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Simulating coarse particle conveying by a set of Eulerian, Lagrangian and hybrid particle models

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ABSTRACT

This paper considers the behaviour of mono-disperse coarse glass particles in a pneumatic conveying experiment which consists of a curved and straight rectangular duct. Thus, the flow situation comprises the formation of a particle strand in the curved section as well as its dispersion in the subsequent straight horizontal channel. Thereby, from a physical point of view the effects of inter-particle collisions, particle rotation and wall roughness are of crucial importance.

Based on this experimental setup six numerical models for the granular phase are applied in order to picture these physical phenomena. While the first set of three models – the (a) Lagrangian Discrete Phase (DP) model, the (b) Discrete Element Method (DEM) and the (c) 'standard' Eulerian-granular (EUgran) model – is readily available in commercial codes the remaining three models represent in-house developments. As a first modification the standard DP model is enhanced by sub-models accounting for inter-particle collisions, wall roughness and particle rotation in order to get an (d) enhanced Discrete Phase (DP+) model. Next, two combinations between the Eulerian and Lagrangian models, the (e) Dense Discrete Phase Model (DDPM), and a (f) Eulerian based hybrid model (EUgran+) are presented and discussed.

Thus, all in all six numerical models are evaluated by qualitatively checking the main flow pattern, subsequently by a quantitative validation of dedicated profiles of particle velocity and concentration and finally, by qualitatively comparing the computational effort of each numerical model. While all 'out of the box' models fail in predicting even basic flow patterns the remaining enhanced models agree well with the experimental results. Nevertheless, their required computational effort is significantly different.

1. Introduction

Particle handling – processing, conveying, and separation – is of crucial importance in process industry. Beside analytical consideration, empirical correlations and experimental investigations, numerical simulations have gained increasing importance in studying applied particle laden flows. Regardless of the method of investigation it is mandatory to cover the dominant flow regime or the dominant flow regimes of the process. The local particle concentration for instance directly affects the importance of inter-particle collisions and thus might define a basic requirement for any modelling attempt. On the other hand the ratio between the individual particle's inertia and its drag force determines whether the effect of turbulence on the particle's trajectory is negligible or not.

In this paper a simple pneumatic conveying section is used as a basis for a comparative analysis of different numerical modelling concepts. Rather coarse mono-disperse particles of approximately 1 mm diameter are fed into a gas stream by a moderate feeding rate. Thus, the resulting average conveying is rather dilute. Nevertheless, in the curved section of the conveying duct a particle strand is formed due to centrifugal forces that represent a significantly higher local particle concentration. In the subsequent horizontal straight channel this particle strand disperses again and the particles accelerate until the normal dilute conveying regime is regained. Thus, any modelling approach should cover the phenomenon of strand formation and dispersion of coarse particles. In contrast to the experiments of Huber and Sommerfeld [9] in our case a square channel is used in order to facilitate adapting the channel's wall roughness by just placing appropriate layers into the horizontal section. Therefore, the effect of wall roughness or wall structure on the dispersion behaviour can be studied in detail, too [11].

In principle, the numerical modelling approaches could be organized in Lagrangian and Eulerian models. In the first model, individual particles or representative parcels of particles are traced by evaluating a local force balance at the actual position of the particle. On their way through the computational domain the particles exert a

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force on the continuous gas phase that acts as a source term in the momentum balance of the continuous gas phase [2]. In the second approach the information of individual particles is somehow smeared out and the multitude of particles is considered as an artificial particle phase that can interpenetrate the continuous gas phase. Based on the kinetic theory of rapid distortion inter-particle collisions go along with an increase in the particle phase's granular temperature and result in macroscopic properties like a granular viscosity or a granular pressure (e.g. [8]).

Obviously, both main approaches have their pros and cons. While within the Lagrangian framework it is difficult to address inter-particle collisions it is quite hard to consider the effects of particle rotation or wall roughness within the Eulerian approach. The Lagrangian model has already been augmented by sub-models that account for inter-particle collisions by defining virtual collisions partners that are based on previously obtained particle statistics [15,24]. In another approach the Lagrangian model tracks each individual particle and resolves each collision by either a soft sphere [4] or a hard sphere (e.g. [30]) collision sub-model. On the other side, also the Eulerian particle model has been augmented by additional equations that handle particle rotation in the cases of perfectly smooth or perfectly rough particle (e.g. [21]).

Beside these two main approaches and their individual expansions hybrid models try to combine Lagrangian and Eulerian methods. This coupling could be achieved either by a domain decomposition method or by a concurrent simulation throughout the computational domain. In the first case the Eulerian model might be applied to dense particle regions since in that regime inter-particle collisions tend to be dominant while the Lagrangian model could cover dilute flow regimes. This domain decomposition concept has been proposed in modelling snow avalanches [31], particle strands in cyclones [18] and the particle behaviour in the vicinity of walls [17]. In the second coupling approach the hybrid model is either based on a Lagrangian or on an Eulerian model throughout the domain. Nevertheless, individual terms in their basic set of equations are modelled by the help of the very other approach. Thus, within a Lagrangian based hybrid model the effect of individual inter-particle collisions could be considered by a granular pressure force that could be deduced from an Eulerian granular model [22,16,20]. An Eulerian based hybrid model on the other hand could incorporate the effect of poly-dispersity by additionally tracing passive Lagrangian particles [19]. In just another hybrid approach the behaviour of small particles is covered by an Eulerian model while large particles are traced in a Lagrangian frame of reference (e.g. [1]).

In the next section this paper starts with a description of the modelling concepts that are applied to the pneumatic conveying experiment. Beside a set of three standard models an enhanced Lagrangian model and two hybrid models are presented in some detail. In Section 3 the experimental facility and the measurement procedure is briefly sketched before in Section 4 numerical results are presented in a comparative way.

1.1. Modelling particle behaviour

In the following sub-sections the individual particle models are presented. Thereby, 'standard' models refer to models that are provided by the commercial codes Fluent 6.3 [7] and EDEM 2.0 [6]. Those 'out of the box' models have been applied without any adaptations. The remaining three enhanced models all tackle additional physical phenomena like inter-particle collisions, particle rotation or the effect of wall roughness. Thereby care is taken to apply physically analogue sub-models in order to guarantee that the results are comparable. All of the standard and enhanced models are based on a turbulent gas flow that is modelled by the Navier–Stokes equations, Eq. (1) in Table 1. Since the gas flow is strongly turbulent and comprises dominant streamline curvatures a Reynolds Stress Model (RSM) has been selected for the gas phase, Eqs. (2)–(4).

Table 1
Mass and momentum balance as well as Reynolds Stress turbulence model of the continuous gas phase; further details can be found in Fluent (2006) and literature cited therein.

$$\frac{\partial}{\partial t}(\alpha_g\rho_g) + \nabla\cdot(\alpha_g\rho_g\mathbf{u}_g) = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\alpha_g\rho_g\mathbf{u}_g) + \nabla\cdot(\alpha_g\rho_g\mathbf{u}_g\mathbf{u}_g) = -\alpha_g\nabla p_g + \nabla\cdot\alpha_g\tau_g + \mathrm{f}_{g,drag} + \mathrm{f}_{g,add}$$

$$\tau_g = \mu_g\left(\nabla\mathrm{u}_g + \nabla\mathrm{u}_g^T\right) - \tau_{g,RS}, \ \tau_{g,RS,i,j} = \rho_g\overline{u_i'u_j'} \quad (2)$$

$$\frac{\partial\left(\rho_g\overline{u_i'u_j'}\right)}{\partial t} + \nabla\cdot\left(\rho_g\mathbf{u}_g\overline{u_i'u_j'}\right) = D_{i,j} + P_{i,j} + \phi_{i,j} - \tfrac{2}{3}\delta_{ij}\rho_g\varepsilon, \quad (3)$$

$$\frac{\partial(\rho_g\varepsilon)}{\partial t} + \nabla\cdot(\rho_g\mathbf{u}_g\varepsilon) = D_\varepsilon + \tfrac{C_{\varepsilon1}}{2}P_{i,i}\tfrac{\varepsilon}{k} - \tfrac{2}{3}C_{\varepsilon2}\tfrac{\varepsilon^2}{k}, \ k = \tfrac{1}{2}\overline{u_i'u_i'} \quad (4)$$

Before embarking with the description of the individual models a general discussion on the influence of fluid turbulence on the particle behaviour is needed. This interaction mechanism is characterized by the particle Stokes number, which sets the particle relaxation time in relation with some characteristic time scale of the gas turbulence, $St = \frac{\tau_p}{\tau_g}$, where $\tau_g = \frac{2}{9}\frac{k}{\varepsilon}$, where $\tau_g = \frac{2}{9}\frac{k}{\varepsilon}$ can be related to the fluid turbulent kinetic energy k and the turbulent dissipation rate ε (e.g. [28]). The particle relaxation time is a measure for the time a particle needs to respond to a change in gas velocity. If the relative particle Reynolds number, $\mathrm{Re}_p = \frac{\rho_g d_p|\vec{u_g} - \vec{u_p}|}{\mu_g}$, is small the particle relaxation time might be expressed as $\tau_{p0} = \rho_p d_p^2/18\mu_g$, which in our situation represents a physical time of $\tau_{p0} = 6.9$ s. Anyhow, in the case of coarse particles the particle Reynolds number might become large and the particle relaxation time has to be adopted by $\tau_p = {}^{\tau}{}_{p0}\big/{}_{f}(\mathrm{Re}_p)$ where $f(\mathrm{Re}_p) = 1 + 0.15\mathrm{Re}_p^{0.687}$. Furthermore, since also the fluid turbulent kinetic energy and the turbulent dissipation rate vary in the computational domain also the typical particle Stokes number might change along a particle's trajectory. If the particle Stokes number is evaluated based on local quantities for fluid turbulence and particle Reynolds number typical Stokes numbers account to $St_{Pos.1,2,3} = 2600, 2900, 3250$ at the measurement positions. These values clearly indicate that in our case of coarse particles and correspondingly large particle relaxation times, the influence of gas turbulence on particle movement (i.e. particle strand formation and dispersion) is very weak and can be neglected. As a consequence none of the following models takes into account the influence of fluid turbulence on the particle behaviour.

1.2. Standard Lagrangian model —DP

The standard Lagrangian DP model is based on a translational force balance, Eq. (5) in Table 2. In our case the particle is accelerated only by drag force and by gravitation. Since in our case of coarse particles with $\rho_p \gg \rho_g$ additional forces like the Saffman, Basset or virtual mass force are negligible and $\mathrm{f}_{add} = 0$. Furthermore, in the standard DP model particle rotation is not considered and thus, Magnus force is neglected, too (Table 3).

Although the translational momentum balance is formulated for an individual sphere, in the standard DP model each particle represents a parcel of particles. In the two-way coupling mode of

Table 2
Translational and angular momentum balances of the Lagrangian models.

$$\frac{d}{dt}\mathrm{u}_p = \frac{18\mu_g}{\rho_p d_p^2}\frac{C_D\mathrm{Re}_p}{24}(\mathrm{u}_g - \mathrm{u}_p) + \mathrm{g} + \mathrm{f}_{p,add}, \quad (5)$$

$$\frac{d}{dt}\mathrm{x}_p = \mathrm{u}_p,$$

$$\tfrac{d}{dt}\omega_p = \mathrm{t}_{p,gas} + \mathrm{t}_{p,add} \quad (6)$$