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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF MIXING IN A CONTINUOUSLY OPERATED FLUIDIZED BED

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Abstract. Many processes require solid material to be fed continuously into a fluidized bed. In order to study the related mixing process of the solid feed with the bed material, a laboratory scale experiment with a continuous supply system is set up and monitored with a high resolution camera system. Additionally, two simulation methods are used: The Euler-Euler and an Euler-Lagrange approach based on the Discrete-Element-Method (DEM) coupled with CFD. Experimental investigations carried out at varying fluid velocities are compared with simulations. A reasonable agreement is found between the coupled DEM-CFD-method and the experimental findings.

1 INTRODUCTION

Fluidized beds are widely used systems for a variety of processes involving particulate solids. These systems have many applications in engineering such as combustion, drying, granulation and coating. Many processes require a solid material to be conveyed into a fluidized bed, to remain a certain time within the bed and to be discharged afterwards. This can be done in batch operation, however for larger quantities continuous operation is more favorable. Since mixing is expected to be “fast” in technical systems, the actual time scales associated with the mixing process are usually unknown. In this context it is important to analyze how the imparted particular solid is mixed in the fluidized bed.

To investigate this process in detail a laboratory scale experiment with a continuous particle supply system is set up in which particle motion is monitored through a high resolution camera system. Additionally, two different simulation methods are applied. The first simulation method is the Euler-Euler-approach [1, 2] where both solids and fluid are modeled in the framework of the Navier-Stokes equations incorporating the kinetic theory of granular flow. In addition as second method the coupled CFD/Discrete-Element-Method (DEM) is used [3, 4] where the particles are modeled on the grain scale based on Newton’s and Euler’s equations while the fluid is considered as a continuum described by the Navier-Stokes equations. In the following the experimental setup and the applied simulation methods are briefly explained, initial results are presented and discussed.

2 EXPERIMENTAL SETUP

The laboratory scale fluidized bed has a square base and is made out of polycarbonate (110 x 110 x 400 mm³). A sketch is given in figure 1. The system is equally fluidized from the bottom through a porous plate at adjustable fluid velocities. The bed initially consists of d=7 mm spherical particles made out of polyoxymethylene (POM). The initial bed height without fluidization is 110 mm. Particles can be inserted into the fluidized bed through a supply system which is connected to the bed at a height of 34 mm above the ground plate. In the experiments performed, a solid mass flow of 7,67 g/s is introduced through this supply for 30 seconds. Particles are discharged from the system in a height of 175 mm through a drain channel. The particles inserted into the system are of smaller size (d=5 mm) and different color than the particles forming the initial bed. Further details on the particles in the bed and in the supply system are presented in table 1.

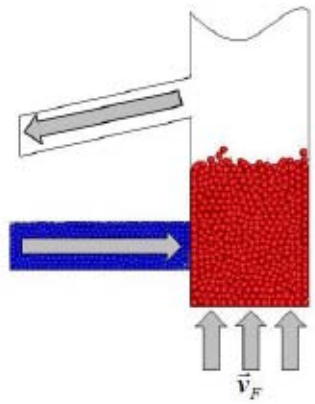

Figure 1 Outline of the experimental setup

Table 1: Details on the particles

	Particles in the bed	***Particles in the supply system***
Diameter	7 mm	5 mm
Density	1182.95 kg/m³	1182.95 kg/m³
Material	POM	POM
Number	4660	2970
Color	Blue (gray)	Yellow (white)
Mass Flow Rate	---	7,67 g/s (≈ 100 particles/s)

The particle motion is monitored through a high resolution camera system Motion Blitz 500 (Mikrotron). Differently coloured particles of varying sizes allow for a quantitative evaluation of mixing and composition within the fluidized bed and at the solid's inlet and outlet.

3 MATHEMATICAL MODELLING

In addition to the experiments two different simulation methods are used and compared. Firstly, the Euler-Euler-framework is described followed by the Euler-Lagrange-method used

as second approach.

A. EULER-EULER-MODEL

The Euler-Euler-Method based on the work by Savage and Jeffrey [1] and Ding and Gidaspow [2] considers the fluid phase as well as the particle phases as a continuum. Derived quantities are averaged per cell. Particles with the same characteristics are pooled in different particle phases. The volume fractions of the particle phases together with the volume fraction of the fluid phase sum up as

$$\varepsilon_F + \sum_{1=1}^{n_p} \varepsilon_{pi} = 1 \tag{1}$$

where $\varepsilon_F \geq 0$ is the porosity of the fluid, $n_p \in \mathrm{N}$ is the number of the particle phases and $\varepsilon_{P1},...,\varepsilon_{pn_p} \geq 0$ are the volume fractions of the respective phases 1,…,n_p. For any phase the equation of continuity applies. On the one hand the equation of continuity for the fluid phase is defined as

$$\frac{\partial(\varepsilon_F \rho_F)}{\partial t} + \nabla(\varepsilon_F \rho_F \vec{v}_F) = \vec{0} \tag{2}$$

where ρ_F is the density of the fluid and $\vec{v}_F$ is the velocity-vector of the fluid. And on the other hand the equation of continuity for the particle phases is defined as

$$\frac{\partial(\varepsilon_{Pi} \rho_P)}{\partial t} + \nabla(\varepsilon_P \rho_P \vec{v}_P) = \vec{0} \tag{3}$$

for all phases 1,…, n_p where ρ_P is the density of the particles, $\vec{v}_p$ is the velocity-vector of the particle phase and $\varepsilon_{Pi} = 1 - \varepsilon_F$ for i=1,…,n_p is the volume fraction of each particle phase considered per cell. Furthermore any phase has to achieve the balance of the momentum. For this purpose the tensor of the shear rate $\overline{\overline{S_F}}$ and the stress tensor $\overline{\overline{\tau_F}}$ for the fluid phase are given as

$$\overline{\overline{S_F}} = \frac{1}{2}\left[\nabla\vec{v}_F + (\nabla\vec{v}_F)^T\right] - \frac{1}{3}\nabla\vec{v}_F \bar{\bar{I}}, \tag{4}$$

$$\overline{\overline{\tau_F}} = 2\varepsilon_F \mu_F \overline{\overline{S_F}}. \tag{5}$$

Analogical the required tensor of the shear rate $\overline{\overline{S_P}}$ and the stress tensor $\overline{\overline{\tau_p}}$ for the particle phases are defined as

$$\overline{\overline{S_P}} = \frac{1}{2}\left[\nabla\vec{v}_P + (\nabla\vec{v}_P)^T\right] - \frac{1}{3}\nabla\vec{v}_P \bar{\bar{I}}, \tag{6}$$

$$\overline{\overline{\tau_P}} = 2\varepsilon_P \mu_P \overline{\overline{S_P}}. \tag{7}$$

The equation of momentum for the fluid phase which interacts with n_p phases of particles, reads

$$\frac{\partial(\varepsilon_F \rho_F \vec{v}_F)}{\partial t} + \nabla(\varepsilon_F \rho_F \bar{\vec{v}}_F \bar{\vec{v}}_F) = \nabla(\bar{\bar{\tau}}_F) + \varepsilon_F \rho_F \vec{g} - \varepsilon_F \nabla p + \sum_{i=1}^{n_p} \beta_i (\bar{\vec{v}}_F - \vec{v}_{pi}) \tag{8}$$

where $\vec{g}$ is the acceleration of gravity, ∇p is the pressure gradient and β is the drag coefficient representing the inter-phase momentum exchange, which is described below. The drag coefficient distinguishes between $\varepsilon_F \le 0.8$ and $\varepsilon_F > 0.8$ according to Gidaspow and Ding [2]:

$$\beta_i = \begin{cases} 150\dfrac{(1-\varepsilon_F)^2}{\varepsilon_F d_p}\mu_F + 1.75\dfrac{(1-\varepsilon_F)\rho_F}{d_p}\,|\,\bar{\vec{v}}_F - \vec{v}_P\,| & for\ \varepsilon_F \le 0.8 \quad [5] \\ \dfrac{3}{4}\rho_F C_d \dfrac{(1-\varepsilon_F)\varepsilon_F^{-1,7}}{d_p}\,|\,\bar{\vec{v}}_F - \vec{v}_{pi}\,| & for\ \varepsilon_F > 0.8 \quad [6] \end{cases} \tag{9}$$

for any phases i=1,…,n_p where d_p is the considered particle diameter, μ_F is the characteristically dynamic viscosity of the fluid and

$$C_d = \begin{cases} \dfrac{24}{\mathrm{Re}_p}[1 + 0.15(\mathrm{Re}_p)^{0.687}] & for\ \mathrm{Re}_p < 1000 \quad [6] \\ 0.44 & for\ \mathrm{Re}_p \ge 1000 \quad [6] \end{cases} \tag{10}$$

with

$$\mathrm{Re}_p = \frac{\varepsilon_F \rho_F \,|\,\bar{\vec{v}}_F - \vec{v}_p\,|\, d_p}{\mu_F}. \tag{11}$$

The equation of momentum for the particle phase j and its interaction with the fluid phase and $(n_p - 1)$ particle phases (n_p>0) is defined as

$$\frac{\partial(\varepsilon_j \rho_p \vec{v}_j)}{\partial t} + \nabla(\varepsilon_j \rho_j \vec{v}_j \vec{v}_j) = \nabla(\bar{\bar{\tau}}_j) + \varepsilon_j \rho_p \vec{g} - \varepsilon_j \nabla p_j + \beta_j(\bar{\vec{v}}_F - \vec{v}_j) + \sum_{i=1}^{n_p - 1} \beta_i (\vec{v}_j - \vec{v}_{pi}) \tag{12}$$

in which ε_j is the volume fraction, $\vec{v}_j$ is the velocity-vector, $\bar{\bar{\tau}}_j$ is the stress tensor, ∇p_j is the pressure gradient, β_j is the drag coefficient of the particle phase j . Using the kinetic theory of granular flow the pressure and the viscosity of the particle phases are calculated. Further details can be found in [2, 7].

B. Euler-Lagrange-Model

In the Euler-Lagrange-Model the particle motion is described by a three-dimensional soft-sphere Discrete-Element-Method (DEM). The mechanical behavior of the particles is calculated by integration of the Newton and Euler equations of motion. Thus, the positions and the translational and rotational velocities can be calculated for any particle in the bed.

The force $\vec{F}_i$, which affects a particle i, is given by

$$\vec{F}_i = m_i \vec{a}_i(t) = \vec{F}_{G,i} + \vec{F}_{D,i} + V_i \nabla p_i + \sum \vec{F}_{PP',i} + \sum \vec{F}_{PW,i}\,, \tag{13}$$

where $\vec{a}_i(t)$ is the acceleration and m_i is the mass of a particle i, $\vec{F}_{G,i} = m_i \vec{g}$ is the gravitational force, $\vec{F}_{D,i} = -\frac{\beta_i(\vec{v}_{Pi} - \bar{\vec{v}}_F)}{1-\varepsilon_F}$ is the drag forces, which results from the relative difference of fluid and averaged particle velocities, V_i is the volume of a particle i, $\nabla p_i = -\frac{\beta_i(\vec{v}_{Pi} - \vec{v}_F)}{\varepsilon_F}$ is the pressure gradient leading to a pressure gradient force and $\vec{F}_{PW,i}$ are the contact forces resulting from the interaction with other particles or walls. Rotational motion of a particle i is given by

$$\vec{M}_i = J_i \frac{d\vec{\omega}_i}{dt} = \sum_{j=1}^{n} \vec{M}_{ij}\,, \tag{14}$$

where $\vec{M}_{ij}$ are the external moments acting on the particle, $\vec{\omega}_i$ is the angular velocity and J_i is the moment of inertia. The interaction between the particles is calculated using a soft-sphere-method, which is based on linear spring-damper models [8, 9].

The fluid phase is modeled by a Computational Fluid Dynamics (CFD) tool. The coupled continuity and momentum equations are solved defined as

$$\frac{\partial(\varepsilon_F \rho_F)}{\partial t} + \nabla(\varepsilon_F \rho_F \bar{\vec{v}}_F) = \vec{0}\,, \tag{15}$$

$$\frac{\partial(\varepsilon_F \rho_F \bar{\vec{v}}_F)}{\partial t} + \nabla(\varepsilon_F \rho_F \bar{\vec{v}}_F \bar{\vec{v}}_F) = \nabla(\varepsilon_F \bar{\bar{\tau}}_F) - \varepsilon_F \nabla \vec{p} + \varepsilon_F \rho_F \vec{g} + \vec{f}_{\text{int}}\,. \tag{16}$$

The vector $\vec{f}_{\text{int}}$ describes the change of the momentum which results from the interaction between the fluid and the particles.

However, instead of solving equations (15) and (16) directly e.g. [3, 4], (15) and (16) can be transformed by rules of differential calculus [10] into

$$\frac{\partial(\rho_F)}{\partial t} + \nabla(\rho_F \bar{\vec{v}}_F) = -\frac{\rho_F}{\varepsilon_F}\left(\frac{\partial \varepsilon_F}{\partial t} + \bar{\vec{v}}_F \nabla \varepsilon_F\right), \tag{17}$$

$$\frac{\partial(\rho_F \bar{\vec{v}}_F)}{\partial t} + \nabla(\rho_F \bar{\vec{v}}_F \bar{\vec{v}}_F) = \bar{\bar{\tau}}_F - \nabla \vec{p} + \rho_F \vec{g} + S_m \tag{18}$$

with $S_m = \left(\frac{\vec{f}_{\text{int}}}{\varepsilon_F} + \frac{\bar{\bar{\tau}}_F}{\varepsilon_F}\nabla \varepsilon_F\right) - \frac{\rho_F}{\varepsilon_F}\left(\frac{\partial \varepsilon_F}{\partial t} + \bar{\vec{v}}_F \nabla \varepsilon_F\right)\bar{\vec{v}}_F$.

On the left side of the equal signs the classical single phase continuity and momentum equations can be identified. The solution of (17) and (18) allows for a faster convergence and therefore faster simulations especially if the momentum source terms $\vec{f}_{\text{int}}$ are further linearized by the fluid velocity [10].

4 RESULTS AND DISCUSSION

For this paper results from two different simulation methods are compared to experimental findings for two different superficial velocities which are larger than the minimal fluidization velocity of the initial bed of v=2 m/s. It is expected that the particles introduced through the supply system mix faster with the particles in the bed if the superficial velocity is chosen larger.

In figure 2 results for the Euler-Euler-Method after 15 s are shown. When comparing the two cases with superficial velocities of 2.3 m/s and 2.8 m/s it is hardly possible to recognize differences in the spatial distribution of the volume fraction introduced by the feed stream. The distribution within the bed is very similar.

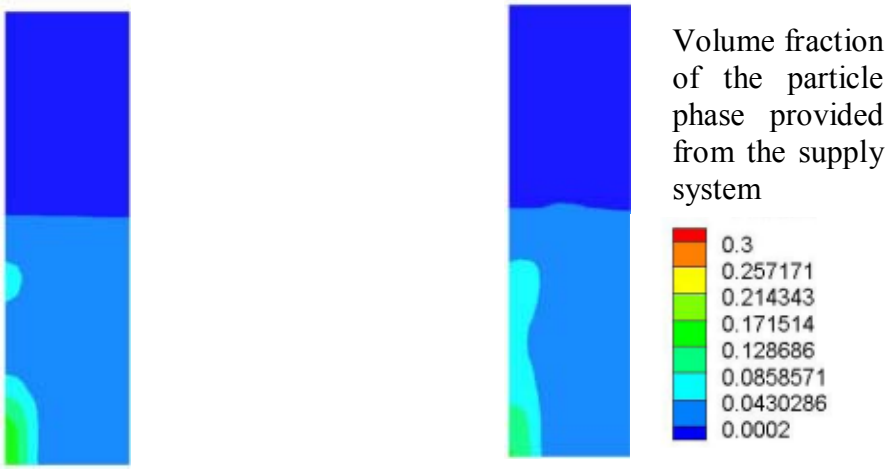

Figure 2 Results of the Euler-Euler-Method (after 15 s) - Distribution of the volume fraction of the particle phase provided through the supply system at superficial velocities of 2.3 m/s (a) and 2.8 m/s (b).

As could be concluded from figure 2, an assessment of the mixing behavior of different particle phases at varying fluid velocities, using the Euler-Euler-Method offers no detailed insight especially for the relatively large particle considered here.

In the following figures results from the experiments (figure 3) and from the coupled CFD-DEM-simulations (figure 4) are shown. In both figures it can be observed that at larger fluid velocities (leading to increased particle motion) the mixing is positively affected. In contrast, at the smaller superficial velocity of 2.3 m/s only few particles from the supply system can be seen on the periphery of the bed.

a) **b)**

Figure 3 Results of coupled CFD-/DEM-simulation (after 15 s) – Representative particle distribution in the bed at a superficial-velocity of 2.3 m/s (a) and 2.8 m/s (b)

In order to analyze the mixing behavior quantitatively, the variance s_m^2 is used:

$$s_m^2 = \frac{1}{m}\sum_{i=1}^{m}(X_i - P)^2\,, \tag{19}$$

where m is the number of spot tests, X is the actual concentration and P is the ideal concentration. Because of the dynamics of the system, the ideal concentration changes with time and is dependent on the feed mass flow.

a) **b)**

Figure 4 Experimental results (after 15 s) - Representative particle distribution in the bed at a superficial-velocity of 2.3 m/s (a) and 2.8 m/s (b)

The variances calculated from the simulations and the experiments confirm the previous results (figure 5). After 15s the variance at the superficial velocity of 2.3 m/s is clearly larger than at a superficial velocity of 2.8 m/s in experiment and simulations. At a larger fluid velocity the particles experience more fluctuations therefore mixing can occur more easily and the variance can thereby decrease. In figures 5d and 5f the variance is presented for the experiment and the Euler-Lagrange-Method at a velocity of 2.8 m/s. Both graphs indicate certain fluctuations in the variance in contrast to the lower velocity of 2.3 m/s. In the Euler-Euler-Method these fluctuation cannot be observed. The fluctuations of the variance are an effect of the particle motion on the micro scale and therefore cannot be observed in the Euler-Euler-method. Differences exist between the overall levels of the variance in the coupled CFD-/DEM-Method and in the experiment. Further effort has to be put into ensuring that conditions in the experiment and simulations are equal.

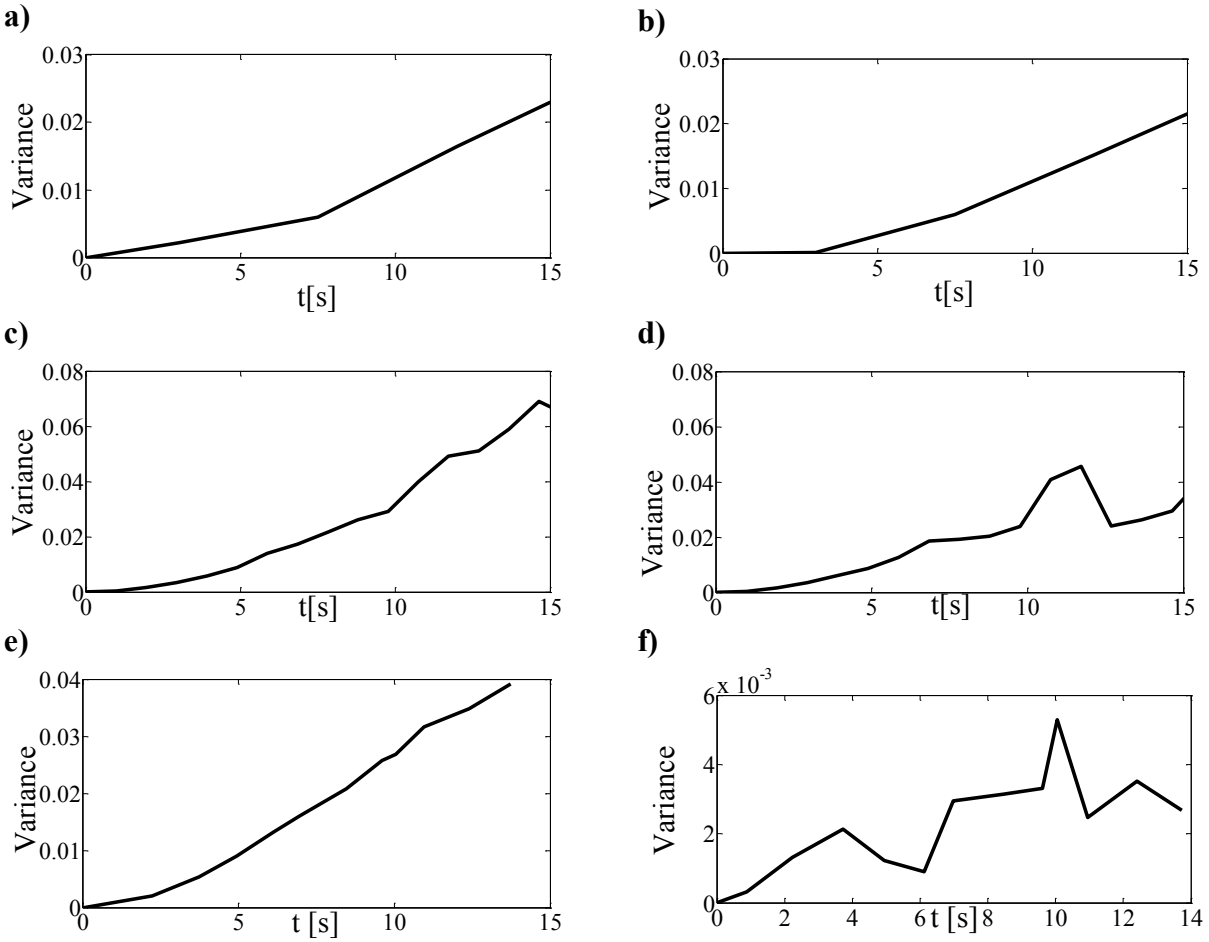

Figure 5 Variance – a)-b) Euler-Euler-Method 2.3 m/s – 2.8 m/s, c)-d) Experiment 2.3 m/s – 2.8 m/s, e)-f) Euler-Lagrange-Method 2.3 m/s – 2.8 m/s

5 CONCLUSIONS

The mixing behavior of a particle feed into a fluidized bed was investigated at different superficial velocities. For this purpose a laboratory scale experiment was set up. Additionally, two different simulation methods were utilized. On the one hand the Euler-Euler-Method, which describes all phases as continuum, was used and on the other hand an Euler-Lagrange-Method, which describes the particles in a discrete way combined with a continuum description for the fluid phase, was applied.

The results show that in the Euler-Euler-Method the superficial velocity has only a minor influence on the mixing behavior. In contrast, the experiment and the Euler-Lagrange-Method reveal that in case of an increased fluid velocity mixing is amplified. It can be concluded that the Euler-Euler-method is of limited applicability to mixing processes of particles of the size studied here. For the future the alignment between the experiment and the simulations has to be further improved to allow for a quantitative comparison.

REFERENCES

[1] Jefrey DJ, Savage SB. The stress tensor in granular flow at high shear rates. Journal of Fluid Mechanics, 110:155-272, 1981.

[2] Ding J, Gidaspow D, A bubbling fluidization model using kinetic theory of granular flow. AIChE Journal, 36:523-538, 1990.

[3] Shimizu Y, Three-dimensional simulation using fixed coarse-grid thermal-fluid scheme and conduction heat transfer scheme in distinct element method. Powder Technology, 165:140-152, 2006.

[4] Deen NG, Van Sint Annaland M, Van der Hoef MA, Kuipers JAM. Review of discrete particle modeling of fluidized beds. Chemical Engineering Science, 62: 28 – 44, 2007.

[5] Ergun S, Fluid flow through packed columns. Chemical Engineering Progress in Energy and Combustion Science, 48:89-94, 1952.

[6] Wen CY, Yu YH, Mechanics of fluidization. Fluid Particle Technology, 62:100-111, 1966.

[7] Gryczka O., Heinrich S., Deen N.G., Kuipers J.A.M., Mörl L., Three-dimensional computational fluid dynamics modelling of a prismatic spouted bed. Chem. Eng. Technol., 32(3):470-481, 2009.

[8] Kruggel-Emden, H., Wirtz, S., Scherer, V., A study on tangential force law applicable to the discrete element method (DEM) for materials with viscoelastic or plastic behavior. Chemical Engineering Science, 63(6): 1523–1541, 2008.

[9] Kruggel-Emden, H., Simsek, E., Rickelt, S., Wirtz, S., & Scherer, V., Review and extension of normal force models for the Discrete Element Method. Powder Technology, 171(3): 157–173, 2007.

[10] Wu CL, Berrouk AS, Nandakumar K, Three-dimensional discrete particle model for gas–solid fluidized beds on unstructured mesh. Chemical Engineering Journal, 152:514–529, 2009.