a vertical tube in the presence of an electrostatic field using the discrete element method (DEM) coupled with computational fluid dynamics (CFD). In another work, Holger Grosshans et.al (2017) evaluated the influence of the material properties of the particle and tube on the pneumatic conveying process. Numerical investigation for the simulation of electrostatic charge in particle pneumatic conveying process are also reported by some researchers (Grosshans and Papalexandris, 2017; Schwindt et al., 2017).

In this study, a particular method is used to analyze the particle movement in a pneumatic conveying process inside an inclined tube. The hydrodynamic model describing the flow behavior of the gas-solid phase is coupled with the equations governing the particle charging phenomenon. In this method, it is assumed that the electrification of a single particle is proportional to the vertical collision velocity and the number of particle collision against the tube wall. Numerical methods are used to solve a set of mathematical equations governing the system. Simulation of the particle movements inside the tube, generation of electrostatic charges over the particle surfaces, as well as the possibility of fire as a result of discharging the electrostatic energy are investigated. Furthermore, the effect of important parameters

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including the particle diameter, the volumetric flow of air inside the tube, and the tube wall material is studied.

It should be noted that in order to better understand the flow dynamics and electrostatic charging of the particles during the process, the commercially available finite element software COMSOL Multiphysics is used to simulate the motion of charged particles under different operating parameters.

The rest of the paper is organized as follows. In the next section, the outline of the simulation is briefly described. In section 3, the developed model including the main assumptions as well as governing equations are demonstrated. The results and discussion about various aspects of the developed model are presented in section 4, while section 5 concludes the paper.

The outline of the simulation

As shown in Figure 1, the particles are discharged from a feeder to an inclined tube and transport under the influence of fluid-dynamic. As a result of the collision between the particles and tube, the particles can be charged, and if the accumulation of electrostatic energy is larger than MIE (minimum ignition energy), the possibility of fire is evaluated. This is all that should be taken into consideration in the modeling and simulation.

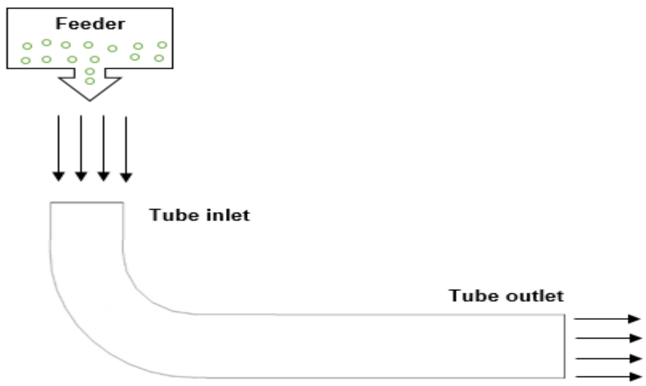

Figure 1: The schematic of the conveying process to be simulated

Model for electrification of particles

The most important variables, the variation of which to be studied are the generated electrostatic charges and the electrostatic energy of the particles. The variables of the model are influenced by several physical phenomena, and thus, the model consists of several differential and algebraic equations. At the first step, the equations related to the variation of the fluid and particle velocity are solved. Then, with the particle collision velocities toward the tube wall in hand, those parts of the equations responsible for calculating the electrostatic charges and electrostatic energy come to the solution sequence of the model, and finally the simulation is performed.

The developed Multiphysics model would be too complex without considering some assumptions. The key assumptions and the main mathematical equations governing the model are described in the following.

1) The momentum equations

The turbulent flow regime (Compressible flow with Mach number < 0.3) is assumed. Moreover, it is assumed that particle transferring does not affect on the velocity profiles of the particles in the tube.

The momentum equation of the air flow is as follows:

$$\rho(u.\nabla)u = \nabla.\left[-pl + (\mu + \mu_T)\left(\nabla u + (\nabla u)^T - \frac{2}{3}(\mu + \mu_T)(\nabla u)l - \frac{2}{3}\rho k l\right] + F + \rho g \quad (1)$$

where p is the pressure, l is the length, μ is the viscosity, ρ is the density, and F denotes to the forces acting on the fluid. Using the k- ε model (Launder and Spalding, 1983), the following equations are used for the variation of turbulent kinetic energy (k) and dissipation (ε):

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + 2\mu_t E_{ij}E_{ij} - \rho\varepsilon \quad (2)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right)+2C_{\varepsilon1}\frac{\varepsilon}{k}\mu_t E_{ij}E_{ij}-C_{\varepsilon2}\rho\frac{\varepsilon^2}{k} \quad (3)$$

where u_i is the velocity in the corresponding direction, E_{ij} denotes the rate of deformation and μ_T is the eddy viscosity. μ_T is calculated as follows.

$$\mu_T=\rho C_\mu\frac{k^2}{\varepsilon} \quad (4)$$

The equations (2) to (4) also consist of some adjustable constants, the values of which have been estimated by numerous iterations of data fitting as follows.

$C_\mu = 0.09$, $\sigma_\varepsilon = 1.3$, $\sigma_k = 1$, $C_{\varepsilon1} = 1.44$, $C_{\varepsilon2} = 1.92$

In addition, the particle momentum equation is:

$$m_p\frac{d^2x}{dt^2}=F_C+F_D+F_G \quad (5)$$

where m_p is the mass of the particle. Moreover, F_C, F_D, and F_G are the contact force (calculated by the particle collision), the drag force and the gravity force, respectively.

The drag coefficient can be calculated by equation (6).

$$C_D=\max\{\frac{24}{Re}(1+0.15Re^{0.687}),0.44\} \quad (6)$$

Note that the grinding process as a result of the particle-particle collision is neglected.

2) The equations of electrostatic charge (Q) and electrostatic energy (E) of the particles

The magnitude of the particle charge (as a result of particle and tube wall collision) depends upon the nature of the wall and particles, actual contact area, and the speed of particle towards the wall (Matsusaka and Masuda, 2003). It is assumed that only the vertical velocity component of the particles determines the impact charging of them. In addition, the contact area between the particle and tube wall is calculated based on Hertzian contact theory (Greenwood and Williamson, 1966) as follows:

$$S=\pi r_t^2=\left\{S_{max}+\left(\frac{8\rho}{3P_m}\right)\pi^2R^4(Vcos(\theta)-V_{el}^2)\right\}^{0.5} \quad (7)$$

$S_{\max}$ is the maximum contact area (Figure 2) calculated according to the following equation.

$$S_{\max}=5.41\left(\frac{1-\sigma_p^2}{E_p}-\frac{1-\sigma_w^2}{E_w}\right)^{0.4}\rho^{0.4}R^2(Vcos\theta)^{0.8} \quad (8)$$

In addition, V is the particle velocity, and V_{el} is the velocity at which the elastic limit is reached. R is the radius of the sphere and r_t denotes the radius of the contact area. P_m denotes the mean pressure over the contact area, and ρ is the density of the particle. Furthermore, E_p and E_w are the elasticity constants of the particle and wall. σ_p and σ_w are also the Poisson's ratio of the particle and wall, respectively.

Note that, since the particles are much smaller than the tube diameter, it is assumed that the particles collide with a flat plate instead of the curved plane of the tube wall.

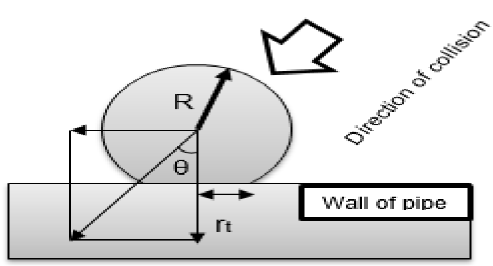

Figure 2 - Particle collision and deformation

The main goal is to estimate the particle charge generation (Q) and electrostatic energy (E) of the particles. Typically, the charging amount of the particle can be described by its charge density. Having the velocity of each particle in hand and with regard to the contact area of each particle calculated by equation (7), the Q is estimated using the following equation.

$$Q = S \times q \qquad (9)$$

In which, q is the charge density of the particle. Note that the charge density of the particle is the function of its material (Masui and Murata, 1983). The summation of the particle charge over the whole number of particle collisions obtains the total generated electrostatic charges.

For calculating the electrostatic energy, first, the charge relaxation time of the particles is calculated using the following equation:

$$\tau = \kappa \varepsilon_0 \gamma \qquad (10)$$

where κ is dielectric constant, ε_0 is vacuum permittivity, and γ is volumetric resistivity. Afterward, special capacity (C) is calculated by the following equation:

$$C = \frac{\tau}{R'} \qquad (11)$$

In which R' (resistance) can be obtained using the following equation:

$$R' = \gamma \frac{L}{A} \qquad (12)$$

Where L is the characteristic length and A denotes to the area of the particles.

In the final step, the electrostatic energy can be calculated using following equation:

$$E = \frac{1}{2} \frac{Q^2}{C} \qquad (13)$$

It should be noted that by comparing the electrostatic energy with minimum ignition energy (MIE) of the particles, the possibility of fire can be evaluated. MIE of a particle is the smallest electrostatic energy needed to ignite an optimum concentration of the material using a spark.

Results and Discussion

For conditions presented in Table 1, the simulation is performed to predict the behavior of the developed model of the particle pneumatic conveying process. The analysis of the effect of particle diameter, the volumetric flow rate of the air, and tube wall material properties on the simulation is performed, and the results are presented in next sub-sections.

Table 1 - Simulation condition

Variable name	Value	Variable name	Value
Tube diameter (m)	0.031	Particle Young module (Pa)	7.3×10^{8}
Tube length (m)	1.91	Particle density (kg/m^3)	800
Number of 90° elbow	1	Particle Poisson's ratio	0.3
Number of particles	500	Particle volumetric resistivity (Ω.m)	10^{10}
Simulation time step	6.84×10^{-5}	MIE (mJ)	25.2
Dielectric constant	6.8	Tube wall material	Stainless Steel 360

In the simulation, the initial air flow rate is 10 m^3/s, the air pressure at the outlet is 1.013×10^5 Pa, the initial values of the velocity of the particles are all zero and the tube wall is stationary. In addition, non-uniform meshing is applied to improve the computational efficiency, where the mesh is fine for great changes of variables, elsewhere the mesh is larger (Figure 3).

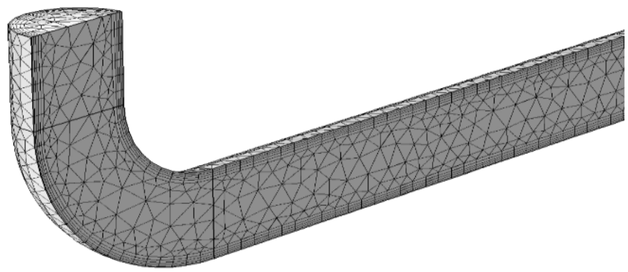

Figure 3 - Meshing scheme of the tube

Since the MIE is influenced by the moisture content of the air, air temperature and the presence of flammable vapor, these factors are kept constant in the simulation.

It is worth underlying that the simulation is in dynamic mode, and the variables are the function of both time and the location. In fact, all the variables (like electrostatic charge and electrostatic energy) have different values at each time and each position along the tube. Accordingly, only the maximum values of the electrostatic charge and electrostatic energy in each case (which indeed are the worst condition) are shown, that can be considered as the basis of the safe design.

The effect of particle diameter

As the first scenario, the effect of particle diameter is studied. Figure 4 presents the results.

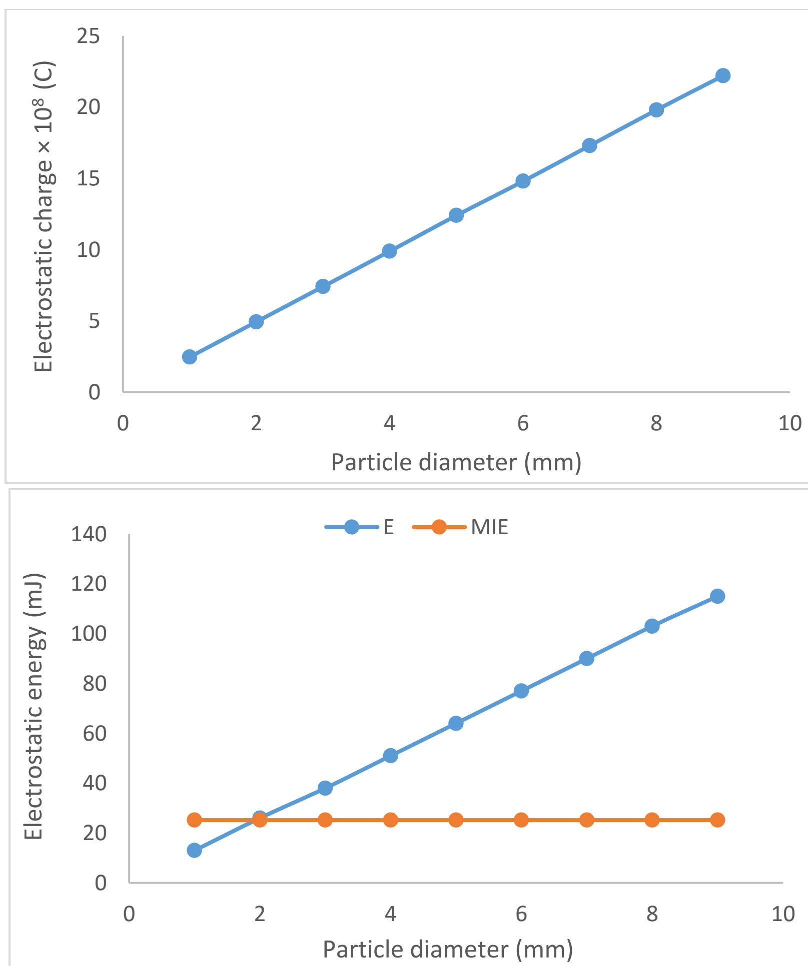

Figure 4 - The effect of particle diameter

As depicted, by increasing the particle diameter, the amount of particle charges enhances due to the possibility of increasing the contact area of the particles colliding with the tube wall. For the diameters more than 2 mm, the electrostatic energy is beyond the MIE, and the fire can be occurred. One solution to manage the risk of fire and explosion can be a reduction in the volumetric flow of air leading to reduction in particle velocity, which in turn, decreases the particle electrostatic charge.

The effect of air volumetric flow rate

As the second scenario, the air flow rate is increased linearly, and its effect is studied (Figure 5).

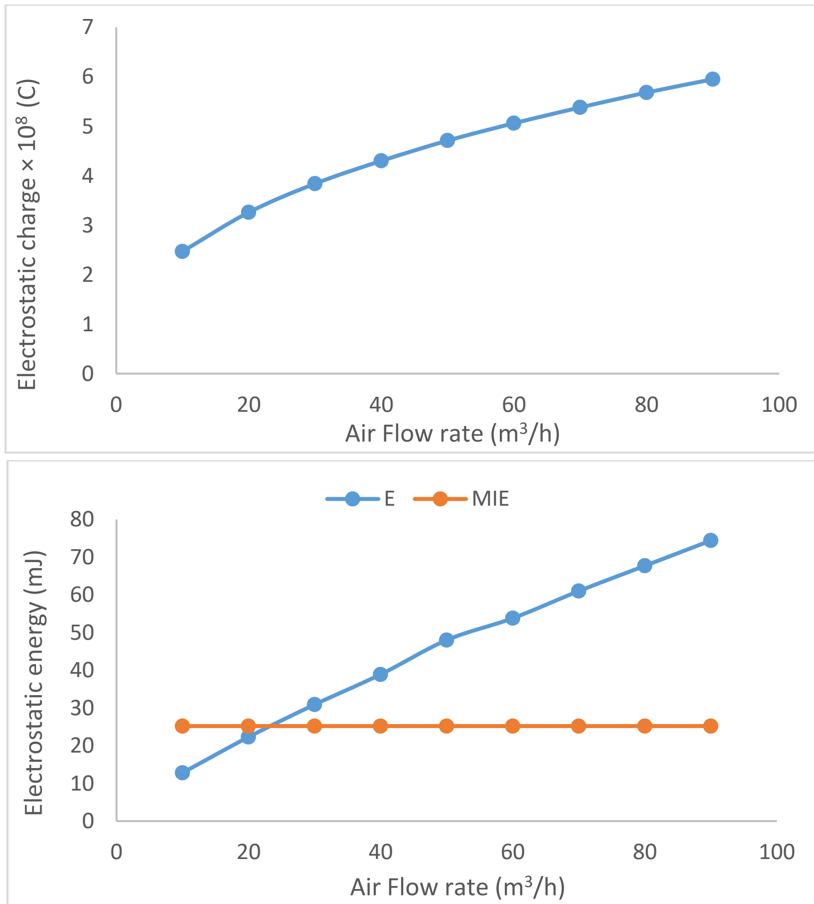

Figure 5 - The effect of air flow rate

By increasing the volumetric flow of the air, the particle velocities increases. As a result, the possibility of colliding the particles with the tube wall will be increased. The electrostatic charges of the particle will be enhanced, yet not linearly. Indeed as the air flow rate becomes larger than near the 40 m^3/h, the generated electrostatic charged tends to deviate very small from the increasing range of the curve. This can be due to the turbulent flow of the air. In other words, the collisions of particles with each other in higher air flow rates are high and make them less likely to collide with the wall.

As depicted, in volumetric flow more than 23 m^3/h the electrostatic energy is more than MIE, and the possibility of fire is high. Reducing the particle diameters or increasing the tube diameter can be two solutions for reducing the risk of fire and explosion.

Quantitavely speaking, the results demonstrate that an increase of air flow rate by near 1000%, causes an increase to particle charge up to about 500% (for the range of values considered herein)

The effect of tube wall material

As the final scenario, we focused on the influence of the tube wall material. Accordingly, the tube wall properties let to vary while other parameters of the simulation are kept constant. Our study focused on changing the main properties of the tube wall, like Poisson's ratio and Young's module. In order to evaluate the tube wall material, five different cases with different elasticity properties are computed as shown below.

First, the base case with properties that correspond to that of Stainless Steel 360 (SS) is simulated. Afterward, the simulations for different types of tube walls are performed. The results are shown in Table 2. The simulation is performed for an air flow rate of 10 m^3/h.

Table 2 – The effect of pipe wall material

Tube wall material	$Q_{max} \times 10^8$ (C)	E_{max} (mJ)
SS	2.4928	13.148
Aluminum	2.4958	13.179
Iron	2.4926	13.145
Polyethylene	2.8040	16.635
Teflon	2.9198	18.037

As shown in the results, it can be concluded that the tube wall material plays an important role in charge generation of particles inside the tube. Among considered cases, the tube wall with Teflon material has a higher value of charge generation and consequently, the higher potential for fire and explosion. It is mainly due to its low value of the Young module (Levy, Bass and Stern, 2004). The low value of the Young module leads to a higher value of contact area and therefore increasing the possibility of electrostatic charge generation over the surfaces of the particles. In the case of using the material like Teflon for the tube wall, it is better to use a smaller size of particles in order to have a safer pneumatic conveying process.

Conclusion

In this paper, the simulation of particle pneumatic conveying process inside an inclined tube was performed, focusing on the generation of particle charge in order to study the hazards related to the discharging the particle energy.

In the developed model, the velocity of the particles inside the tube was obtained in the first step. It was assumed that only the vertical component of the collision velocity determines the impact charging of the particle. Having calculated the contact area using Hertzian contact theory, the amount of charge of the particles at a single collision was calculated regarding the charge density of the particles. Afterward, the electrostatic energies of the particles as a result of the accumulation of the electrostatic charge were estimated. By comparing the amount of electrostatic energy with MIE of the particles, the possibility of the fire was studied. Finally, the effect of important parameters on the generation of particle charge, the amount of electrostatic energy as well as the possibility of fire and explosion were studied. It was shown that by increasing the particle diameter, the electrostatic energy was linearly increased. On the other hand, the linear increase in air flow rate doesn't linearly increase the electrostatic energy and the increasing rate was decreased in the higher flow rates. Moreover, during the analysis of changing the pipe wall material, it was demonstrated that those materials with lower elasticity value have a higher risk for utilizing in the pneumatic conveying process.

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