Particle transport in turbulent flows along horizontal ducts

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PARTICLE TRANSPORT IN TURBULENT FLOWS ALONG HORIZONTAL DUCTS

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***Abstract*— The present contribution describes three-dimensional Euler/Lagrange calculations of confined horizontal gas-particle flows (i.e. channel and pipe flows) emphasizing the importance of elementary processes, such as particle collisions with rough walls and inter-particle collisions, on the predicted overall flow pattern and pressure drop along the duct.**

***Keywords*— Pneumatic conveying, wall roughness, inter-particle collisions, gas-solid flow, turbulence.**

I. INTRODUCTION

The numerical prediction of industrial relevant particle-laden dispersed multiphase flows is nowadays mostly based on the Reynolds-averaged conservation equations in connection with appropriate turbulence models which have to be selected based on the considered flow situation (Laín, 2010). For the numerical treatment of two or multiphase flow the hybrid Euler/Lagrange–approach is frequently used.

This approach was applied to pneumatic conveying in a number of recent studies with more or less sophisticated modelling approaches for the dispersed phase (see Sommerfeld, 2003). A very detailed numerical calculation for a particleladen horizontal channel flow on the basis of the Euler/Lagrange-approach was presented by Lun and Liu (1997). In the Lagrangian particle-phase simulations, the drag force and transverse lift forces due to shear and particle rotation were considered. Moreover, interparticle collisions and particle-wall collisions, however without wall roughness, were considered. One of the first fully coupled Euler/Lagrange calculations of horizontal particle-laden channel flow by accounting for wall roughness effects was introduced by Lain *et al.* (2002) in comparison with experimental data. The agreement of the calculations with measurements was found to be reasonably good and it was shown that inter-particle collisions yield a redistribution of the mean particle phase fluctuation components, namely the stream-wise component is reduced while the vertical component is enhanced. In Lain and Sommerfeld (2008) a detailed comparison of two-dimensional (2-D) calculations and experiments was performed for the turbulent channel flow. The agreement of calculation and experiment (Sommerfeld and Kussin, 2004) for the vertical profiles of gas and particle phase properties was found to be very good for different particle size, mass loading and also different degree of wall roughness. Especially, the consideration of the pressure drop along the channel revealed a drastic increase of the additional pressure drop due to the particle phase when the wall roughness height is increased. This is the result of the fact that wall roughness enhances the wall collision frequency (Sommerfeld, 2003), whereby the average energy dissipation of the particle phase increases and accordingly the pressure drop due to the required particle reacceleration. For mass loading of 1.0 and a low roughness of 2.3 μm the total pressure drop at the channel end was about 500 Pa, whereas a mean roughness height of 17 μm yielded more than 1000 Pa total pressure drop. The calculated pressure drop for different particle sizes and mass loading was in excellent agreement with the measurements. Moreover, Laín *et al.* (2009) studied the pneumatic conveying of solids in horizontal pipe turbulent flow. In it the authors discus the effect of wall roughness, particle size and particle mass loading ratio on the secondary flow developing in the duct promoted by the presence of particles through momentum coupling. The computations were validated against the experimental results of Tsuji and Morikawa (1982). The secondary flow could have two or four recirculation cells depending on the particle dispersion, which is related to particle inertia, wall roughness and consideration of inter-particle collisions (i.e., the so-called four-way coupling). It was also demonstrated that the secondary flow strength increased with roughness and particle number density.

In this paper, the EulerLagrange approach is applied to study the three-dimensional characteristics of the turbulent flow in a horizontal channel and pipe with the same hydraulic diameter. Attention is paid to compare the particle-driven secondary flow pattern and pressure drop in both configurations.

II. SIMULATION METHODOLOGY

The numerical scheme adopted to simulate confined particle-laden two-phase flows was the fully coupled three-dimensional Euler/Lagrange approach (Lain and Sommerfeld, 2008). The fluid flow was calculated based on the Euler approach by solving the Reynolds-averaged conservation equations in connection with the standard k-ε turbulence model. The conservation equations were extended in order to account for the effects of the dispersed phase, i.e., two-way coupling.

The simulation of the particle phase by the Lagrangian approach is based on tracking a large number of particle trajectories through the beforehand computed flow field. Particles are treated as point masses and their shape is assumed to be spherical. Tracking requires the solution of the equations of motion for each computational particle or parcel, which is a collection of real particles with the same properties. The forces which were considered include particle inertia, drag, gravity/buoyancy, slip-shear lift force (i.e., Saffman force) and slip-rotational lift force (i.e., Magnus force). The Basset history term, the added mass and the fluid inertia are negligible for high ratios of particle to gas densities. The change of the angular velocity along the particle trajectory results from wall collisions and the viscous interaction with the fluid (i.e. the torque T_i). The different forces acting on the particles and the respective coefficients allowing the extension of the equation of motion to higher particle Reynolds numbers are presented by Lain and Sommerfeld (2008) and therefore not repeated here.

The instantaneous fluid velocity components along the particle trajectory are determined from the local mean fluid velocity interpolated from the neighboring grid points and a fluctuating component generated by a single-step Langevin model described by Sommerfeld *et al.* (1993).

Two-way coupling considers the momentum transfer from the dispersed phase to the continuous phase through appropriate source terms in the momentum, turbulent kinetic energy and dissipation rate conservation equations. These source terms are sampled for each control volume during the Lagrangian tracking procedure. An under-relaxation approach is used when introducing the source terms in the conservation equations of the fluid flow (for details see Kohnen *et al.,* 1994; and Lain and Sommerfeld, 2008). Hence, a sequential calculation of fluid flow and particle phase is performed until the coupled system has converged.

In confined flows, the modeling of particle-wall collisions is of utmost importance. The change of the 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. Hence, two model parameters are needed to calculate the wall collision process, restitution and friction coefficients, which are depending on impact velocity, particle size and impact angle and generally have to be extracted from measurements (Sommerfeld and Huber, 1999). 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. The wall roughness seen by the particle is simulated assuming that the impact angle is composed of the particle trajectory angle plus a stochastic contribution due to wall roughness, $\Delta\gamma$, which depends on the structure of wall roughness and particle size. In sampling the instantaneous roughness angle from a normal distribution with standard deviation $\Delta\gamma$, the so-called shadow effect (Sommerfeld and Huber, 1999) has to be accounted for. Inter-particle collisions are modeled by the stochastic approach described in detail by Sommerfeld (2001). This model relies on the generation of a fictitious collision partner in each Lagrangian time step and accounts for a possible correlation of the instantaneous velocities of the colliding particles in turbulent flow.

III. RESULTS

The horizontal channel has a length of 6 m, a height of 35 mm and a width of 350 mm. The computational domain was discretised by a single block structured grid consisting of about 240,000 hexahedral control volumes. The pipe was chosen in such a way that the hydraulic diameter is identical with that of the channel, yielding a diameter of 63 mm. The pipe length was again 6 m. The computational domain was discretised by 5 blocks with 280,000 control volumes in total. For both configurations the conveying gas velocity is 20 m/s and the particles are spherical glass beads with a diameter of 130 μm (mono-disperse) and density ρ_p = 2,450 kg/m^3. The particle mass loading (particle mass flow rate/gas mass flow rate) was set to be 1.0 for the considered cases. In each of the coupling iterations, the particle phase was simulated by tracking 240,000 parcels through the flow field in order to yield statistically reliable particle phase properties and source terms. Cross-sectional distributions of the different gas and particle phase properties are considered at 5.8 m downstream of the inlet, where the flow is fully developed. The wall collision process was modelled as described above, accounting for a certain degree of roughness as it will be specified below.

A comparison of cross-sectional distributions of gas and particle phase properties at the end of the channel and the pipe is shown in Fig. 1 demonstrating the influence of inter-particle collisions and the degree of wall roughness at constant mass loading of 1.0. It is clear, that neglecting inter-particle collisions in the case of low wall roughness, $\Delta\gamma$ = 0. 8°, results in an unrealistic accumulation of the particles near the bottom of pipe or channel (Fig. 1a). Collisions between particles yield a somewhat better dispersion of the particles, which are however still concentrated in the lower half of the cross-sections. An increase of the wall roughness to $\Delta\gamma$ = 5° causes a much better dispersion of the particles in the cross-section. The stream-wise mean velocity of the particles (not shown) has a maximum in the core of the pipe, but the region of the highest velocity has a different shape for the three calculations. Due to the strong gravitational settling of the particles, when neglecting inter-particle collisions, the highest particle velocities are found above the region of high particle concentration where the flow resistance is larger. For the low roughness case with inter-particle collisions the particle velocity distribution is almost symmetric with respect to the pipe axis. In the high roughness case, the region of highest particle velocities has an ellipsoidal shape, flattened in the horizontal direction. Similar cross-sectional distributions are found for the stream-wise mean gas velocity, since the particles are of course conveyed by the gas flow (Fig. 1b).

In the graphs for the stream-wise gas velocity also the streamlines of the cross-sectional component of the gas velocity are shown (Fig. 1b). It is obvious, that a secondary flow develops in the cross-section of the pipe for all cases. Without inter-particle collisions and for low roughness two circulation cells are visible, whereas the other two conditions yield four circulation cells. This phenomenon is only observed in circular pipes and not in channels. Such a secondary flow is originating from the so-called focusing effect. Particles sedimenting in a horizontal pipe will collide with the bottom part of the pipe wall and then rebound towards the core of the pipe. This is associated with a concentrated momentum transfer to the fluid (if the mass loading is high enough) inducing such a secondary flow. In the case of strong gravitational settling (i.e. without inter-particle collisions and at low roughness) the particles preferably collide with the bottom wall. Almost no particles are colliding with the top wall. Hence, the cross-sectional flow is pushed upwards by the particle focusing forming only two circulation cells. If the vertical dispersion of the particles is enhanced (i.e. due to roughness or inter-particle collisions), the collision frequency with the upper pipe wall increases. As a consequence these particles also rebound from the upper wall towards the core of the pipe and due to the momentum transfer to the fluid four circulation cells develop in the pipe cross-section (Fig. 1b).

Finally, a comparison of the pressure drop along channel and pipe is shown in Fig. 2 for the pure gas flow and the particle-laden flow. The single-phase pressure drop is almost identical for channel and pipe since the hydraulic diameter was chosen to be the same. In the particle-laden flow an additional pressure drop arises mainly due particle-wall collisions (i.e. particle wall friction). For a low roughness situation this additional pressure drop is considerably smaller than for the higher roughness case, caused by the enhanced wall collision frequency (Sommerfeld 2003). Remarkable is the considerably higher pressure drop in the pipe com-

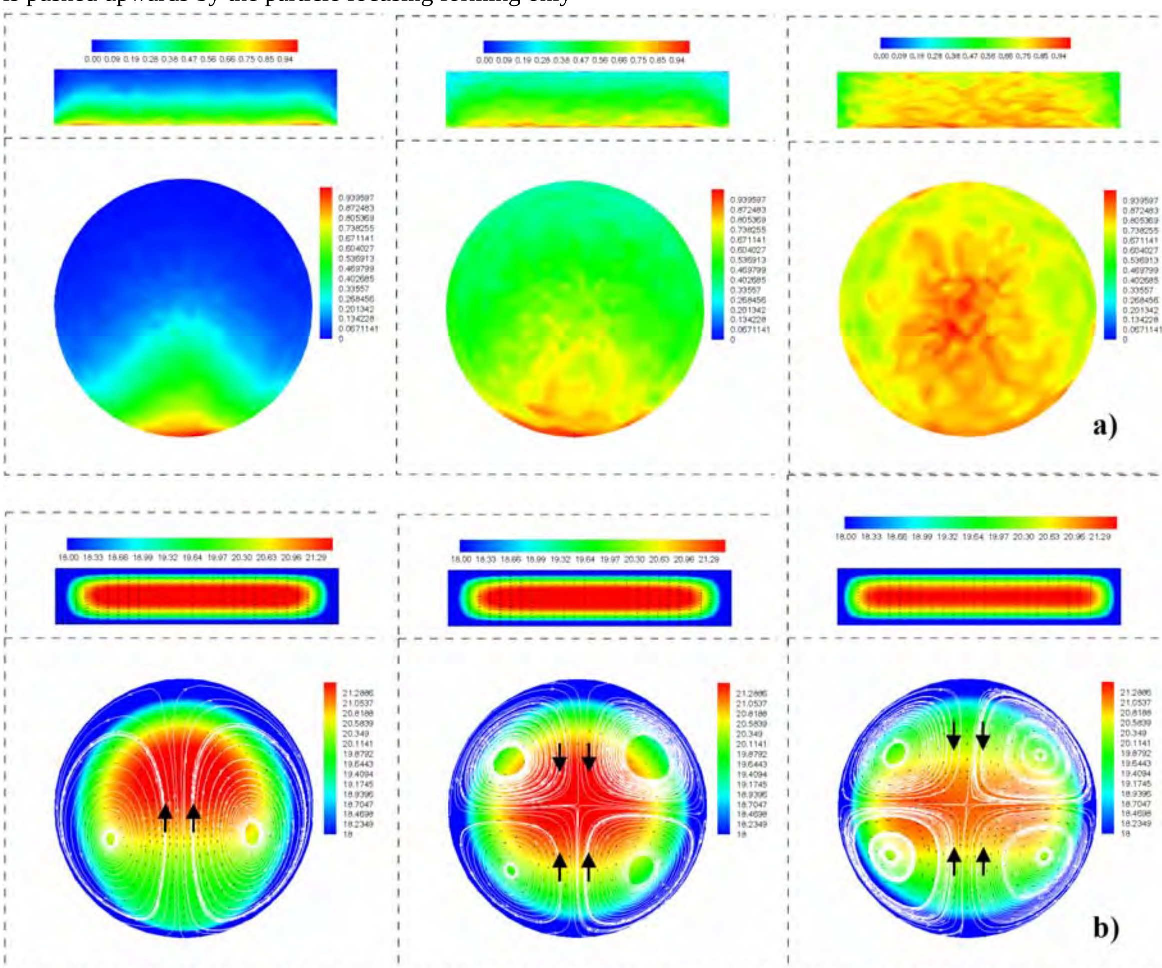

Figure 1. Comparison of calculated flow structure in a particle-laden developed channel and pipe flow for different cases; left column: two-way coupling and without inter-particle collisions, $\Delta\gamma = 0.8°$; middle column: four-way coupling, $\Delta\gamma = 0.8°$; right column: four-way coupling with $\Delta\gamma = 5°$; a) particle concentration distribution; b) distribution of stream-wise gas velocity and white lines: streamline of gas-phase cross-sectional velocity (average conveying velocity 20 m/s; D_P = 130 µm, particle mass loading 1.0).

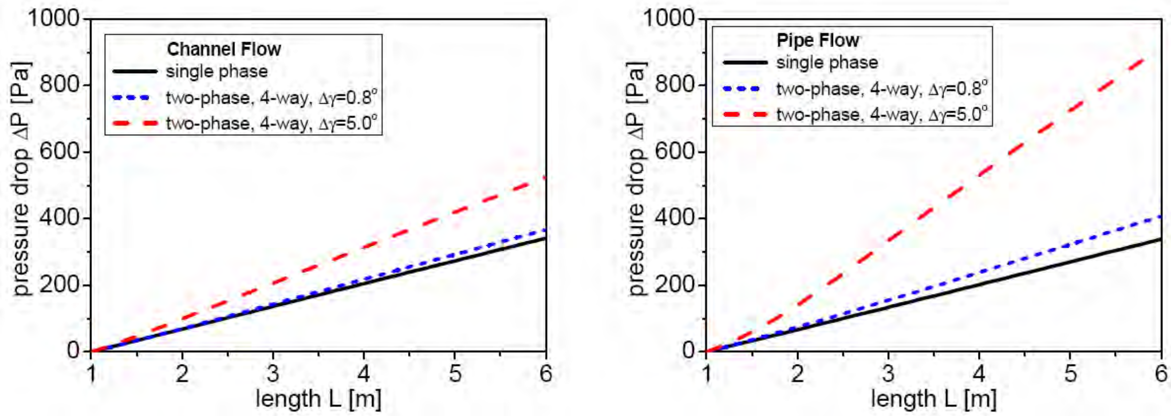

Figure 2. Calculated pressure drop along the channel (left) and the pipe (right), comparing single-phase flow and particle-laden flow (mass loading 1.0) for different wall roughness (four-way coupled calculation, D_P = 130 µm, particle mass loading 1.0, conveying velocity of 20 m/s).

pared to the channel which is again the result of the larger wall collision frequency of the particles in a pipe. From this finding one may conclude, that a channel used for pneumatic conveying requires less energy than a pipe. For validating this interesting finding, experiments on a particle-laden pipe flow are in preparation.

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