Pneumatic Conveying of Solids along a Channel with Different Wall Roughness

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The present contribution describes three-dimensional Euler/Lagrange calculations of confined horizontal gas-particle flows emphasizing the importance of elementary processes, such as particle collisions with rough walls and interparticle collisions, on the predicted two-phase flow variables and pressure drop along the duct. In the chosen configuration the pneumatic conveying of spherical particles along a 6 m long horizontal channel with rectangular cross section is described from a numerical perspective. Calculations were carried out for spherical glass beads of different diameters (130 and 195 μm) with a mass loading of 1.0 (kg particles/kg gas). Additionally, different wall roughnesses were considered. In the experiments, the air volume flow rate was constant to maintain a fixed gas average velocity of 20 m/s. The numerical computations were performed by the Euler/Lagrange approach in connection with a Reynolds stress turbulence model accounting for two-way coupling and interparticle collisions. For the calculation of particle motion all relevant forces (i.e., drag, slip-shear and slip-rotational lift, and gravity), interparticle collisions and particle-rough wall collisions were considered. The agreement of the computations with the experiments of Sommerfeld and Kussin (2004) was found to be satisfactory for pressure drop and mean and fluctuating velocities of both phases as well as for the normalized particle mass flux.

Keywords Euler-Lagrange approach; Interparticle collisions; Pneumatic conveying; Turbulence; Wall roughness

Introduction

Pneumatic conveying is widely used in industry for transporting fine powders within a production process over large distances. It is found in numerous engineering applications such as the chemical, pharmaceutical, and food industries, power generation (conveying of pulverized coal), and air conditioning technology. The size of the conveyed particles typically ranges from a few micrometers to several millimeters. The wide application of pneumatic conveying is connected to numerous advantages for powder transport: dust-free transportation, high flexibility, and low cost as well as maintenance. Similar wall-bounded two-phase flow systems are found in cyclone separators, classifiers, and dilute fluidized beds. Due to the presence of confinement

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in these systems, collisions of solid particles with the walls play an essential role in the particle transport process. Wall collision frequency is directly responsible for the additional pressure drop due to the solids as a result of the momentum and energy loss involved in the inelastic collision process (Adam, 1960). Additionally, wall roughness considerably affects the wall collision process (Sommerfeld and Huber, 1999; Tsuji et al., 1987) and causes an enhancement of the wall collision frequency in pipes or channels for inertial particles. On the other hand, the wall collision frequency might be also reduced for smaller particles ($\tau_p < 50$ ms) as a consequence of wall roughness (Sommerfeld, 2003).

Particle inertia and the effect of gravity have a pronounced effect on powder conveying and will cause a segregation of the mixture, whereby rather dense ropes of solids may be formed near the bottom of horizontal conveying lines (Fokeer et al., 2004; Yilmaz and Levy, 2001). The increasing local solids concentration supports the occurrence of interparticle collisions. This again results in a dispersion of particles out of a dense rope due to the transfer of momentum from the main stream direction to the transverse component (Laín, 2010). Hence, collisions between particles may cause a destruction of dense ropes and therefore also will have an effect on particle transport and wall collision frequency and hence pressure drop in such two-phase systems.

For the numerical treatment of two or multiple interpenetrating phases, two approaches are commonly used, namely the two-fluid (often also referred to as Euler/Euler) approach and the hybrid Euler/Lagrange approach (Laín, 2010). The first approach is based on the assumption of two or more interacting continua and therefore results in similar conservation equations for the continuous and dispersed phases (Laín and Aliod, 2000, 2003), which can be solved with the same discretization schemes. Therefore, this method is preferred by industry, since the considered problem can be numerically solved rather fast. The drawback of the continuum assumption for the dispersed phase, however, is the sophisticated modeling needed of the relevant elementary processes affecting particle motion and behavior. Additionally, the consideration of particle size distribution, which is inherent for many processes in powder technology, requires the solution of a set of conservation equations, one for each particle size fraction, by accounting for their interaction through collisions. The Euler/Lagrange approach is applicable only to dispersed two-phase flows and is based on a coupled computation of fluid flow (Eulerian) and particle phase (Lagrangian). The dispersed phase is modeled by tracking a large number of representative point particles through the previously computed flow field by solving the equations of motion accounting for all relevant forces acting on the particles and other important elementary processes (Laín, 2010). Local average properties such as dispersed phase density or velocities are obtained by ensemble averaging for each control volume in the computational domain. The effect of the dispersed phase on the continuous phase has to be accounted for by appropriate source terms in the Eulerian conservation equations, which also need to be sampled during the Lagrangian tracking. A converged solution is achieved by sequential calculation of the Eulerian and Lagrangian parts. An essential advantage of this method is that the discrete nature of the dispersed phase particles is retained. Moreover, physical effects influencing particle motion (i.e., elementary processes), such as particle-turbulence interaction, particle-wall collisions, interparticle collisions, or agglomeration, can be modeled on the basis of physical principles. Additionally, particle size distribution may be easily considered by sampling the size of the injected particles from a given distribution function.

Essential in the application of both approaches is the modeling of the elementary processes affecting particle motion, which considerably influences the temporal and spatial distributions of the dispersed phase in the process being considered. For operational conditions where the influence of the particle phase on the fluid flow, i.e., the so-called two-way coupling, becomes important the fluid flow is also strongly affected by the elementary processes. As a consequence, integral parameters are also influenced, as, for example, the pressure drop in pneumatic conveying. Since in the processes considered here, particle size distribution is of eminent importance, the Euler/Lagrange approach is used in this study.

For the numerical prediction of pneumatic conveying the Euler/Lagrange approach was further developed to account for all relevant elementary processes, such as transverse lift forces, wall roughness, interparticle collisions, and coupling between the phases (Laín, 2010, 2011; Laín and García, 2006; Laín et al., 2011). The present investigation is a three-dimensional (3-D) study of particle behavior in a particle-laden 6 m long horizontal channel with rectangular cross section from a numerical perspective. Calculations were carried out for spherical glass beads with different sizes (130 and 195 μm) and a mass loading of 1.0 (kg particles/kg gas). Additionally, different wall roughnesses were considered. As in the experiments of Sommerfeld and Kussin (2004) the air volume flow rate is constant in order to maintain a fixed gas average velocity of 20 m/s. The numerical computations were performed by the Euler/Lagrange approach in connection with a Reynolds stress turbulence model (RSM) accounting for the interaction between the phases. For the calculation of particle motion all relevant forces (i.e., drag, slip-shear and slip-rotational lift, and gravity), interparticle collisions, and particle-wall collisions with wall roughness were considered. The agreement of the computations with the experiments of Sommerfeld and Kussin (2004) was found to be satisfactory for the gas and particle variables.

Experimental Setup

The test facility has been described in detail previously (Kussin and Sommerfeld, 2002; Laín et al., 2002), hence only a brief summary of the main characteristics of the system will be given here. The main component of the experimental rig is a horizontal channel of 6 m length with a height of 35 mm and a width of 350 mm, so almost two-dimensional flow conditions can be established. The upper and lower channel walls were made of stainless steel plates that could be exchanged in order to study the effect of wall material and wall roughness on particle behavior. The measurements were performed close to the end of the channel at a distance of 5.8 m from the entrance. A two-component phase-Doppler anemometer (PDA) was used to determine gas and particle velocities. In all the experiments the air volume flow rate was kept constant in order to maintain a fixed averaged gas velocity of 20 m/s. Measurements were conducted for spherical glass particles ($\rho_p = 2450 \text{ kg m}^{-3}$) with different diameters (60, 130, 195, and 625 μm), variable mass loadings up to 1.5, and different wall roughness. The particle size distribution was rather narrow in all the considered cases (Sommerfeld and Kussin, 2004). Full details about the experimental facility as well as the main experimental findings can be found in Kussin and Sommerfeld (2002) and Sommerfeld and Kussin (2004).

Summary of Numerical Approach

The numerical scheme adopted to simulate dispersed two-phase flow along the channel was the fully coupled stationary and three-dimensional Euler/Lagrange approach (Laín et al., 2002).

The fluid flow was calculated based on the Euler approach by solving the Reynolds-averaged conservation equations in connection with the Reynolds stress turbulence model (version of Jones and Musonge (1988) and Jones (1994)), which were extended in order to account for modulation by the dispersed phase, i.e., two-way coupling (Kohnen and Sommerfeld, 1997). The time-dependent three-dimensional conservation equations for the fluid may be written in the general form (using tensorial notation) as:

$$(\rho\phi)_{,t} + (\rho U_i \phi)_{,i} = (\Gamma_{ik} \phi_{,k})_{,i} + S_\phi + S_{\phi p} \quad (1)$$

where ρ is the fluid density, U_i are the Reynolds-averaged velocity components, and Γ_{ik} is an effective transport tensor. The usual source terms within the continuous phase equations are summarized in S_ϕ , while $S_{\phi p}$ represents the additional source term due to phase interaction. In the following, P denotes the mean pressure, μ the gas viscosity, and $R_{ji} = \overline{u_j' u_i'}$ the components of the Reynolds stress tensor.

The simulation of the particle phase by the Lagrangian approach is based on tracking a large number of particles through the previously computed flow field. Particles are treated as point masses, and their shape is assumed to be spherical. Tracking requires the solution of the equation of motion for each computational particle or parcel, which is a collection of real particles with the same properties. This equation includes particle inertia, drag, gravity-buoyancy, slip-shear lift, and slip-rotational lift forces. The Basset history term, added mass, and fluid inertia are negligible for high ratios of particle-to-gas density. The change of angular velocity along the particle trajectory results mainly from wall collisions but also viscous interaction with the fluid (i.e., the torque $\mathbf{T}$). Hence, the equations of motion for the particles are given by:

$$\frac{dx_{pi}}{dt} = u_{pi} \quad (2)$$

$$m_p \frac{du_{pi}}{dt} = \frac{3}{4} \frac{\rho}{D_p} m_p c_D (u_i - u_{pi}) |\vec{u} - \vec{u}_p| + m_p g_i \left(1 - \frac{\rho}{\rho_p}\right) + F_{lsi} + F_{lri} \quad (3)$$

$$I_p \frac{d\omega_{pi}}{dt} = T_i \quad (4)$$

Here, x_{pi} are the coordinates of the particle position, u_{pi} are its velocity components, $u_i = U_i + u_i'$ is the instantaneous velocity of the gas, D_p is the particle diameter, ρ_p is the density of the solids, $m_p = (\pi/6) \rho_p D_p^3$ is the particle mass, and $I_p = 0.1 m_p D_p^2$ is the moment of inertia for a sphere. The drag coefficient is obtained using the standard correlation (Schiller and Naumann, 1933):

$$c_D = \begin{cases} 24 \text{Re}_p^{-1} (1 + 0.15 \text{Re}_p^{0.687}) & \text{Re}_p \leq 1000 \\ 0.44 & \text{Re}_p > 1000 \end{cases} \quad (5)$$

with $\text{Re}_p = \rho D_p |\vec{u} - \vec{u}_p| / \mu$, the particle Reynolds number.

The slip-shear force is based on the analytical result of Saffman (1965) and extended for higher particle Reynolds numbers according to Mei (1992):

$$\vec{F}_{ls} = 1.615 D_p \mu \text{Re}_s^{1/2} c_{ls} [(\vec{u} - \vec{u}_p) \times \vec{\omega}] \quad (6)$$

where $\vec{\omega} = \nabla \times \vec{u}$ is the fluid rotation, $\text{Re}_s = \rho D_p^2 |\vec{\omega}| / \mu$ is the particle Reynolds number of the shear flow, and $c_{ls} = F_{ls} / F_{ls, \text{Saff}}$ represents the ratio of the extended lift force to the Saffman force:

$$c_{ls} = \begin{cases} (1 - 0.331\sqrt{\beta})e^{-\text{Re}_p/10} + 0.331\sqrt{\beta} & \text{Re}_p \leq 40 \\ 0.0524\sqrt{\beta\text{Re}_p} & \text{Re}_p > 40 \end{cases} \quad (7)$$

and β is a parameter given by $\beta = 0.5\text{Re}_s / \text{Re}_p$.

The applied slip-rotational lift force is based on the relation given by Rubinow and Keller (1961), which was extended to account for the relative motion between particle and fluid. Moreover, several authors allowed an extension of this lift force to higher particle Reynolds numbers (Loth, 2008, and references therein). Hence, the following form of the slip-rotation lift force has been used:

$$\vec{F}_{lr} = \frac{\pi}{8} D_p^3 \rho \frac{\text{Re}_p}{\text{Re}_r} c_{lr} [\vec{\Omega} \times (\vec{u} - \vec{u}_p)] \quad (8)$$

with $\vec{\Omega} = 0.5 \nabla \times \vec{u} - \vec{\omega}_p$, and the Reynolds number of particle rotation is given by $\text{Re}_r = \rho D_p^2 |\vec{\Omega}| / \mu$. The lift coefficient according to Oesterlé and Bui Dinh (1998) is given for $\text{Re}_p < 2000$ by:

$$c_{lr} = 0.45 + \left(\frac{\text{Re}_r}{\text{Re}_p} - 0.45 \right) e^{-0.05684 \text{Re}_r^{0.4} \text{Re}_p^{0.3}} \quad (9)$$

For torque acting on a rotating particle the expression of Rubinow and Keller (1961) was extended to account for the relative motion between fluid and particle and higher Reynolds numbers:

$$\vec{T} = \frac{\rho}{2} \left(\frac{D_p}{2} \right)^5 c_R |\vec{\Omega}| \vec{\Omega} \quad (10)$$

where the coefficient of rotation is obtained from Rubinow and Keller (1961) and direct numerical simulations of Dennis et al. (1980) in the following way:

$$c_R = \begin{cases} \frac{64\pi}{\text{Re}_R} & \text{Re}_R \leq 32 \\ \frac{12.9}{\sqrt{\text{Re}_R}} + \frac{128.4}{\text{Re}_R} & 32 < \text{Re}_R < 1000 \end{cases} \quad (11)$$

The equations to calculate particle motion are solved by integration of the differential equations (2)–(4). For sufficiently small time steps (typically of the order of 10^{-6} – 10^{-5} s in the present computations) and assuming that the forces remain constant during this time step, the new particle location and the linear and angular velocities are calculated. The time step for the particle tracking was chosen to be 50% of the smallest of all relevant time scales, such as the particle relaxation time, the integral time scale of turbulence, and the mean interparticle collision time. This choice guarantees the stability of the numerical integration scheme (Göz et al., 2004, 2006).

In confined flows, the modeling of particle-wall collisions is of utmost importance. The change of linear and angular particle velocity during a wall collision process is calculated based on the solution of the impulse equations coupled with Coulomb's law of friction. Separating the process into a compression and rebound period and introducing a restitution coefficient as the ratio of the normal impulse of rebound to that of the compression yield two sets of equations for a sliding and sticking collision. The distinction between these two types of collisions is made on the basis of the friction coefficient. Hence, two model parameters are needed to calculate the wall collision process, which are dependent on impact velocity, particle size, and impact angle and generally have to be extracted from measurements (Sommerfeld and Huber, 1999). According to the experimental results the variation of the restitution (e_w , defined as the absolute value of the ratio of the normal velocity components after collision to that before collision) and friction (μ_w) coefficients versus the impact angle α (expressed in degrees) for spherical particles is given by:

$$\begin{aligned} e_w &= \max(1 - \beta_e \alpha, e_\infty) \\ \mu_w &= \max(\mu_0 - \beta_\mu \alpha, \mu_\infty) \end{aligned} \quad (12)$$

where the parameters β_e , β_μ , μ_0 , e_∞ , and μ_∞ depend on particle-wall material combination.

In addition, wall roughness was found to have a substantial influence on the particle-wall collision process, depending on particle size and wall roughness structure. Since a detailed consideration of the wall roughness profile in the Lagrangian calculations is not feasible, a stochastic model was developed. For that purpose it was assumed that the instantaneous wall collision angle α is composed of the particle trajectory angle α_0 and a stochastic contribution from wall roughness:

$$\alpha = \alpha_0 + \xi \Delta\gamma \quad (13)$$

where ξ is a random number with zero mean and variance of 1, and $\Delta\gamma$ is the standard deviation of the roughness angle distribution depending on particle size and roughness height (Sommerfeld and Huber, 1999). From thorough experiments and numerical calculation, correlations between $\Delta\gamma$ and particle diameter with the degree of roughness as a parameter have been elaborated (Laín et al., 2002; Sommerfeld and Huber, 1999).

The probability distribution function (PDF) of the roughness angle γ is built as a normal function with zero mean and standard deviation $\Delta\gamma$. However, due to the so-called shadow effect (meaning that in the wall collision process a particle cannot reach the lee side of the roughness structure) this distribution function is effectively

skewed to positive values of the roughness angle, especially for smaller wall impact angles (Sommerfeld and Huber, 1999). Such an effect enhances the effective transfer of horizontal to transverse particle momentum, especially for shallow angles of attack, causing a strong enhancement of the wall-normal velocity component and a redispersion of particles in a horizontal channel. Moreover, this effect is associated with a strong increase of particle fluctuation velocity and as a consequence wall collision frequency.

Interparticle collisions are modeled by the stochastic approach described in detail in Sommerfeld (2001). This model relies on the generation of a fictitious collision partner and the calculation of the collision probability according to the kinetic theory of gases. The fictitious particles are representative of the local particle population, hence, their size and velocity are sampled from previously determined local distribution functions. The velocity distributions are assumed to be normally distributed, and the possibility of a correlation between the velocities of colliding particles is accounted for through a dependence on the particle turbulent Stokes number. During each time step of the trajectory calculation of the considered particle a fictitious second particle is generated. The size and velocity of this fictitious particle are randomly sampled from local distribution functions. The advantage of this model is that it does not require information on the location of the surrounding particles, hence it is also applicable if a sequential tracking of the particles is adopted, as usually done when applying the Euler/Lagrange approach to stationary flows. The validation of such a strategy was carried out in Sommerfeld (2001) and applied to a two-dimensional channel flow in Lain et al. (2002).

Since interparticle collisions will modify the particle phase properties and eventually the gas phase, the consideration of this combined effect is often referred to as four-way coupling.

Influence of Particles on Carrier Flow

The source terms for the momentum equations resulting from the momentum exchange between particles and fluid are obtained on the basis of the particle-source-in-cell (PSI cell) concept. Hence, the momentum exchange is calculated by averaging over all parcels traversing a given control volume during one Lagrangian calculation. Instead of summing up all fluid dynamic forces acting on the particles, which is quite cumbersome, the momentum exchange is calculated from the velocity change of the parcels when traversing the control volume. In this procedure, however, the external forces have to be subtracted, yielding the momentum source in the following form:

$$\overline{S_{U_{ip}}} = -\frac{1}{V_{cv}} \sum_k m_k N_k \sum_n \left\{ \left([u_{pi}]_k^{n+1} - [u_{pi}]_k^n \right) - g_i \left(1 - \frac{\rho}{\rho_P} \right) \Delta t_L \right\} \quad (14)$$

where the sum over n indicates averaging along the particle trajectory (time averaging) and the sum over k is related to the number of computational particles, or parcels, passing the considered control volume with the volume V_{cv} . The mass of an individual particle is m_k , N_k is the number of real particles in one computational

particle, and Δt_L is the Lagrangian time step, which is used in the solution of Equations (2)–(4).

The source term in the conservation equation of the Reynolds stress components, R_{ji} , is expressed in the Reynolds average procedure as:

$$S_{R_{ji}p} = \overline{u_j S_{U_{ip}}} + \overline{u_i S_{U_{jp}}} - (\overline{U_j S_{U_{ip}}} + \overline{U_i S_{U_{jp}}}) \quad (15)$$

while the source term in the ε -equation is modeled in the standard way:

$$S_{\varepsilon p} = c_{\varepsilon 3} \frac{1}{2} \frac{\varepsilon}{k} S_{R_{ii}p} \quad (16)$$

with $C_{\varepsilon 3} = 1.0$ and the sum is implicit in the repeated sub-index i .

A converged solution of the coupled two-phase flow system is obtained by successive solution of the Eulerian and Lagrangian parts. Initially, the flow field is calculated without particle phase source terms until a converged solution is achieved. Thereafter, a large number of parcels are tracked through the flow field (typically 480,000) and the source terms are sampled for each control volume. In this first Lagrangian calculation interparticle collisions are not considered, since the required particle phase properties are not yet available. Hence, for each control volume the particle concentration, the local particle size distribution, and the size-velocity correlations for the mean velocities and the root-mean-square (rms) values are sampled. These properties are updated each Lagrangian iteration in order to allow correct calculation of interparticle collisions. Additional particle phase properties and profiles may be sampled for each transverse cell when the computational particle crosses a predefined location. From the second Eulerian calculation, the source terms of the dispersed phase are introduced using an under-relaxation procedure (Kohnen et al., 1994). For the present calculations typically about 25 to 35 coupling iterations with an under-relaxation factor between 0.5 and 0.1 were necessary in order to yield convergence of the Euler-Lagrange coupling.

Results

The horizontal channel flow configuration has been described above. It consists of a rectangular cross section channel 6 m in length, 35 mm in height, and 350 mm in width. Measurements were performed at the center of the channel close to the end at a distance of 5.8 m from the entrance. The computational domain consists of one block structured grid, with a rectangular prism shape according to the real geometry, consisting of 240,000 hexahedral elements, which was found to be sufficient to obtain grid-independent results.

The 3-D numerical calculations were compared with experimental data obtained in the horizontal channel facility (Sommerfeld and Kussin, 2004). Average conveying velocity was maintained fixed and equal to 20 m/s. Spherical glass beads with two diameters, $D_p = 130, 195 \mu\text{m}$, were considered with a material density of $\rho_p = 2450 \text{ kg m}^{-3}$. In the computations the particles were assumed to be mono-disperse due to the narrow size distribution, and the resulting small value of the standard deviation was normalized by the mean particle diameter (Sommerfeld and Kussin, 2004). This implies that the particle response characteristics are quite similar for the largest and smallest particles in the distribution. The simulations were performed using the

Table I. Data for the considered roughness cases (all values given in μm)

Degree of roughness	Roughness in streamwise direction		Roughness in lateral direction	
	Mean roughness	Maximum roughness	Mean roughness	Maximum roughness
Case R0	2.32	2.86	2.09	3.34
Case R2	6.83	8.32	6.89	7.83

Reynolds stress turbulence model mentioned in the previous section and accounting for particle-wall as well as interparticle collisions, i.e., considering the so-called four-way coupling, as was previously mentioned. The gas density and the dynamic viscosity were $\rho = 1.25 \text{ kg m}^{-3}$ and $\mu = 1.8 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$, respectively, according to the experimental conditions.

Two particle diameters, $D_p = 130, 195 \mu\text{m}$, were considered with a mass loading ratio of $\eta = 1.0$ (kg particles/kg gas) and two wall roughnesses, the so-called cases R0 and R2 referred to in Table I. The corresponding roughness values were measured by a Perthometer (Type S3P) (Sommerfeld and Kussin, 2004).

In the present calculations, the dependencies between $\Delta\gamma$ and D_p shown in Figure 1 have been used, according to the experimental studies of Sommerfeld and Huber (1999).

Table II summarizes the wall roughness parameter employed in the actual computations for the combination of particle sizes and wall roughness.

The parameters characterizing the particle-wall collision used in the present simulations, according to Equation (12), are given in Table III. Moreover, based on the experiments of Sommerfeld and Huber (1999), for particle-particle collisions the restitution coefficient e_{pp} was taken as a constant equal to 0.9 and the static and dynamic friction coefficients were made equal to $\mu_{pp} = 0.4$.

Figure 1. $\Delta\gamma$ - D_p correlation for the two roughness cases considered. (Figure provided in color online.)

Table II. Summary of wall roughness parameter $\Delta\gamma$ for the considered combinations of particle size and wall roughness

D_p [μm]	Roughness case	$\Delta\gamma$ [degrees]
130	R0	1.5
195	R0	1.3
130	R2	5.5
195	R2	4.5

Before proceeding further, it is useful to summarize the influence of wall roughness on particle transport in channel flow (Sommerfeld, 2003). The degree of response of particles to fluid turbulence is characterized by the Stokes number, defined as the quotient between the particle response time and the Lagrangian integral time scale of the turbulence. Without wall roughness, small particles (Stokes numbers much smaller than one) are greatly dispersed by gas turbulence whereby the wall collision frequency is relatively low. On the other hand, the motion of large particles (Stokes number well above one) is governed mainly by inertia, so the particle mean free path between successive wall collisions reduces, increasing wall collision frequency. There are two regimes. In the first one, particles bounce along the lower wall after some distance of development downstream from the inlet, revealing a strong influence of gravity, and implying that they perform a saltating motion without contacting the upper wall. In the second regime, reached when the inertia is further increased, particles bounce from wall to wall and the wall collision mean free path approaches a maximum. With wall roughness, for the large particles, the mean free path between wall collisions becomes shorter than in the case with smooth wall. Hence, particle motion is almost completely controlled by wall collisions and wall roughness. For small particles, however, the mean free path between wall collisions is considerably higher than for the case without roughness due to the redispersion effect of wall roughness mentioned above.

In our computations, two particle diameters, $D_p = 130, 195 \mu\text{m}$, are considered. Their corresponding Stokes numbers (based on the Lagrangian integral time scale calculated at the center of the channel) are 22.2 and 38.0 respectively, which implies that the motion of both is governed mainly by inertia, particle-wall collisions, and interparticle collisions. Comparison of the obtained numerical results with the experimental data were carried out at a measuring section located 5.8 m downstream from the channel inlet.

First, the performance of the numerical method is addressed, comparing the obtained results versus the experimental data in single-phase flow (denoted hereafter “clean” in the graphics) in the channel. The measuring section at 5.8 m downstream from the inlet is located beyond 160 times the channel height of 35 mm; therefore, at that section turbulent flow is fully developed with zero vertical and lateral mean

Table III. Parameters characterizing particle-wall collision and interparticle collisions

β_e [–]	e_∞ [–]	β_μ [–]	μ_0 [–]	μ_∞ [–]	e_{pp} [–]	μ_{pp} [–]
0.0136	0.7	0.0175	0.5	0.15	0.9	0.4

Figure 2. Comparison of measurements and computations for the low roughness case (R0) with $D_p = 130 \mu\text{m}$ and $\Delta\gamma = 1.5^\circ$. Results are presented for an average conveying velocity of 20 m/s and mass loading $\eta = 1.0$. (a) Mean velocities of both phases; (b) single-phase flow fluctuating velocities; (c) two-phase flow fluctuating velocities for both phases. (Figure provided in color online.)

velocities and with the streamwise mean velocity being independent of the streamwise coordinate. Figure 2(a) shows the profile of the streamwise mean velocity obtained with the Reynolds stress turbulence model (RSM). As could be expected, the numerical results agree very well with the measured values. Figure 2(b) presents the fluctuating velocities predicted by the RSM, streamwise (u'), vertical (v'), and lateral (w') components, versus the experimental data. As in the experiments a two-component PDA was employed, only the streamwise and vertical components of the fluctuating velocity were measured. The rms values of the velocity (u' and v') are in good agreement with the measured data, especially in the center of the channel. When approaching the wall, the streamwise velocity fluctuation falls below the experiments. The calculated vertical fluctuation is in good agreement with the measurements except in the near-wall region. On the other hand, the lateral fluctuating velocity profile falls between the streamwise and vertical rms profiles. This behavior is typical for the application of the RSM in channel flow (Shima, 1998).

Figure 2 also summarizes the results for the two-phase flow condition obtained with interparticle collisions and the case of low roughness (R0) in Table I. Here, based on Figure 1, a value of $\Delta\gamma = 1.5^\circ$ has been chosen for the $130 \mu\text{m}$ particles. With this choice, the agreement between calculations and measurements is very good for the mean velocities (Figure 2(a)) of both phases and very reasonable for the fluctuating velocities (Figure 2(c)) of gas and particles. Regarding the particle-laden flow mean velocities, the model including interparticle collisions is able to predict

the right momentum transfer between both phases, which is reflected in the good agreement between computations and experimental data for both phases, gas and particles (Figure 2(a)). As can be appreciated in Figure 2(c)), all the components of fluid fluctuating velocity are reduced in the two-phase case regarding single-phase flow, which is consistent with the observation that small particles tend to suppress turbulence. This turbulence modulation is correctly predicted by the model described above. Moreover, their profiles compare favorably with the measured data, with the same comments as made in the single-phase flow case. It is necessary to point out that the use of the Reynolds stress turbulence model is the reason for the agreement between computations and measurements, which is much better than that one would obtain with an isotropic turbulence model, such as the $k-\epsilon$ model.

In the case of particle fluctuating velocities (see Figure 2(c)), the computations are able to reproduce well the experimental profiles. However, a higher value of the streamwise fluctuating velocity component in the lower half of the channel than in the upper half is predicted in these three-dimensional computations. Agreement with the measurements is very good for most parts of the profile, but the computations under-predicted near the upper wall, which can be associated with an underestimation of the particle-wall collision frequency in the model. Nevertheless, the computational results seem to be logical since the particle concentration near the channel bottom is high (see Figure 4(a)) and hence the wall collision frequency, yielding a broader particle velocity distribution and, hence, higher fluctuations. Nevertheless, the asymmetry of the profiles due to higher wall collision frequency with the channel bottom is captured very well by the computations. The vertical component of the particle fluctuation, on the other hand, agrees well with the measurements, being uniform across the channel height. In Figure 2(c)) additionally the lateral horizontal fluctuating component is shown, which is for a rectangular channel only about half the vertical component, due to the reduced wall collision frequency with the lateral walls compared to that with the upper and lower walls.

It is necessary to remark that if interparticle collisions are neglected, the solids velocity profile is not accurately reproduced (Lain et al., 2002) as well as their fluctuating components. Without interparticle collisions an over-prediction of the particle horizontal fluctuating and mean velocities is observed as well as an underestimation of the vertical rms velocity values (Lain et al., 2002). These findings are associated with the following effects:

- Interparticle collisions increase the wall collision frequency for larger particles, resulting in a higher momentum loss due to wall collisions and hence a reduction of the mean particle velocity.
- As a consequence of interparticle collisions a redistribution of the fluctuating components occurs, namely the streamwise component is reduced while the vertical component is enhanced. This implies an isotropization of the particle phase fluctuating motion.

Without interparticle collisions the particle mass flux profile is also not correctly reproduced. Particles show remarkable gravitational settling, even in the presence of wall roughness, which means a decreasing particle mass flux for the upper to the lower wall of the channel. Such gravity influence is greatly reduced by interparticle collisions: they have the effect of resuspending the particles, increasing wall collision frequency with the upper wall and implying a more uniform particle mass flux profile (see Figure 4(a)).

Figure 3. Comparison of measurements and computations for the low roughness case (R0) with $D_p = 195 \mu\text{m}$ and $\Delta\gamma = 1.3^\circ$. Results are presented for an average conveying velocity of 20 m/s and mass loading $\eta = 1.0$. (a) Mean velocities and (b) fluctuating velocities, horizontal u' and vertical v' , for both phases. (Figure provided in color online.)

Therefore, the consideration of both processes, interparticle collisions and wall roughness, have been essential to reproduce the experimental results.

Figure 3 shows the computed gas and particle variables for the $D_p = 195 \mu\text{m}$ particles and small roughness (R0) case in comparison with the available experimental data. Here, the wall roughness parameter was estimated as $\Delta\gamma = 1.3^\circ$ from the corresponding curve of Figure 1. Similar to Figure 2, the predicted mean gas and particle velocities match very well the experimental data, as is shown in Figure 3(a). It can be observed that the particle mean velocity of the $195 \mu\text{m}$ particles is clearly lower than that for the $130 \mu\text{m}$ particles, indicating that the formers have higher particle-wall collision frequency. Also interesting is the behavior of rms values of velocities. The fluid fluctuating velocities and turbulence suppression by the particles with increasing mass loading are satisfactorily reproduced by the computations. It should be noted that for the $195 \mu\text{m}$ case turbulence modulation by the particles is lower than for the smaller $130 \mu\text{m}$ particles (see Figure 2(b)) due to the larger particle Stokes number and lower particle number density. The agreement between computations and experiments for the particle variables is quite good, especially for the mean velocity. The same as the experiments, the computed particle fluctuating velocities show a fairly uniform profile due to effect of interparticle collisions mentioned above. The reduction of the particle fluctuating energy is found to be stronger than for the $130 \mu\text{m}$ particles, which is also observed in the computations and is a result of particle inertia. Moreover, the experimental profiles of the streamwise component of particle fluctuating velocity for the larger, more inertial, particles show no pronounced asymmetry, as found for the $130 \mu\text{m}$ particles (compare Figures 2(c) and 3(b)).

Figure 4(a) shows the normalized particle mass flux, at 5.8 m downstream from the inlet, for both particle sizes. As can be appreciated from the experiments, the normalized particle mass flux is very similar for both particle sizes, a fact that it is well captured by the computations. In the case of rough walls the effect of interparticle collisions on the profiles of the normalized particle mass flux is less pronounced than for smooth walls, and only a slight reduction is observed near the bottom of the channel. Hence, particle dispersion is mainly governed by wall roughness in this case. Without wall roughness the redispersion of the particles due to interparticle collisions is much more visible (Sommerfeld, 2003). Moreover, the agreement of the

Figure 4. Comparison of measurements and computations for (a) normalized particle mass flux and (b) pressure drop along the channel in the low roughness case (R0) for both particle sizes, $D_p = 130, 195 \mu\text{m}$. Results are presented for an average conveying velocity of 20 m/s and mass loading $\eta = 1.0$.

computations with the measurements is very good for both particle diameters, showing only small differences near the walls, which can be attributed to the applied wall collision model because it produces somewhat higher rebound velocities at very shallow impact angles (Sommerfeld and Huber, 1999). This fact might be associated with multiple wall bouncing of the particles (Kannengieser et al., 2007), which is not accounted for in the present model yet. Let us also note that in this case of low roughness gravitational settling is still marked.

Figure 4(b) compares the measured and computed pressure drop along the channel for both particle sizes in the low roughness (R0) case. The results are presented by subtracting the static pressure at the first measurement location at 1 m. From this position all the curves are approximately straight lines, indicating that flow development and initial particle acceleration are already completed to a large extent at that location. In the plot, the data for single-phase flow are also included. As expected, the pressure drop for the particle-laden flow is higher than for the single-phase case. Due to higher particle-wall collision frequency the pressure drop for the 195 μm particles is consistently higher than that for the 130 μm particles. In all conditions the computed pressure drop agrees pretty well with the measurements, demonstrating that the present approach can be effectively used to predict the transport characteristics of solids in a channel flow.

It is necessary to remark that interparticle collisions by themselves do not contribute significantly to pressure loss along the channel. The only reason interparticle collisions can affect pressure loss is the dissipation of energy due to particle deformation in the collisions, which is described through the restitution ratio. In the simulations a restitution ratio of 0.9 was assumed for interparticle collisions, which is a realistic value for collisions between glass beads. Hence, the overall energy dissipation due to interparticle collisions is rather low. In a narrow channel, moreover, the particle motion in the horizontal direction prevails and the lateral velocity component is much lower. Therefore, interparticle collisions will not markedly change the streamwise particle velocity component, whereby the momentum extracted from the fluid for re-acceleration is also small. The main effect of collisions between particles is lateral dispersion of particles due to oblique collisions and lateral motion of particles induced mainly by wall collisions. Therefore, the main

Figure 5. Comparison of measurements and computations for the higher roughness case (R2) with $D_p = 195 \mu\text{m}$ and $\Delta\gamma = 4.5^\circ$. Results are presented for an average conveying velocity of 20 m/s and mass loading $\eta = 1.0$. (a) Mean velocities and (b) fluctuating velocities, horizontal u' and vertical v' , for both phases. (Figure provided in color online.)

contribution of the particle phase to pressure loss comes from wall collisions originating from the strong change of streamwise particle velocity.

The performance of the wall roughness model is further illustrated by comparing the velocity profiles obtained for a different wall roughness in the case of $D_p = 195 \mu\text{m}$ and loading ratio $\eta = 1.0$ (Figure 5). The considered case is the higher roughness case (R2) in Table I. To model the wall roughness a value of $\Delta\gamma = 4.5^\circ$ was chosen for the $195 \mu\text{m}$ particles according to the upper curve presented in Figure 1. With this choice, the agreement between calculations and measurements is quite good for the mean velocities (Figure 5(a)) of both phases and very reasonable for the fluctuating velocities (Figure 5(b)) of gas and particles.

In this case of higher roughness, R2, the roughness considerably promotes redistribution of the particle phase, reducing gravitational settling, and particle mass flux becomes more even across the channel (Figure 6(c)). However, a low wall roughness of only $2.32 \mu\text{m}$ is also very important for the behavior of inertial particles, and only a slight increase of mass flux towards the bottom is observed. As a consequence of wall roughness, the particles will bounce from wall to wall, causing an increase of particle-wall collision frequency and accordingly a reduction of particle mean velocity (compare Figures 3(a) and 5(a)) due to higher momentum loss. Also, as a consequence of the increase of slip velocity between phases, there is an increase of drag force that yields a slight reduction of fluid mean velocity (Figure 5(a)). The computations, however, overpredict slightly the particle mean velocity for R2 roughness compared to the experiments. The particle rms velocities of the R2 case are considerably higher and also more isotropic than those of the R0 case. These two facts are captured satisfactorily by the model, and agreement with the measurements is very good for the two measured components, horizontal and vertical, of particle fluctuating velocity (Figure 5(b)). The isotropization of the particle fluctuating energy components is due to the increase in the number of interparticle collisions, which, as already mentioned, redistribute the fluctuating kinetic energy among the different components. The measured fluid rms velocity values in the streamwise and vertical directions for the R2 case show a rather strong scatter compared to the R0 data. To explain this, it should be mentioned that the R2 measurements were done some time before the more recent R0 measurements using an older PDA system with a

Figure 6. Comparison of measurements and computations for the higher roughness case (R2) with $D_p = 195 \mu\text{m}$ and $\Delta\gamma = 4.5^\circ$ and computational results for $D_p = 130 \mu\text{m}$ ($\Delta\gamma = 5.5^\circ$). Results are presented for an average conveying velocity of 20 m/s and mass loading $\eta = 1.0$. (a) Mean velocities; (b) fluctuating velocities, horizontal u' and vertical v' , for both phases; and (c) normalized particle mass flux. Experimental data are presented for only the 195 μm particles. (Figure provided in color online.)

covariance processor less accurate than the FFT processor used for the R0 measurements.

To complete the study, Figure 6 shows the computational results for the 130 μm diameter particles in the R2 case (for which, unfortunately, there are no experimental measurements) compared with the experiments and computations for the 195 μm particles. In this case, according with the upper curve in Figure 1, a parameter $\Delta\gamma = 5.5^\circ$ has been chosen to describe wall roughness effects. Mean velocities for both particle diameters are presented in Figure 6(a) and fluctuating velocities in Figure 6(b). The 130 μm mean particle velocity is markedly higher than that of the 195 μm and less flat, indicating that particle-wall collision frequency is quite a bit lower for smaller particles. On the other hand, the influence of particles on the fluid variables is quite similar in both cases. As happened in the R0 case, the 130 μm particles have a slightly stronger effect on turbulence modulation than the 195 μm particles (Figure 6(b)). Accordingly, particle rms velocities are somewhat lower for smaller particles than for larger ones owing to the lower particle-wall collision frequency. Figure 6(c) shows the normalized particle mass flux, at 5.8 m downstream from the inlet, for both particle sizes and high roughness, R2. As can be readily seen, both profiles are very similar and flat, revealing that particle motion is, in this case, governed by wall-to-wall bouncing, as the particle fluctuating velocities suggested.

Although not shown due to the lack of measurements to compare, the pressure drop for the higher roughness case (R2) increases considerably compared to the R0 case. This is a main consequence of the increase of particle-wall collision frequency promoted by higher wall roughness. In this case, interparticle collisions enhance lateral dispersion and, hence, also increase the particle-wall collision frequency, resulting in a larger pressure drop than with the two-way coupling computations (i.e., neglecting interparticle collisions).

Summary and Conclusions

In this article a detailed analysis of particle behavior in a horizontal channel has been presented based on the Euler-Lagrange approach. Three-dimensional numerical computations of dilute phase pneumatic conveying in a 6 m long horizontal channel with a rectangular cross section (width 350 mm, height 35 mm) have been presented and compared with experimental data. Computations were carried out by means of the Euler-Lagrange approach using a Reynolds stress turbulence model for the gas phase and accounting for two-way coupling. For particle motion all relevant forces (i.e., drag, slip-shear and slip-rotational lift, and gravity) were considered. Particle-rough wall interactions and interparticle collisions were also taken into account, i.e., considering the so-called four-way coupling.

Spherical glass beads of different diameters were considered in the study. In addition, the degree of wall roughness was varied in the computations according to the experimental studies. Comparisons between computations and measurements were made for gas and particle velocities as well as normalized particle mass flux. The predicted mean gas and particle velocities agreed satisfactorily with the measurements. Turbulence attenuation by the particles was reasonably well described for the 130 and 195 μm glass beads by the applied Reynolds stress model with standard coupling terms. Moreover, the computed particle velocity fluctuations capture satisfactorily the main tendencies shown by the experiments for different roughness cases. The present results clearly emphasize that numerical predictions of wall bounded flows, such as pneumatic conveying, cannot be performed properly when neglecting wall roughness effects.

The additional pressure drop due to the presence of particles in the flow increases for larger particles (keeping the same mass loading ratio) and higher wall roughness, mainly as a result of increased particle-wall collision frequency. These trends shown by the experiments have been fairly well reproduced by the simulation scheme. Consequently, such numerical computations can largely support understanding the influence of the relevant elementary transport effects on pneumatic conveying characteristics. Moreover, with the validation of numerical computations by experiments, it is possible to use the computations to design pneumatic conveying systems and predict relevant integral parameters such as the pressure drop.

Future work will be addressed to consider particle transport in pneumatic conveying systems including different elements such as bends and/or bifurcations, which are common in industrial processes.

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