Influence of Bubble-Bubble Interactions on the Macroscale Circulation Patterns in a Bubbling Gas-Solid Fluidized Bed

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INFLUENCE OF BUBBLE-BUBBLE INTERACTIONS ON THE MACROSCALE CIRCULATION PATTERNS IN A BUBBLING GAS-SOLID FLUIDIZED BED

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ABSTRACT

The macro-scale circulation patterns in the emulsion phase of a gas-solid fluidized bed in the bubbling regime have been studied with a 3D Discrete Bubble Model. It has been shown that bubble-bubble interactions strongly influence the extent of the solids circulation and the bubble size distribution.

INTRODUCTION

In many industrial applications of bubbling gas-solid fluidized bed reactors, the reactor performance is determined by the macro-scale solids circulation patterns. For example, in gas-phase polymerization reactors, the overall heat removal rate and consequently the overall production capacity is dominated by the solids convection. Unfortunately, a profound understanding of the prevailing mechanisms is still lacking and especially quantitative information on the macro-scale circulation patterns in large fluidized bed reactors is still quite scarce. To investigate the complex hydrodynamic phenomena prevailing in freely bubbling gas-solid fluidized beds, a 3D Discrete Bubble Model (DBM) has been developed (Bokkers et al. (1)). In this Euler-Lagrange model, the bubbles that constitute the visible bubble flow (i.e. excess flow), are modeled as discrete spherical elements and are tracked individually during their rise through the emulsion phase using Newton’s second law, while accounting for bubble coalescence when two or more bubbles collide. The emulsion phase is considered as a continuum, described with continuity and Navier-Stokes equations. Although the DBM idealizes the bubbles as perfect spheres, its strong advantage is that it fully accounts for the two-way coupling, i.e. the emulsion phase velocity patterns will be influenced by the bubbles and their behavior via the drag exerted by the bubbles on the emulsion phase, and vice versa, the bubble dynamics (such as the bubble rise velocity and the extent of bubble coalescence) will be influenced by the emulsion phase velocity patterns. When the two-way coupling is disregarded, as for example in the agent-based model developed by Pannala et al. (2, 3), the emulsion phase circulation patterns cannot be computed. Another advantage of the DBM is that no a priori assumptions are required on the encounter frequency, an important factor determining the bubble coalescence rate. The DBM requires closures to model the behavior of individual bubbles (in the presence of many other bubbles) and the emulsion phase rheology, which can be derived from experiments...
or from simulations with more fundamental, discrete particle or continuum (Euler-Euler), models (often referred to as multi-scale or multi-level modeling). When fluidizing a Geldart B type powder, the actual gas velocity exceeds the bubble velocity and correspondingly, a large part of the gas flows from bubble to bubble through the fluidized bed. This results in an increased rise velocity of the bubbles compared to the rise velocity of a single isolated bubble due to an additional apparent force acting on the bubble. Pannala et al. (2, 3) used an empirical correlation for the magnitude of the modified bubble rise velocity, and the bubble velocity was simply directed toward its closest leading bubble. In the DBM, the bubble velocity results from a force balance where the momentum exchange with the emulsion phase is fully accounted for. The bubble velocity is subsequently adjusted to model the effects caused by the presence of the wake of a leading bubble, using the equations derived by Farrokhalaee (4) based on potential flow theory. Here, multiple pair-wise interactions between leading and tailing bubbles are considered, where it has been assumed that the potential streams around one bubble are not affected by the presence of other neighboring bubbles.

In this paper we investigate the influence of bubble-bubble interactions on the macro-scale emulsion phase circulation patterns. First, a short description of the DBM is given focusing on the equations describing the bubble-bubble interactions, followed by a discussion of simulation results elucidating their effects on the solids circulation patterns.

**DISCRETE BUBBLE MODEL**

The hydrodynamics of the emulsion phase are described with the continuity and volume-averaged Navier-Stokes equations (the symbols used are explained in the notation section):

\[
\frac{\partial (\varepsilon \rho_e)}{\partial t} + \nabla \cdot (\varepsilon \rho_e \mathbf{u}) = 0
\]

\[
\frac{\partial (\varepsilon \rho_e \mathbf{u})}{\partial t} + \nabla \cdot (\varepsilon \rho_e \mathbf{u} \mathbf{u}) = -\varepsilon \nabla P - \nabla \cdot \varepsilon \mathbf{t} + \varepsilon \rho_e \mathbf{g} + \Phi
\]

(1)

The momentum transfer \(\Phi\) between the bubble and emulsion phase (where the emulsion phase is assumed to behave like a Newtonian fluid) is described by:

\[
\Phi = -\frac{1}{V_{cell}} \sum_{v_{cell}} (\mathbf{F}_{d,j} + \mathbf{F}_{vm,j})
\]

(2)

The bubble trajectories are calculated by integrating Newton’s second law,

\[
m_b \frac{d\mathbf{u}}{dt} = \sum \mathbf{F} = \mathbf{F}_g + \mathbf{F}_p + \mathbf{F}_d + \mathbf{F}_{vm}
\]

(3)

where gravitational, pressure, drag and virtual mass (added mass) forces are accounted for. A more detailed description of the model and its numerical implementation can be found in Bokkers (5) and Bokkers et al. (1).
Two different types of bubble-bubble interactions can be distinguished, namely bubble coalescence and the bubble acceleration in the wake of a leading bubble. The description of bubble coalescence in the DBM has been simplified by assuming 100% coalescence efficiency for a bubble-bubble encounter, if the bubble diameter is smaller than a pre-described maximum bubble diameter. When a bubble collides with another bubble and would yield a bubble larger than the maximum bubble diameter after coalescence, the bubbles are assumed not to coalesce but collide elastically, approximating the dynamic equilibrium between bubble break-up and bubble coalescence. More detailed closures for bubble coalescence and bubble break-up could in principle be easily implemented in the DBM. Note, that due to bubble coalescence, the bubbles can grow to diameters much larger than the size of the Eulerian grid cells that is required to accurately resolve the emulsion phase velocity patterns. For details on the numerical implementation, the interested reader is referred to Bokkers (5) and Bokkers et al. (1). The influence of bubble coalescence on the macro-scale circulation patterns has been investigated in Bokkers et al. (1).

The second bubble-bubble interaction is the influence of the wake of a leading bubble on the velocity of the tailing bubble. According to the model proposed by Farrokhlaee (4), the velocity $v_j$ of a leading bubble ($j$) remains unaltered, while the velocity of the tailing bubble ($i$) $v_i$ is affected according to:

$$v'_i = v_i + \sum_{j=1}^{N_b} c_{i,j} v_j$$

with

$$c_{i,j,x} = \left( \frac{x_i - x_j}{\sqrt{\Delta x^2 + \Delta y^2}} \right) m_{i,j}; \quad c_{i,j,y} = \left( \frac{y_i - y_j}{\sqrt{\Delta x^2 + \Delta y^2}} \right) m_{i,j}; \quad c_{i,j,z} = l_{i,j}$$

where the relations for the coefficients $m_{i,j}$ and $l_{i,j}$ proposed by Johnsson (see Clift and Grace (6)) have been extended for three-dimensional bubble motion, given by:

$$n_{i,j} = 2 \left[ \left( z_i - z_j \right) + R_j \right]^2 + \left( \sqrt{\Delta x^2 + \Delta y^2} \right)^2$$

$$m_{i,j} = \frac{3R_j^3 \left( (z_i - z_j) + R_j \right) \left( \sqrt{\Delta x^2 + \Delta y^2} \right)}{n_{i,j}}$$

$$l_{i,j} = \frac{2 \left( (z_i - z_j) + R_j \right)^2 - \left( \sqrt{\Delta x^2 + \Delta y^2} \right)^2}{n_{i,j}} R_j^3$$

If the distances between a bubble and its neighbors become larger than about 5 times the radius of the leading bubbles, the bubble velocity approaches the bubble
velocity of an isolated bubble. The additional velocity term in equation (4) accounting for the bubble-wake interaction has not been included in the momentum transfer to the emulsion phase, since the bubble-wake interaction has been modeled as a sub-grid phenomenon.

RESULTS AND DISCUSSION

Influence of Bubble-Wake Interaction
The influence of the pair-wise bubble-wake interactions has been investigated by considering three cases: A) case without bubble-wake interactions; B) case with bubble-wake interactions, but only considering the binary interaction with its nearest leading neighbor; and C) case with bubble-wake interactions, accounting for binary interactions with all leading bubbles; in all these cases bubble coalescence was accounted for. The emulsion phase density and viscosity and also the gas phase density were set to values that are commonly encountered in polymerization fluidized bed reactors. Details on the simulation settings can be found in Table 1. Time-averaged velocity profiles were computed by averaging over 190 s, starting after 10 s to eliminate start-up effects.

Table 1: Simulation settings.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion density</td>
<td>400 kg.m⁻³</td>
<td>Width</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Emulsion viscosity</td>
<td>0.1 Pa.s</td>
<td>Depth</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Gas density</td>
<td>25 kg.m⁻³</td>
<td>Height</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Initial bubble diameter</td>
<td>0.08 m</td>
<td>Time step flow solver</td>
<td>5x10⁻³</td>
</tr>
<tr>
<td>Superficial gas velocity</td>
<td>0.25 m.s⁻¹</td>
<td>Time step bubbles</td>
<td>5x10⁻⁴</td>
</tr>
<tr>
<td>Number of nozzles</td>
<td>49</td>
<td>C_v</td>
<td>0.5</td>
</tr>
<tr>
<td>NX</td>
<td>20</td>
<td>C_D</td>
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</tr>
<tr>
<td>NY</td>
<td>20</td>
<td>Maximum bubble diameter</td>
<td>0.40 m</td>
</tr>
<tr>
<td>NZ</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Figure 1 and Figure 2 snapshots of the bubbles and the time-averaged emulsion phase velocity vector plots are given for the three simulated cases. This figure clearly shows the very large influence of the bubble-wake interactions on the average bubble size and the extent of solids circulation. When accounting for bubble-wake interactions, the bubble coalescence rate, especially at the bottom of the fluidized bed, is strongly enhanced, resulting in fewer, but larger and faster rising bubbles through the centre of the fluidized bed (which in its turn enhances the bubble encounter frequency). Also the time-averaged porosity plots (Figure 3) clearly show the increased tendency of the bubbles to move towards the centre of the fluidized bed. From Figure 4, showing the time-averaged lateral emulsion phase velocity profiles at about 2/3 of the bed height, the strongly increased solids circulation (strongly increased down flow near the walls) is evident when accounting for bubble-wake interactions. The figures also show that the effects of the bubble-wake interactions (increased bubble coalescence and solids circulation) are even more pronounced, when accounting for multiple bubble-wake interactions (case C) relative to single binary bubble-wake interactions (case B). In case a small bubble is the leading bubble (i.e. the nearest bubble above), while a much larger bubble is very near, only the interaction with the small bubble is considered, while the interaction with the larger bubble is completely ignored. Therefore, in case C, where the bubble-wake interactions with all leading bubbles is taken into account, the bubble coalescence is strongly enhanced, resulting in an increased averaged bubble
diameter and narrowed bubble size distribution. For case C, the average bubble rise velocity is about 1.3 times higher than the rise velocity of an isolated bubble, which corresponds quite reasonably to the findings of Krishna and van Baten (7). According to the correlations proposed by Krishna and van Baten, based on experimental results on an air-FCC catalyst (Geldart A) system, the bubble velocity should be increased by a factor of 1.8 compared to the undisturbed bubble rise velocity due to the bubble-bubble interactions.

Figure 1: Snapshots of the bubbles after 200 s for the three cases: A) case without bubble-wake interactions; B) case with single binary bubble-wake interactions; C) case with multiple binary bubble-wake interactions.

Figure 2: Time-averaged emulsion phase vector plots for the three cases: A) case without bubble-wake interactions; B) case with single binary bubble-wake interactions; C) case with multiple binary bubble-wake interactions.
Figure 3: Time-averaged porosity plots: A) case without bubble-wake interactions; B) case with single binary bubble-wake interactions; C) case with multiple binary bubble-wake interactions.

Figure 4: Time-averaged emulsion phase velocity profile at a height 2.1 m (right) above the distributor and a depth of 0.5 m.
CONCLUSIONS

The effects of bubble-wake interactions on the macroscopic behavior of freely bubbling fluidized beds have been investigated with the DBM. It has been found that bubble coalescence and macro-scale solids circulation is strongly enhanced when single or multiple binary bubble-wake interactions are accounted for. It has been demonstrated that bubble-wake interactions with all leading bubbles should be taken into consideration (and not just the nearest leading bubble), to avoid missing important bubble-wake interactions in case the nearest leading bubble is a small bubble, while a much larger bubble is very near. The increase in the bubble rise velocity due to bubble coalescence and bubble-wake interactions corresponds reasonably with literature findings. More detailed experimental work to validate the DBM is ongoing.

AKNOWLEDGMENT

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NOTATION

c  bubble-bubble interaction coefficient, -
F  Force, N
G  gravitational acceleration, m.s^{-2}
l  bubble-bubble interaction coefficient, -
m  bubble-bubble interaction coefficient, -
m  mass of a bubble, kg
NX grid cells in x-direction, -
NY grid cells in y-direction, -
NZ grid cells in z-direction, -
P  pressure, Pa
R  radius of bubble, m
t  time, s
u  emulsion phase velocity, m.s^{-1}
V  volume, m^3
v  bubble velocity, m.s^{-1}
x  x-position, m
y  y-position, m
z  z-position, m
\Delta  distance, -
\varepsilon  volume fraction, -
\rho  density, kg.m^{-3}
\tau  stress tensor, Pa
\Phi  source term, N.m^{-3}

Subscript
b  bubble
cell  gridcell
d  drag
e  emulsion
g  gravity
i  tailing bubble
j  leading bubble

p  pressure
tot  total
vm  virtual mass
x  x-direction
y  y-direction
z  z-direction
REFERENCES


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