A discrete particle simulation study on the influence of restitution coefficient on spout fluidized bed dynamics

Maureen S. van Buijtenen¹, Niels G. Deen¹, Stefan Heinrich², Sergiy Antonyuk² and J.A.M. Kuipers¹

¹University of Twente, Faculty of Science and Technology, Institute for Mechanics Processes and Control Twente
PO Box 217, Enschede, 7500 AE, The Netherlands
N.G.Deen@utwente.nl
²Otto-von-Guericke-University Magdeburg, Faculty of Process and Systems Engineering
PO Box 4120, 39106 Magdeburg, Germany

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Abstract

Spout fluidized beds find widespread application in the process industry in granulation processes, in which efficient contacting between large particles, droplets and gas is of paramount importance. However, detailed understanding of the complex behavior of these systems is lacking. In this paper we study the effect of the inter-particle interaction on the bed dynamics, by investigating the bed height, pressure drop and vertical particle velocity as function of the restitution coefficient. In addition, the amplitude of the fluctuations of these quantities is displayed in terms of the root mean square (RMS). This is done computationally, by using the discrete element model (DEM) which describes the dynamics of the continuous gas-phase and the discrete particles. The objective of this work is to gain insight in the effect of the restitution coefficient on the flow behavior of spout fluidized beds at different flow regimes using DEM. The three flow regimes comprise the intermediate / spout-fluidization regime (B1), spouting-with-aeration regime (B2) and the jet-in-fluidized-bed regime (B3). The pressure drop and the vertical particle velocity are compared to experimental data obtained by Link et al. (2007). The computed results with εn = 0.97 show the same resemblance with the experiments as reported by Link et al. (2007).

It is shown that if the restitution coefficient decreases, more bubbles are present causing more pronounced heterogeneity (instability) in the overall flow structure of the bed, in more or less extent dependent on the flow regime. The particle velocity and RMS profiles confirm the effect on the stability of the bed and show that the spout channel for cases B1 (intermediate/spout-fluidization regime) and B3 (jet-in-fluidized-bed regime) becomes unstable when the restitution coefficient decreases. For case B2, a transition occurs from the spouting-with-aeration to the intermediate/spout-fluidization regime at low restitution coefficient.

These findings show the great importance of the influence of the restitution coefficient on the dynamics of the bed. During the granulation process, when the particles contain different moisture contents, regions in the bed exist that contain particles with different restitution coefficients. These regions thus experience different dynamics, resulting in varying performance. In future work we intend to improve the discrete element model, by giving each particle its own restitution coefficient dependent on its moisture content.

Introduction

Spout fluidized beds are frequently used for the production of granules or particles through granulation, which are widely applied for example in the production of detergents, pharmaceuticals, food and fertilizers (Mörl et al., 2007). Spout fluidized beds have a number of advantageous properties, such as high mobility of the particles preventing undesired agglomeration and enabling excellent heat transfer control. The particle growth mechanism in a spout fluidized bed as function of the particle-droplet interaction has a profound influence on the particle morphology and thus on the product quality. During the granulation process, particles contain different loadings of moisture which results in varying collision properties in time and location across the bed. Consequently, the bed dynamics depend, amongst others, on collision properties. This has been shown by Passos & Mujumdar (2000) and Vieira & Rocha (2004), who experimentally investigated the flow behavior in spouted beds with dry respectively wet particles. They both observed a decrease of the particle velocity in the annulus with increasing moisture content, keeping constant all the operating conditions during a coating experiment. In addition, the bed pressure drop was found to decrease with increase of the instantaneous bed saturation degree. The stable spout pressure drop in the dry bed was found to be higher than that in the wet bed.

Fu et al. (2004) also studied the effect of the moisture content on collision properties experimentally. The collision properties between particles are captured in the restitution coefficient which is the ratio of the velocities associated with impact and rebound. They found that the restitution coefficient decreases with increasing moisture content, which they attributed to the reduction of the Young’s modulus.

Mangwandi et al. (2007) experimentally investigated the impact behavior of three different types of granules, viz. wet, melt and binderless granules. Wet granules are defined as granules in which the primary particles are held together by liquid bridges; the melt granules are wet granules with solidified binder. The binderless granules are granules without binder. They also found differences in restitution...
coefficients for the different types of granules. Research has thus shown that the moisture content in spout fluidized beds has a great influence on the inter-particle collision properties and hence on the flow behavior. It may therefore be concluded that a detailed description of the influence of the restitution coefficient on the bed dynamics is of great importance. However, a description has not yet been obtained in detail due to the practical problems faced in the experimental study of spouted beds, such as infeasible non-intrusive access of the spout channel. Therefore, computational methods provide a powerful and attractive alternative for laborious experimental studies. In this work we use fundamental, deterministic models to enable the detailed investigation of granulation behavior in a spout fluidized bed. A discrete element model (DEM) is used, which describes the dynamics of the continuous gas-phase and the discrete particles. The model is based on the hard-sphere DEM originally developed by Hoomans et al. (1996) and extended by Link et al. (2007) for the simulation of spout fluidized beds. The objective of this work is to gain insight in the effect of the restitution coefficient on the flow behavior of spout fluidized beds at different flow regimes using the DEM. The simulation results are compared with experimental data obtained by Link et al. (2007). The organization of this paper is as follows: first, the DEM is briefly discussed. Then, the studied test cases are described, followed by an explanation of the experimental procedure conducted by Link et al. (2007). Finally, the simulation results are discussed and compared with the experiments.

Numerical model

The simulations are conducted with a discrete element model that describes the dynamics of the continuous gas-phase and particles. For each element momentum balances are solved. The momentum transfer among each of the phases is calculated from the Newtonian equation of motion:

$$m_p \frac{d^2 r_p}{dt^2} = -\nabla \rho_p + \frac{\beta}{\varepsilon_p} (\mathbf{u}_p - \mathbf{v}_p) + m_p g \quad (1)$$

where \(\beta\) represents the inter-phase momentum transfer coefficient due to drag, which is calculated using a drag relation proposed by Koch & Hill (2001) based on lattice-Boltzmann simulations:

$$\beta_{\text{Koch\&Hill}} = \frac{18 \mu_p \varepsilon_p}{d_p^2} \left( F_\beta(\varepsilon_p) + \frac{1}{2} F_\beta(\varepsilon_p) \Re_p \right) \quad (2)$$

where \(\varepsilon_p = 1 - \varepsilon_p\) and \(\Re_p\) is given by:

$$\Re_p = \frac{\varepsilon_p \rho_p |\mathbf{u}_p - \mathbf{v}_p| d_p}{\mu_p} \quad (3)$$

and with:

$$F_\beta(\varepsilon_p) = \frac{1}{3} \left[ 1 - \frac{25}{3} \varepsilon_p^3 + \frac{135}{64} (\ln(\varepsilon_p) + 16.14\varepsilon_p) \right] \quad (4)$$

where \(\mu_p\) is determined using the ideal gas law and the viscous stress tensor, \(\mathbf{\tau}\), is assumed to obey the general form for a Newtonian fluid (Bird et al., 1960):

$$\mathbf{\tau} = -\frac{\lambda_p}{3} \left[ \left( \nabla \cdot \mathbf{u}_p \right) \mathbf{1} + \mu_p \left( \left( \nabla \mathbf{u}_p \right) + \left( \nabla \mathbf{u}_p \right)^T \right) \right] \quad (7)$$

Two-way coupling is achieved via the sink term, \(S_p\), which is computed from:

$$S_p = \frac{1}{V_{cel}} \sum \beta \left( \mathbf{u}_p - \mathbf{v}_p \right) D(r - r) \quad (9)$$

The distribution function, \(D\), distributes the reaction force acting on the gas phase to the velocity nodes in the staggered Eulerian grid.

Test cases

The objective of this work is to study the effect of the restitution coefficient on the bed dynamics. Therefore several simulations have been conducted using different values of the restitution coefficient, ranging from 0.2 to 0.97. In addition, its influence is investigated for various flow regimes, which are chosen in accordance with the experiments of Link et al. (2007). In Table 1 the particle properties are listed, the studied flow regimes are shown in Table 2, whereas the numerical settings and time step per simulation are listed in Table 3 and Table 4, respectively.

Table 1: Particle properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Glass</td>
<td>n.a.</td>
</tr>
<tr>
<td>(d_p)</td>
<td>4.0</td>
<td>mm</td>
</tr>
<tr>
<td>(\rho_p)</td>
<td>2526</td>
<td>kg/m³</td>
</tr>
<tr>
<td>(\varepsilon_{p,\text{up}})</td>
<td>0.2 – 0.97</td>
<td>-</td>
</tr>
<tr>
<td>(\varepsilon_{p,\text{out}})</td>
<td>0.2 – 0.97</td>
<td>-</td>
</tr>
<tr>
<td>(\mu_{p,\text{up}})</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>(\mu_{p,\text{out}})</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>(\beta_{0,\text{up}})</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>(\beta_{0,\text{out}})</td>
<td>0.33</td>
<td>-</td>
</tr>
</tbody>
</table>
Experimental methods

Link et al. (2007) used positron emission particle tracking (PEPT) as a non-intrusive measuring technique, which supplies detailed information about the particle motion. PEPT tracks the motion of a single activated particle in a spout fluidized bed over a long period of time in a non-intrusive manner. For further details on the experimental method the interested reader is referred to the work of Link et al. (2007).

The 3D spout fluidized bed set-up used by Link et al. (2007) consists of a gas-fluidized bed, which is schematically represented in Figure 1. The side walls of the bed are made of aluminum, while the front and back walls are made of polycarbonate. Pressurized air was fed to the bed through three separate sections. A 2 mm thick porous plate with an average pore size of 100 μm provided a homogeneous gas distribution over the two fluidization sections. Figure 1 shows that the bed contains a spout section, which is covered by a 0.5 mm metal gauze and located on the border between the two fluidization sections at the geometrical centre of the bottom plate. The particles possess the same properties as given in Table 1 and the true normal restitution coefficient in the experiments is 0.97. The experiments conducted by Link et al. (2007) provide results of the time-averaged vertical particle velocity and the root mean square (RMS) belonging to the flow regimes B1, B2 and B3. These results will be compared with the results obtained from the DEM simulations.

Results and Discussion

To study the effect of the restitution coefficient on the bed dynamics, the following aspects will be examined:

- Bed height
- Pressure drop fluctuations
- Particle velocity

The bed height and pressure drop fluctuations are presented to study the overall bed dynamics, and the particle velocity to capture more details of the particle motion in the bed as function of the restitution coefficient. The experimental results reported by Link et al. (2007) are used to validate the simulated results.

First, snapshots of the simulated instantaneous particle positions are presented in Figure 2, to show the bed behavior for different restitution coefficients for the three cases.

Subsequently, the results of the bed height will be shown, followed by a presentation of the pressure drop and finally the particle velocity will be discussed.

Bed height

In Figure 3 the time-averaged bed height averaged over a period of 8 s is shown. The first 2 s of the simulations were excluded from the spectral analysis to prevent start-up effects from influencing the results. The simulated results were obtained at a frequency of 250 Hz. It is found that the average bed height decreases with increasing restitution coefficient. This is due to decreasing bubble hold-up. Particles with low restitution coefficient tend to promote the formation of dense regions and passage of gas through the bed mainly in the form of bubbles. It appears that the restitution coefficient influences the bed height most for case B2, the spouting-with-aeration regime. The gas velocity in the spout is quite large in this regime and consequently the particle clusters are dragged higher in the bed. As a result, the bed height increases more with decreasing restitution coefficient in the spouting-with-aeration regime.

Table 2: Flow regimes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Flow regime</th>
<th>$u_{bg}$ [m/s]</th>
<th>$u_{w0}$ [m/s]</th>
<th>$u_{w1}$ [m/s]</th>
<th>$u_{w2}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Intermediate / Spout-fluidization</td>
<td>2.5</td>
<td>1.4</td>
<td>60</td>
<td>34</td>
</tr>
<tr>
<td>B2</td>
<td>Spouting-with-aeration</td>
<td>2.5</td>
<td>1.4</td>
<td>90</td>
<td>51</td>
</tr>
<tr>
<td>B3</td>
<td>Jet-in-fluidized-bed</td>
<td>3.5</td>
<td>2.0</td>
<td>65</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 3: Numerical settings.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_x$</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>$N_y$</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$N_z$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$t_{end}$</td>
<td>8</td>
<td>s</td>
</tr>
<tr>
<td>$N_p$</td>
<td>$4.48\cdot10^4$</td>
<td></td>
</tr>
<tr>
<td>$k_x$</td>
<td>$10^4$</td>
<td>N/m</td>
</tr>
</tbody>
</table>

Table 4: Time step used in the simulations.

<table>
<thead>
<tr>
<th>$\epsilon_x$</th>
<th>$\Delta t_{h1}$ [s]</th>
<th>$\Delta t_{x2}$</th>
<th>$\Delta t_{x3}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>$10^3$</td>
<td>$10^2$</td>
<td>$5\cdot10^4$</td>
</tr>
<tr>
<td>0.4</td>
<td>$10^3$</td>
<td>$10^2$</td>
<td>$5\cdot10^4$</td>
</tr>
<tr>
<td>0.6</td>
<td>$10^3$</td>
<td>$10^2$</td>
<td>$2.5\cdot10^4$</td>
</tr>
<tr>
<td>0.8</td>
<td>$10^3$</td>
<td>$5\cdot10^2$</td>
<td>$2.5\cdot10^4$</td>
</tr>
<tr>
<td>0.97</td>
<td>$10^5$</td>
<td>$10^5$</td>
<td>$2.5\cdot10^5$</td>
</tr>
</tbody>
</table>

Figure 1: Schematic representation of the geometry of the 3D spout fluidized bed, dimensions are given in mm.
The amplitude of the fluctuations of the bed height is also shown in Figure 3 in terms of the root mean square (RMS). It can be seen that the RMS for case B3, the jet-in-fluidized-bed regime is much larger than the RMS for

\[ e_n = 0.2 \quad e_n = 0.4 \quad e_n = 0.6 \quad e_n = 0.8 \quad e_n = 0.97 \]

### Pressure drop fluctuations

The measured pressure drop fluctuations, which reflect the dynamic behavior of the bed, are used for model validation. During the experiments, the pressure drop was recorded at a frequency of 100 Hz. The NL-experiments were conducted for about one minute, while most of the UK-experiments lasted one hour. The simulated pressure drop fluctuations were averaged over a period of 8 s. The first 2 s of the simulations were excluded from the spectral analysis to prevent start-up effects from influencing the results. The simulated results were obtained at a frequency of 250 Hz. Note that in the experiments only a single particle was tracked, whereas in the simulations all particles were used to obtain time-averaged quantities.

The amplitude of the pressure drop fluctuations is represented in terms of the root mean square and is listed in Table 5. The simulated values with \( e_n = 0.97 \) show good agreement with the experimental data as reported in Link et al.
The RMS of the measured and simulated pressure drop fluctuations [Pa].

<table>
<thead>
<tr>
<th>Case</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment-NL $e_n = 0.97$</td>
<td>209</td>
<td>166</td>
<td>795</td>
</tr>
<tr>
<td>Experiment-UK $e_n = 0.97$</td>
<td>241</td>
<td>84</td>
<td>763</td>
</tr>
<tr>
<td>Simulation Link $e_n = 0.97$</td>
<td>226</td>
<td>34</td>
<td>463</td>
</tr>
<tr>
<td>Simulation $e_n = 0.97$</td>
<td>187</td>
<td>37</td>
<td>415</td>
</tr>
<tr>
<td>Simulation $e_n = 0.8$</td>
<td>260</td>
<td>161</td>
<td>532</td>
</tr>
<tr>
<td>Simulation $e_n = 0.6$</td>
<td>174</td>
<td>162</td>
<td>533</td>
</tr>
<tr>
<td>Simulation $e_n = 0.4$</td>
<td>364</td>
<td>202</td>
<td>522</td>
</tr>
<tr>
<td>Simulation $e_n = 0.2$</td>
<td>301</td>
<td>154</td>
<td>538</td>
</tr>
</tbody>
</table>

The RMS of the pressure drop for case B3 is higher compared to the other flow regimes, because this regime is less stable as mentioned earlier. The RMS values listed in Table 5 are also presented in Figure 4, where lines are added to indicate the trend of the effect of the restitution coefficient. It can be seen that the near-ideal case, with $e_n = 0.97$, gives a small RMS value, indicating small fluctuations in the pressure drop. In addition, a clear transition is noticeable from the near-ideal to non-ideal cases around $e_n = 0.8$, whereas at lower restitution no further increase of RMS is observed. This trend is also found in the averaged pressure drop. The influence of the restitution coefficient on the pressure drop exhibits a different trend than on the bed height. Apparently, contrary to conventional fluidized beds, for spout fluidized beds the pressure drop is not inversely proportional to the bed height. This may be due to the heterogeneity prevailing in spout fluidized beds, i.e. the presence of a core-annulus structure.

Particle velocity

The particle velocities resulting from the PEPT measurements are used to validate the simulation results in a more detailed manner. In the work of Link et al. (2007), the PEPT data consisted of particle trajectories from which a particle velocity history was retrieved. Consequently, for each time step the particle velocity was only known at a single location. To obtain a time-averaged velocity field the results from a measurement over a longer period of time were combined. In the simulations, the time averaged velocities were calculated by averaging over all particles, employing the same numerical grid that is used to solve the gas phase dynamics:

$$\langle v_{i,j,k} \rangle = \frac{\sum_{i,j,k} v_{i,j,k} \delta}{\sum_{i,j,k} \delta}, \quad \forall \delta = \begin{cases} 1 & \forall p \in (i,j,k) \\ 0 & \forall p \notin (i,j,k) \end{cases}$$

where $p$ represents a particle in cell $(i,j,k)$. $N_p$ is the number of particles, $t_0$ initial time and $t_{end}$ is the simulation time. The particle velocity profiles in the central xz-plane are shown at a height $z = 0.15$ m to illustrate the particle velocities in the annulus and the spout channel. At this level a profile of the root mean square (RMS) of the particle velocity in the vertical direction and the horizontal x-direction is displayed, as well. The RMS of the velocity in the x-direction is presented to study the fluctuations of the lateral particle velocity which is caused by the presence of bubbles and periodic lateral movement of the spout channel.

Spout-fluidization regime

According to Link et al. (2007), a spout channel is present in the spout-fluidization regime which is periodically blocked by particles from the annulus.

Figure 5 shows the time-averaged vertical particle velocity and the RMS of velocities for case B1, the spout-fluidization regime, obtained from both simulation and experiment. The simulation results with $e_n = 0.97$ (both velocity and RMS) show good resemblance with the experimental results compared to the results reported by Link et al. (2007). It is noted that the experimentally determined RMS of the velocities are obtained from a series of six particle positions, which has a smoothing effect, according to Link et al. (2007). When the restitution coefficient decreases, the vertical velocity in the spout channel slightly increases and in the annulus more down flow of the particles is observed. The RMS of the vertical velocity increases with decreasing restitution coefficient, caused by the more frequently opening and closing of the spout channel. As a result, particles are moved upwards in the bed in clusters, by which a higher vertical velocity is
reached. The stability of the spout is also influenced by the restitution coefficient, shown by the altered shape of the RMS profile of the vertical velocity.

The RMS of both the vertical and lateral velocity in the annulus increases as the restitution coefficient is decreasing, which is attributed to the presence of more bubbles in the annulus.

**Spouting-with-aeration regime**

In the spouting-with-aeration regime, the spout channel is stable and continuously penetrates the entire bed, due to the relatively high gas velocity in the spout.

Figure 6 shows the time-averaged vertical particle velocity and the RMS of velocities for case B2, the spouting-with-aeration regime, obtained from both simulation and experiment.

The simulation results with $e_n = 0.97$ show good resemblance with the experimental results. In Figure 6 it is shown that the vertical particle velocity in the spout channel increases with decreasing restitution coefficient. The difference in downwards velocity in the annulus is less pronounced compared to case B1. In this case, the RMS of the vertical velocity in the spout channel also increases as the restitution decreases. This is attributed to the more frequently opening and closing of the spout channel. In addition, the flow regime turns from spouting-with-aeration into intermediate/spout-fluidization regime at $e_n \approx 0.4$. This is consistent with the flow regime maps of particles with different restitution coefficient, presented in the work of Link (2006). The RMS of the vertical and lateral velocity in the annulus increases with decreasing restitution, indicating that more bubbles are present in the annulus at low restitution coefficient.

The shape of the RMS of the vertical and lateral velocity presented in Figure 6 shows a regular profile. Apparently, the restitution coefficient does not influence the stability of the spout in this flow regime. This may be due to the sufficiently high gas velocity in the spout, which transports all particles in the spout, independent of the state the particles are in (i.e. having high or low restitution coefficient).

**Jet-in-fluidized-bed regime**

In the jet-in-fluidized-bed regime, the bed contains both a spout channel and bubbles in the annulus with mutual interaction, which causes either stable or unstable behavior. The stable behavior has been indicated as the single frequency mode and the unstable behavior as the multiple frequency mode by Link et al. (2005). In the single frequency mode the bubbles leave the bed through the spout channel and in the multiple frequency mode the bubbles and the spout influence each other.

Figure 7 shows the time-averaged vertical particle velocity and its RMS of vertical and lateral particle velocity for case B3, the jet-in-fluidized-bed regime, obtained from both simulation and experiment.

The simulation results of the vertical particle velocity at $e_n = 0.97$ show corresponding resemblance with the experimental data compared to the results reported by Link et al. (2007). The vertical velocity is barely affected by the restitution coefficient. However, the RMS in the vertical velocity does significantly change with varying restitution coefficient, implying that the spout channel becomes unstable. It is very likely that a transition from the single frequency to the multiple frequency mode occurs at lower restitution coefficient.
Conclusions

In this paper the influence of the restitution coefficient on the bed dynamics is studied using the discrete element model (DEM). The fluctuations in the bed height, bed pressure drop, and the time-averaged vertical particle velocity were determined. In addition, the amplitude of the fluctuations was studied in terms of the root mean square (RMS). For our study three flow regimes were investigated: the intermediate / spout-fluidization regime (B1), spouting-with-aeration regime (B2) and the jet-in-fluidized-bed regime (B3). The pressure drop and the vertical particle velocity were compared to the experimental data reported by Link et al. (2007) to validate the DEM model. The computed results with $e_n = 0.97$ showed good resemblance with the experiments as well as the simulations reported by Link et al. (2007). Furthermore, it was found that with decreasing restitution coefficient, the average bed height increased for all flow regime cases. The averaged pressure drop was lowest at $e_n = 0.97$ for all three regime cases, showing the
near-ideal mutual interaction of the particles. A transition from near-ideal to non-ideal behavior is observed around \( \varepsilon_n = 0.8 \). This was confirmed with the trend of the RMS of the pressure drop.

Thus, as the restitution coefficient decreases, the dynamic behavior of the bed becomes more pronounced, with an extent depending on the flow regime.

The particle velocity and RMS profiles confirmed the effect on the dynamics of the bed and revealed that the spout channel for cases B1 (intermediate/spout-fluidization regime) and B3 (jet-in-fluidized-bed regime) becomes unstable when the restitution coefficient decreases. For case B2, a transition occurs from the spouting-with-aeration to the intermediate/spout-fluidization regime at low restitution coefficient.

These findings reveal the significant impact of the influence of the restitution coefficient on the dynamics of the bed. During the granulation process, when the particles contain different loadings of moisture, regions in the bed exist that contain particles with different restitution coefficient. These regions thus display distinctly different bed dynamics. It is therefore desirable to further improve the discrete element model, by giving each particle its own restitution coefficient dependent on its moisture content.

**Acknowledgements**

The authors would like to thank FOM, STW and Yara Sluiskil, The Netherlands, for their financial support to the project.

**Nomenclature**

- \( d \) diameter (m)
- \( D \) distribution function (-)
- \( \varepsilon_n \) coefficient of normal restitution (-)
- \( g \) gravitational acceleration (m/s\(^2\))
- \( \langle H_{\text{bed}} \rangle \) time-averaged bed height (m)
- \( l \) unit vector (-)
- \( k_s \) spring stiffness (N/m)
- \( m_p \) particle mass (kg)
- \( N_p \) number of particles (-)
- \( N_t \) number of time steps (-)
- \( N_x \) number of gridcells x-direction (-)
- \( N_y \) number of gridcells y-direction (-)
- \( N_z \) number of gridcells z-direction (-)
- \( p \) pressure (Pa)
- \( \langle p \rangle \) time-averaged pressure drop (Pa)
- \( r \) position (m)
- \( \text{Re}_p \) particle Reynolds number (-)
- \( S_p \) particle drag sink term (N/m\(^2\))
- \( t \) time (s)
- \( \Delta t \) time step in simulation (s)
- \( u \) gas velocity (m/s)
- \( v_p \) particle velocity (m/s)
- \( \langle v_p \rangle \) time-averaged particle velocity (m/s)
- \( V \) volume (m\(^3\))

**Greek letters**

- \( \beta \) inter-phase momentum transfer coefficient (kg/(m/s))
- \( \beta_\theta \) coefficient of tangential restitution (-)
- \( \varepsilon \) volume fraction (-)

**Subscripts**

- \( bg \) background fluidization
- \( \text{end} \) end of simulation
- \( \text{exp} \) experimental
- \( f \) fluid phase
- \( \text{mf} \) minimum fluidization
- \( p \) particle
- \( \text{pdf} \) pressure drop fluctuations
- \( \text{sim} \) simulation
- \( \text{sp} \) spout fluidization
- \( \text{sup} \) superficial
- \( w \) wall
- \( x \) horizontal direction
- \( z \) vertical direction
- \( 0 \) initial

**Abbreviations**

- 3D three-dimensional
- DEM discrete element model
- NL at the University of Twente in The Netherlands
- PEPT positron emission particle tracking
- RMS root mean square
- UK at the University of Birmingham in the United Kingdom

**References**


