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Calculation of particle–wall adhesion in horizontal gas–solids flow using CFD

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Abstract

The horizontal pneumatic conveying of fine particles is simulated with Computational Fluid Dynamics (CFD) including the particle–wall adhesion. The simulation is performed with FLUENT, whereby the dispersed phase (quartz powder, $d_{P,50}$=3 μm) is described with the Lagrange approach. The continuous phase is resolved with the Realizable k–ϵ model. Models not provided by FLUENT are implemented via user defined functions. A horizontal pipe with a length of 3 m and an inner diameter of 50 mm is used for the calculation. The influence of different wall treatments on pressure drop and particle–wall adhesion is shown. Furthermore, several parameters are varied (e.g., electrostatic charge of particles, air velocity). The results are evaluated with measured data.

Keywords: CFD; Horizontal gas–solids flow; Particle–wall adhesion

1. Introduction

In the last years, Computational Fluid Dynamics (CFD) has gained importance even for investigating multiphase flows. If CFD is applied for simulating multiphase flows, generally two approaches are available to describe the dispersed phase. Both are based on the "Eulerian" consideration of the continuous phase, i.e., the continuous phase is resolved by the "Reynolds-averaged" Navier–Stokes (RANS) equations. The decisive parameter for the application of one of the approaches describing dispersed phases is their volume fraction. If it is less than 0.1, the Euler–Lagrange approach is recommended; otherwise the Euler–Euler approach should be implemented. The latter describes the dispersed phase as a further continuous phase and solves the respective conservation equations. In the Euler–Lagrange approach theoretically each single particle is tracked through the continuous phase based on a force balance at the particle. Since this yields a vast requirement of computational effort even for small volume fractions, it has become widely accepted that only a defined number of particle packages is calculated. One package represents a certain number of particles of one diameter and thereby a fraction of the total particle mass flow rate.

Regarding the Euler–Lagrange approach, main efforts of research concerned particle–wall and particle–particle collisions as well as the effect of the dispersed phase on the fluid-turbulence. Tsuji et al. [18,19] introduced equations describing the particle collision. Frank et al. [3] and Sommerfeld and Huber [14] developed models regarding the wall roughness-structure and the coefficient of restitution. In addition, Sommerfeld [15] derived correlations for the particle–particle collision based on the kinetic gas theory. Among others Hetsroni [6], Gore and Crowe [5], Kenning and Crowe [7] as well as Triesch and Bohnet [17] investigated the effect of particles on fluid-turbulence. In these investigations the particle size was held constant. The particles were mostly larger than 100 μm. By all means noncohesive particles were used.

However, if cohesive particles are conveyed, the design of conveying systems is still mainly based on experiments and experience. In order to predict its pressure drop, a tool

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to describe the particle–wall interaction is of interest. Under the prerequisite of suitable models for the wall roughness and particle–wall adhesion, such a tool is CFD.

This paper explains an approach to model the particle–wall interaction based on the Lagrange treatment of the dispersed phase. The influence of several parameters like air velocity and electrostatic particle charge is shown. In addition, the limits of this approach are presented.

2. Numerical models

The simulation is performed with the software FLUENT which provides the possibility to implement several subroutines for additional forces or models through user defined functions (UDF).

For modelling and solving the Reynolds stresses of the continuous phase, the Realizable k–ϵ model is used.

The dispersed phase is treated with the Lagrange approach in a transient flow. In FLUENT a time-dependent two-phase flow is solved by calculating for each time step firstly the continuous flow field. As a second step in each time step, the equation of motion for the particles is solved [4] as if it was a steady state.

$$\frac{\vec{w}_P}{dt} = \frac{18\eta}{\rho_P d_P^2}\frac{c_D Re_P}{24}(\vec{u} - \vec{w}_P) + \frac{g(\rho_P - \rho)}{\rho_P} + F_i \tag{1}$$

With the particle Reynolds number defined as:

$$Re_P = \frac{\rho d_P |\vec{w}_P - \vec{u}|}{\eta} \tag{2}$$

The angular velocity is considered, following a suggestion of Sommerfeld/Zivkovic [16].

$$\vec{\omega}_{P,\mathrm{new}} = \frac{1}{2}(\nabla\times\vec{u})(\vec{\omega}_P - \frac{1}{2}(\nabla\times\vec{u}))\exp\left(-\frac{60\eta}{d_P^2\rho_P}\Delta t\right) \tag{3}$$

The drag coefficient is described in dependence of the particle Reynolds number (Clift et al. [2]):

$$c_D = \frac{3}{16} + \frac{24}{Re_P} \text{ for } Re_P<0.01 \tag{4}$$

$$c_D = \frac{24}{Re_P}\left(1 + 0.1315 Re_P^{0.82-0.05\log_{10}Re_P}\right) \text{ for } 0.01<Re_P>20 \tag{5}$$

Besides the gravity provided by FLUENT the Magnus- and the Saffman-force are considered:

$$\vec{F}_M = c_M\pi\left(\frac{d_P}{2}\right)^3 \rho(\vec{\omega}_P - \nabla\times\vec{U})\times(\vec{w}_P - \vec{u}) \tag{6}$$

with c_M=2 (Rubinow and Keller [11])

$$\vec{F}_{Saff} = 6.46\rho\nu^{1/2}\frac{d_P^2}{4}(\vec{u} - \vec{w}_P)\left|\frac{d\vec{u}}{d\vec{x}}\right|^{1/2} \tag{7}$$

This is the Saffmann [12] definition, which is valid for a laminar flow around a particle, which is the case for the considered particles.

Furthermore, the electrostatic charge of the particles is regarded by implementing the Coulomb force

$$|\vec{F}_C| = \frac{q_P q_0}{4\pi\varepsilon_0 l^2}. \tag{8}$$

It is assumed that q_0=q_P and that the Coulomb force is only orientated to the wall.

The effect of turbulence on particle motion is taken into account through the discrete random walk (DRW) model [4]. There the particle velocity is determined by the instantaneous gas velocity $\bar{u}$+u'. The fluctuating part u' is kept constant as long as the particle is within the turbulent eddy. The latter is dependent on the smaller of two time scales. One is the eddy life time

$$\tau_e = T_L\zeta \tag{9}$$

where the Lagrangian time scale

$$T_L \approx 0.15\frac{k}{\varepsilon} \tag{10}$$

The other is the eddy crossing time

$$t_{cross} = -\tau_P \ln\left(1 - \frac{L_e}{\tau_P(\vec{u} - \vec{w}_P)}\right). \tag{11}$$

As soon as the smaller time scale is exceeded, a new fluctuation part is generated basing on the isotropy assumption of the k–ϵ model.

$$u' = \zeta\sqrt{\bar{u}_x'^2} = \zeta\sqrt{\bar{u}_y'^2} = \zeta\sqrt{\bar{u}_z'^2} = \zeta\sqrt{\frac{2k}{\varepsilon}} \tag{12}$$

The effect of the dispersed phase on the continuous phase is considered through a momentum source term for the continuous phase.

$$S_P = \sum_i\left(\frac{18\eta c_D Re}{\rho_P d_P^2 24}(\vec{u}_P - \vec{w}_P)\right)\dot{M}_P\Delta t \tag{13}$$

2.1. Particle–wall adhesion

The model of the particle–wall adhesion is based on a suggestion of Löffler and Muhr [9] and consists of an energy balance around the particle–wall collision. Additionally, the applied model includes an electrostatic part, so that the involved energy balance becomes

$$E_{kin,1} + E_{el,1} = E_{vdW} + E_{kin,2} + E_{el,2} + E_l \tag{14}$$

with the kinetic energy (E_{kin}), the electrostatic part (E_{el}) before (1) and after (2) the wall collision, respectively, the