The effect of riser scale on the hydrodynamics and particle residence-time distribution

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Keywords: scale up, fluidized bed, riser, hydrodynamics, height of riser, pressure drop, inventory, residence time distribution

Abstract—The effect of riser scale on the hydrodynamics of riser was numerically studied in this paper. A commercial software package, BARRACUDA, was employed to calculate the behaviour of the riser. First, experiments have been done to evaluate the performance of BARRACUDA. The comparison of the experiment and calculation showed that the calculations by BARRACUDA were reasonable. Secondly, numerical calculations of risers have been carried out for three scales of risers (riser heights, $H$, were 7.5 m, 15 m and 30 m, and other geometrical structures were ratio to the height). Particle circulation rate $G_s$, superficial gas velocity $U_0$, and bed material were specified in this study. It was found that the distribution of volume fraction of particle was different for different scale riser. The velocity field of particle and gas were also changed when the scale was changed. It was found that the inventory was proportional to the square root of riser height. The pressure profile along altitude direction was almost the same if the pressure was normalized by the weight of inventory. For low volume fractions of particle, it was found that the mean residence time was proportional to $H^{0.706}$.

INTRODUCTION

A gasifier of coal and biomass TIGAR® has been developed by IHI Company. This is a circulating fluidized bed with dual reactor, one is the riser combustor and the second is bubbling bed gasifier (Figure 1)[1]. The solid fuel is thrown into the bubbling bed gasifier, where part of fuel is gasified. The remaining char goes to riser and is combusted for the heat. The heated bed material goes to the gasifier to supply the heat for the endothermic gasification reaction. Previous studies showed scale effect on the hydrodynamic behaviour in the bubbling bed gasifier.[2] In this paper, we showed the effect of riser scale on the hydrodynamic behaviour of the riser using numerical calculation.

A large riser can be scaled down with similarity, if a specified bed material and specified superficial velocity are selected.[3] Qi[4] proposed an empirical similarity parameter for fully developed zone of riser. There are two kinds of approach to study hydrodynamics of riser by numerical calculation. One is Euler-Lagrange approach,[5] in which fluid is described by Euler approach and particles are described by Lagrange approach. Another is Euler-Euler approach,[6] which take particles as continuous phase and both of fluid and particles are described by the Euler approach. In this paper, we use BARRACUDA’s multiphase particle in a cell approach (Euler-Lagrange Hybrid)[7] to calculate the behaviour of hydrodynamics of riser.
Firstly, the results calculated by BARRACUDA were validated with experiments. It is found that the results of BARRACUDA were reasonable. Secondly, BARRACUDA was applied to simulate the risers of different scale, (heights are 7 m, 15 m and 30 m). After which, the hydrodynamics of riser with different scales were compared by terms of dimensionless values. The distribution of fraction of particle, velocities of fluid and particles were studied in addition to the pressure drop, inventory and residence time distribution of particle. The relationship between the riser scale and hydrodynamics of riser was explored.

VALIDATION OF NUMERICAL SIMULATION

Experiments

Experiments have been done to validate the numerical calculation. The experimental apparatuses are schematically shown in Figure 1. The height of riser was 15 m and inner diameter of riser was 0.36 m. The bed material is the silica sand. The diameter distribution of sand is shown in Figure 2. Three test cases were listed Table 1. The pressures at various elevations were measured by pressure sensors. The particle circulation rate was measured by a sensor in the cyclone diapleg. The sensor measures the particle circulation rate by measuring the impact of falling particles on a detection plate. The calibration has been made for the sensor. The results of pressure drop are shown in Figure 3.
Figure 2. Diameter distribution of bed material

Table 1. Conditions of experiments

<table>
<thead>
<tr>
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<th>unit</th>
<th>Case 1</th>
<th>Case 2</th>
<th>case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of riser $H_m$</td>
<td>m</td>
<td>1.5</td>
<td></td>
<td></td>
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<tr>
<td>Diameter of riser $D_m$</td>
<td>m</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed material</td>
<td></td>
<td>silica sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of bed material</td>
<td>kg/m³</td>
<td>2610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density of bed material</td>
<td>kg/m³</td>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate of primary air $Q_p$</td>
<td>m³/h</td>
<td>454.8</td>
<td>366.9</td>
<td>322.0</td>
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<tr>
<td>Particle circulation rate $G_s$</td>
<td>kg/(m²s)</td>
<td>26.6</td>
<td>18.8</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Numerical calculations

The same conditions were set to the numerical calculations with the experiments, i.e., the same geometries, the same velocities of air flow, the same particle circulation rates. The calculations were transient. When the mass flow rate at the exit was unchanged and equal to that of inlet, the riser numerical results were consider to be at steady state. Analysis was based on time-averaged numerical results over a period of 70 s. The calculating results of pressure drop are show in Figure 3.

Figure 3. Comparisons of experiments and calculations on the pressure drop
Comparisons of numerical simulation and experiment

The results of numerical calculation and experiments were compared to validate the BARRACUDA. In the Figure 3, the comparisons were made for the pressure drop of three cases of different particle circulation rate \( G_s \) (\( G_s = 26.6 \text{ kg/m}^2\text{s}, G_s = 18.8 \text{ kg/m}^2\text{s} \) and \( G_s = 10.1 \text{ kg/m}^2\text{s} \)). Here, pressure drop is defined as \( P - P_0 \), where \( P_0 \) is the pressure at exit of riser. It was found that the calculations of BARRACUDA were reasonable.

**THE EFFECT OF SCALE OF RISER ON THE HYDRODYNAMICS**

**Conditions of calculation**

In order to investigate the effect of riser scale, three cases were studied. The conditions of three cases were similar, because it was expected to find correlations with scale under simple condition. The calculation conditions are listed in Table 2. The geometries of riser were in proportion to the height of riser. The particle circulation rate \( G_s \) and superficial velocity \( U_0 \) were kept the same. The bed material for the calculations was based on the properties of the silica sand.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height of riser H</strong></td>
<td>m</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td><strong>Inner Diameter of riser D</strong></td>
<td>m</td>
<td>0.18</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>H/D</strong></td>
<td>-</td>
<td>41.7</td>
<td></td>
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<tr>
<td><strong>Bed material</strong></td>
<td>-</td>
<td>silica sand</td>
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</tr>
<tr>
<td><strong>Density of Bed material</strong></td>
<td>kg/m³</td>
<td>2610</td>
<td></td>
</tr>
<tr>
<td><strong>Velocity of primary air Uo</strong></td>
<td>m/s</td>
<td>5.44</td>
<td></td>
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<tr>
<td><strong>Particle circulation rate Gs</strong></td>
<td>kg/(m²s)</td>
<td>29.87</td>
<td></td>
</tr>
</tbody>
</table>

The following was the results deduced from calculation.

**Distribution of volume fraction of particle**
Figure 4. The volume fraction of particle of different scale

Figure 4(a) shows the distribution of $\varepsilon_P$ the volume fraction of particle, for whole risers. It was found that the $\varepsilon_P$ distributions were different, especially in the bottom of riser. In order to observe clearly, the bottom parts were enlarged in Figure 4(b). It was found that the particles concentrated on the inlet side for large scale $(H = 30 \, \text{m})$, but the particles concentrated on the opposite of the inlet for small scale $(H = 7.5 \, \text{m})$. If the scales of riser changed, the $\varepsilon_P$ distributions changed much. So it was not expected to find similarity even the riser was scaled up with similar geometry and similar flow conditions.

**Velocity of particles**

The velocities of particles are shown in Figure 5. The vertical component of particle velocity $V_z$ is shown in Figure 5(a). It was found that the upward velocity of particle in the core zone was larger for the larger riser. This was because that wall effect had little effect on the larger riser. Figure 5(b) shows the vector of particle velocity at bottom. The main flow patterns are marked with dash lines. It was found that the flow pattern was much different for different scale. The large riser was more affected by inlet, because the mass flow rate (kg/s) was large for large riser. We realized again that similarity did not exist for these risers.
Inventory and pressure profile

We failed to find the exact similarity for these risers, but we still intended to find some correlations between riser scale and values concentrated in industry. Using these correlations, we expected to make prediction approximately for industrious design. In this section, we tried to find how to estimate the pressure drop.

Industries pay a lot of concern on the pressure drop, when we design a riser and select the blower for it. It is important that we should predict the pressure drop when the scale of riser is changed. Is it correct that the pressure drop is caused by the weight of bed material? How to estimate the inventory weight of bed material in riser when the particle circulation rate is given?

The pressure drop is related to the inventory for low loading riser where the magnitude of the particle acceleration is negligible. The inventory height $H_0$ is defined as the heap height that all the bed material in the riser is heaped in the bottom with zero superficial velocity.

In the Figure 6 shows the calculation results of inventory height $H_0$. It was found that the $H_0/H$ was approximately expressed as equation (1). Of course, the coefficient 0.136 will be changed if the particle circulation rate $G_s$ or other conditions are changed, but the fact will not change much that inventory height $H_0$ is in proportion to the square root of height of riser $H$.

$$H_0 = 0.136 \sqrt{H}$$  \hspace{1cm} (1)
Figure 6. Inventory height $H_0$

Figure 7 shows the calculation results of pressure at each elevation for three riser configurations. $Z$ is elevation of riser. Figure 7(b) shows the dimensionless pressure drop profile did not change with the riser scale.

The three lines became one line approximately. It meant that the dimensionless pressure drop profile did not change with the riser scale.

b) The total dimensionless pressure drop was close to 1 in these cases, which meant that the pressure was mainly caused by the weight of bed material and the effect of acceleration of particle was negligible for these cases.

Residence time distribution (RTD)

When the heat and mass transfer and reaction of particles are considered, it is very important to predict the residence time of particle. Because Lagrange approach was used in this study, the entry time and exit time of particles could be counted, so the residence time distribution (RTD) of particles could be gotten. Figure 8 shows the results of RTD. It was found that the residence time is longer for higher riser and the peak of RTD curve is lower for higher riser.

$$F = \frac{P}{\rho g H_0}$$

(2)

Where $\rho_b$ is the bulk density of sand.
There are two ways to estimate the mean residence time in the riser\(^8\). One way is from pressure drop across the riser, \(\Delta P_{\text{riser}}\), by calculating the riser volume occupied by particles divided by the volumetric flow of particles in the riser.

\[
\overline{t_{\text{mfp}}} = \frac{A \chi H}{\Delta P_{\text{riser}} \left( \bar{\varepsilon}_p \bar{V}_p \right)}
\]

where \(A\) is area of cross section of the riser, \(\bar{\varepsilon}_p\) is the average volume fraction of particle.

Since the acceleration pressure drop was neglected in this study, the pressure drop across the riser can be written as

\[
\Delta P_{\text{riser}} = \bar{\varepsilon}_p \rho P g H
\]

where \(g\) is gravity acceleration.

Equation (3) can be rewritten as follows by substituting Equation (4) into it:

\[
\overline{t_{\text{mfp}}} = \frac{\bar{\varepsilon}_p \rho P g H}{\bar{V}_p}
\]

Another way to estimate the mean time is calculation of breakthrough time of particle \(t_{\text{thr}}\) by assumption of plug flow.

\[
t_{\text{thr}} = \frac{H}{\bar{U}_0 \left( \frac{1}{\bar{V}_t} - \frac{1}{\bar{U}_0} \right)}
\]

where \(\bar{U}_0\) is superficial velocity and \(\bar{V}_t\) is terminal velocity of particle.

Figure 8. Residence time distribution (RTD)
Figure 9. Mean residence time

(t_m = 2.82H^{0.706})

The mean residence time calculated by BARRACUDA simulation t_m is shown in Figure 9. As references, t_{m,p} and t_{th} are also shown in Figure 9. The correlations between the mean residence time and riser height were expressed as equations (7). It was found that the mean residence time was close to t_{m,p}, and t_m became closer to t_{m,p} for larger scale riser, which means that the t_{m,p} could be a good prediction of mean residence time for large scale riser. It was found that t_m was much larger than t_{th}, which meant that the particles in the riser did not break-through the riser straightly, but went upwards and downwards. The total path of particle was longer than the riser height. Referring Equation (7), mean residence time t_m was proportional to H^{0.706}, instead of proportional to H.

CONCLUSIONS

The effects of riser scale on hydrodynamics were investigated in this paper. The followings were concluded:

1. Numerical calculation of riser by software BARRACUDA was reasonable.
2. Even if the geometry of riser was similar and the super velocity and particle circulation rate were fixed, the distribution of volume fraction of particle, velocity field of particles and gas were different for different scale risers. The hydrodynamics was not of similarity under these conditions.
3. Even though, some correlations between the hydrodynamics and riser scale were found. The pressure drop profile was almost the same if it was normalized by the weight of inventory. The inventory height was proportional to the square root of riser height. The mean residence time was proportional to H^{0.706}. Equation (5) was a good estimation of residence time for large scale riser.

REFERENCES