COMPARISON OF PIV MEASUREMENTS AND A DISCRETE PARTICLE MODEL IN A RECTANGULAR 3D SPOUT-FLUID BED

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ABSTRACT

Particle image velocimetry and a 3D hard sphere discrete particle model were applied to determine particle velocity profiles in the plane around a spout in a spout-fluid bed for various initial bed heights, spout and background fluidization velocities. Comparison between experimental and numerical results revealed that the particle velocities are underestimated by particle image velocimetry, which is probably caused by steep velocity gradients, and overestimated by the model, which is probably caused by the closure for fluid-particle drag.

INTRODUCTION

Spout-fluid beds are used for a variety of processes involving particulate solids, like coating, drying, granulation and pyrolysis. The spout-fluid bed combines a number of favorable properties of both spouted and fluidized beds. Unfortunately a detailed understanding of the fundamentals of spout-fluid beds is lacking.

In early numerical studies (f.i. Littman et al. (1)) only the overall behavior of the bed was considered neglecting the details of particle motion. Only recently Kawaguchi et al. (2) studied the particle behavior in a spouted bed in detail using a discrete particle model. They solved the volume-averaged Navier-Stokes equations for the gas phase, taking momentum transfer between the gas and the particles into account. Newton’s second law was used to compute the motion of each individual particle.

Regarding the treatment of particle-particle interaction two approaches can be distinguished; Tsuji et al. (3) modeled collisions between particles with a soft sphere approach, while Hoomans et al. (4) used a hard sphere approach. The former is most suited to model systems in which defluidized zones can prevail, whereas the latter is more suited for vigorously fluidized systems, like spout-fluid beds. In this study a hard sphere discrete particle model has been adopted to study the bed motion in detail.

Optical probes have been used to study the solids flow behavior in spout-fluid beds and spouted beds (He et al. (5); Pianarosa et al. (6)). In a few recent studies optical whole-field techniques have been used to study particle behavior in fluidized beds. Agarwal et al. (7) and Goldschmidt (8) used imaging techniques to study segregation and bubbling behavior in flat (pseudo-2D) fluidized beds.
In this work a combined computational and experimental study of the flow in a 3D spout-fluid bed has been conducted for a wide range of operating conditions. A discrete particle model was used to predict the time-averaged particle velocities, whereas particle image velocimetry (PIV) was used to determine instantaneous and time-averaged particle velocity profiles from digital images.

### Table 1 Particle properties.

<table>
<thead>
<tr>
<th>$d_p$</th>
<th>4.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_p$</td>
<td>2526 kg/m$^3$</td>
</tr>
<tr>
<td>$u_{\text{inf}}$</td>
<td>1.77 m/s</td>
</tr>
<tr>
<td>$\theta_{n, p \leftrightarrow p}$</td>
<td>0.97 -</td>
</tr>
<tr>
<td>$\theta_{n, p \leftrightarrow w}$</td>
<td>0.97 -</td>
</tr>
<tr>
<td>$\mu_{p \leftrightarrow p}$</td>
<td>0.10 -</td>
</tr>
<tr>
<td>$\mu_{p \leftrightarrow w}$</td>
<td>0.10 -</td>
</tr>
<tr>
<td>$\beta_{0, p \leftrightarrow p}$</td>
<td>0.33 -</td>
</tr>
<tr>
<td>$\beta_{0, p \leftrightarrow w}$</td>
<td>0.33 -</td>
</tr>
</tbody>
</table>

### DISCRETE PARTICLE MODEL

The discrete particle model (DPM) used in this work is based on the hard-sphere model developed by Hoomans et al. (4). A short description of the model is given in this section. For details the interested reader is referred to Hoomans et al. (4).

In the DPM rigid particles are assumed to interact through binary, instantaneous collisions. Particle collision dynamics are described by collision laws, which account for energy dissipation due to non-ideal particle interaction by means of the empirical coefficients of normal and tangential restitution and the coefficient of friction. The particle collision characteristics play an important role in the overall bed behavior as was shown by Goldschmidt et al. (9). For this reason the collision properties, for both particle-particle and particle-wall collisions, of the particles used for the experimental validation were accurately determined by detailed impact experiments and supplied to the model. An overview of the particle properties is given in Table 1.

The motion of every individual particle in the system is calculated from the Newtonian equation of motion:

$$ m_j \frac{d \mathbf{v}_j}{dt} = -V_p \nabla p + \frac{V_j \beta}{1 - e_j} (\mathbf{u}_p - \mathbf{v}_p) + m_j \mathbf{g} \tag{1} $$

where $\beta$ represents the inter-phase momentum transfer coefficient, which is modeled as the minimum of the Ergun equation (10) and the Wen and Yu correlation (11):

$$ \beta = \min(\beta_{\text{Ergun}}, \beta_{\text{WenYu}}) \tag{2} $$

$$ \beta_{\text{Ergun}} = 150 \left(1 - e_j\right) \frac{\mu_j}{e_j} \left(\varphi_j d^2 + 1.75(1 - e_j) \frac{\rho_j}{\varphi_j} d^2 \right) \left| \mathbf{u}_p - \mathbf{v}_p \right| \tag{3} $$

$$ \beta_{\text{WenYu}} = \frac{3}{4} C_d (1 - e_j) \frac{\rho_j}{\varphi_j} d^2 \left| \mathbf{u}_p - \mathbf{v}_p \right| e^{-1.45} \tag{4} $$

The gas phase flow field is computed from the volume-averaged Navier-Stokes equations:

$$ \frac{\partial}{\partial t} (c_j \rho_j) + \nabla \cdot (c_j \rho_j \mathbf{u}_j) = 0 \tag{5} $$

$$ \frac{\partial}{\partial t} (c_j \rho_j \mathbf{u}_j) + \nabla \cdot (c_j \rho_j \mathbf{u}_j \mathbf{u}_j) = -e_j \nabla p - \nabla \cdot (e_j \mathbf{r}_j) - S_p + e_j \mathbf{g} \tag{6} $$
where two-way coupling is achieved via the sink term $S_p$, which is computed from:

$$S_p = \frac{1}{V_{ol}} \sum_{i=1}^{N} V_i \beta (u_i - v_{z_i}) D(r - r_{z_i})$$

(7)

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

**EXPERIMENTAL**

**Experimental Set-up**

A schematic representation of the 3D gas-fluidized bed used in this work, together with its dimensions is given in Figure 1. The side walls of the bed are made of aluminum. The front and back walls are made of polycarbonate. Pressurized air is fed to the bed through three separate sections. A 2 mm thick porous plate with an average pore size of 100 µm provides a homogeneous gas distribution over the two fluidization sections. A 0.5 mm metal gauze covers the spout section located on the border between the two fluidization sections. The flow rate of the gas in each section is controlled by control valves.

Digital images are recorded with a 262 Hz CCD camera (Dalsa CA-D6) equipped with a 12.5 mm lens. The aperture of the camera is set to f4 and the exposure time is fixed at 3.8 ms. The recorded images consist of 532 x 516 8-bit pixels. The image quality depends on the illumination of the bed, which should be strong and continuous. This is accomplished with the use of two 500 W halogen lamps positioned along each side of the camera, which are illuminating the bed under a small angle (< 45º), preventing reflections of the lamps in the bed.

**Particle Image Velocimetry**

Particle image velocimetry (PIV) is an optical, non-intrusive measurement technique that produces instantaneous 2D velocity data for a whole plane in a 3D flow field. It has already been used in the field of experimental fluid dynamics to study two-phase flows in dilute systems (Deen et al. (12)). In this work PIV has been applied to study the particle flow patterns in a rectangular 3D spout-fluid bed. A short description of the technique is given in this section. The interested reader is referred to the work of Westerweel (13) for further details.

Two subsequent images of the flow, separated by a short time delay, $\Delta t$, are divided into small interrogation areas. Cross-correlation analysis is used to determine the volume-averaged displacement, $s(x, t)$, of the particle images between the interrogation areas in the first and second image. The velocity within the interrogation area is then easily determined by dividing the measured displacement by image magnification, $M$, and $\Delta t$:
\[ v_p(x,t) = \frac{s_p(x,t)}{M \Delta t} \tag{8} \]

provided that \( \Delta t \) is sufficiently small. A median filter technique was used to eliminate spurious vectors, see Westerweel (14).

RESULTS AND DISCUSSION

The hydrodynamics in the region around the spout are of most interest. Unfortunately this region is not accessible to visual techniques. Therefore, it would be convenient to place a wall in the centre plane of the bed and study the particle behavior in the vicinity of the wall. To check whether the presence of such a wall influences the overall bed behavior two DPM simulations were carried out. In the first simulation a bed was modeled with the spout located in the center, whereas in the second simulation the bed was split where a rigid wall, with experimentally determined collision properties, was positioned in the plane of the spout.

Furthermore, a regime map is made for an initial bed height of 20 cm (aspect ratio ~ 1) and 30 cm (aspect ratio ~ 1.5) through visual observation of digital images.

Finally the magnitude of the particle velocity is determined using PIV and DPM. This parameter is used to compare the particle motion for different spout and background fluidization velocities at initial bed heights of 20 cm (44,829 particles) and 30 cm (67,244 particles).

Proximity Of The Wall

Figure 2 displays the simulated time-averaged particle velocity profiles for the cases with and without a proximate wall. The average difference between these particle velocity profiles is within 1%. The particle flow behavior observed with the spout at the wall is therefore representative for the particle flow behavior around a spout in the interior of the bed. Given the model result and the fact that the wall is treated in the same way by the model and the experiments only a slight wall effect can be expected in the experimental results.

Figure 2. Simulated particle velocity profiles around the spout with a spout in the centre (a) and at the wall (b). The reference vector represents a velocity of 1 m/s.
Regime Mapping

Three different regimes (Figure 3) were observed for these spout-fluid beds:

1. Non penetrating spout; only the particles in the spout area are moving, and the spout is not penetrating the entire bed.
2. Submerged spout; up to a certain height a stable spout is present, but on top of this spout the particles display regular fluidized bed behavior.
3. Penetrating spout; a stable spout penetrates the bed completely.

The observed regime largely depends on the initial bed height; if the initial bed height approximates the bed width a penetrating spout is the preferred regime, at higher aspect ratios the submerged spout is more usual. At higher initial bed heights spout penetration is more difficult since particles are more likely to block the spout channel.

![Figure 3](image)

**Figure 3** Experimental regime map of a spout-fluid bed as a function of the dimensionless spout \(u_{sp}\) and background fluidization velocity \(u_{bf}\) for two initial bed heights: 20 cm (a) and 30 cm (b).

Magnitude Of The Particle Velocity

PIV was applied for a wide range of operating conditions. Figure 4 shows an example result. Although the porosity and therefore the particle flux cannot be measured, the PIV technique is able to measure the flow structures in the front plane of the set-up.

For every operating condition the magnitude of the particle velocity was determined by averaging its norm over time (5 seconds), width and initial height of the bed:

\[
|v_{p}| = \frac{1}{N_t N_x N_y} \sum_{i=1}^{N_t} \sum_{j=1}^{N_x} \sum_{k=1}^{N_y} |v_{p_{i,j,k}}|
\]  

(9)

The dimensionless magnitude of the particle velocity in Figure 5 reveals that particle motion is more profound for a smaller initial bed height. Only at very high spout velocities the initial bed height does not really affect the particle motion. At these high spout velocities the background fluidization velocity is also irrelevant. However, at lower spout velocities high background fluidization velocities increase the particle motion.
Figure 4 Example of PIV results. a: original image; b: corresponding instantaneous particle velocity profile; c: corresponding time-averaged particle velocity profile. The reference vector represents a velocity of 1 m/s.

Figure 5 Measured dimensionless magnitude of the particle velocity as a function of the dimensionless spout and background fluidization velocity for an initial bed height of 20 cm (a) and 30 cm (b).

Table 2 Simulated cases.

<table>
<thead>
<tr>
<th>Bed Height</th>
<th>( U_{bf} / U_{mf} )</th>
<th>( U_{sf} / U_{mf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm</td>
<td>1.13</td>
<td>34.5</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.69</td>
<td>23.2</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.69</td>
<td>34.5</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.69</td>
<td>45.8</td>
</tr>
<tr>
<td>30 cm</td>
<td>1.13</td>
<td>34.5</td>
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<td>30 cm</td>
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<td>23.2</td>
</tr>
<tr>
<td>30 cm</td>
<td>1.69</td>
<td>34.5</td>
</tr>
</tbody>
</table>

Figure 6 Parity plot for the dimensionless magnitude of the particle velocity.
A few cases were also simulated with the use of DPM. The simulated cases are presented in Table 2. A parity plot comparing the experimental and numerical results is presented in Figure 6. Figure 6 shows that the magnitude of the particle velocities is generally larger in the numerical than in the experimental cases. This is probably due to the limited accuracy of PIV caused by the steep velocity gradient near the spout and overestimation of the drag force by DPM.

**CONCLUSIONS**

The proximity of the wall has a negligible effect on the time-averaged particle velocity profile. Therefore, the particle flow patterns observed with a spout near the wall are a reasonable representation for the flow around a spout without a proximate wall.

Increasing the initial bed height from 20 cm to 30 cm expands the operation window of the submerged spout.

At low spout velocities the dimensionless magnitude of the particle velocity is increased by a high background fluidization velocity and a low initial bed height. At high spout velocities the magnitude of the particle velocity is high regardless of the background fluidization velocity and the initial bed height.

The magnitude of the particle velocity is underestimated by PIV, which is probably caused by steep velocity gradients, and overestimated by the model, which is probably caused by the closure for fluid-particle drag. The PIV measurements can be improved by using a camera with a shorter shutter time and time between frames. Further study of the closure for fluid-particle drag will be subject of future work.

**ACKNOWLEDGEMENTS**

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**NOTATION**

- \( C_d \): drag coefficient, -
- \( d \): diameter, \( m \)
- \( D \): distribution function
- \( e_n \): coefficient of normal restitution, -
- \( g \): gravitational acceleration, \( m/s^2 \)
- \( m \): mass, \( kg \)
- \( M \): image magnification, -
- \( N \): number, -
- \( p \): pressure, \( Pa \)
- \( r \): position, \( m \)
- \( s \): volume-averaged displacement, \( m \)
- \( S_p \): particle drag sink term, \( Pa/m \)
- \( t \): time, \( s \)
- \( u \): velocity, \( m/s \)
- \( v \): velocity, \( m/s \)
- \( V \): volume, \( m^3 \)
- \( x \): coordinate vector, \( m \)

**Greek Symbols**

- \( \beta \): inter-phase momentum transfer coefficient, \( kg/(m^3 \cdot s) \)
- \( \beta_0 \): coefficient of tangential restitution, -
- \( \varepsilon \): volume fraction, -
- \( \varphi \): shape factor, -
- \( \mu \): shear viscosity, \( kg/(m \cdot s) \)
- \( \rho \): density, \( kg/m^3 \)
- \( \tau \): stress tensor, \( Pa \)
Subscripts

\(a\)  particle \(a\)  
\(bf\)  background fluidization  
\(exp\)  experimental  
\(f\)  fluid phase  
\(mf\)  minimum fluidization  
\(num\)  numerical  
\(p\)  particle  
\(sf\)  spout fluidization  
\(sup\)  superficial  
\(t\)  time  
\(w\)  wall  
\(x\)  in the horizontal direction  
\(z\)  in the vertical direction

REFERENCES