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OPERATING PARAMETER EFFECTS ON THE SOLID CIRCULATION RATE IN A DUAL FLUIDIZED-BED GASIFICATION SYSTEM

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ABSTRACT

The solid circulation is crucial for sustaining biomass gasification within dual fluidized-bed systems, since the heat utilization between the gasifier and combustor is mainly implemented through the circulation of bed material. In this work, a three-dimensional model was established to simulate the hydrodynamics of a dual fluidized-bed gasification system. The purpose of this work is to determine effective ways to improve the solid circulation. In this CFD model, the gas phase was described by large eddy simulation (LES) while the particle phase was described by the multiphase particle-in-cell (MP-PIC) method. This hydrodynamic model successfully predicted the bubbling fluidized-bed gasifier and the pneumatic riser combustor for the dual fluidized-bed system. A grid resolution study was conducted to examine the model accuracy. A series of case studies were implemented to investigate the impact of operating parameters on the solid circulation rate to include: steam to the gasifier, the bed height of the gasifier, and the air supplies to the combustor on the solid circulation.

NOMENCLATURE

Greek Symbols

α	volume fraction
ρ	density
u	velocity
p	pressure
F	drag force
g	standard gravity
τ	stress tensor
f	particle size distribution function
P_s	model constant
D_p	drag coefficient

Subscripts

g	gas phase
p	particle phase
lam	laminar flows
t	turbulence

INTRODUCTION

A dual fluidized-bed gasification system mainly consists of a bubbling fluidized-bed gasifier and a pneumatic riser combustor. In the bubbling fluidized bed gasifier, steam is introduced to fluidize the bed material and react with biomass and other gases to generate producer gas. Meanwhile, some char generated from biomass pyrolysis is entrained by the bed material and transported to the combustor. Char burns with air in the combustor and most of char combustion heat is absorbed by the bed material. The heated bed material is then transported back to the bubbling fluidized-bed gasifier to provide the heat to the endothermic gasification reactions. As described above, the heat utilization in the dual fluidized-bed system is primarily implemented by the circulation of the bed material (Guan *et al.*, 2014). Therefore, the efficient solid circulation is crucial for sustaining the whole process in a dual fluidized-bed gasification system (Wang *et al.*, 2014). A thorough understanding of the effect of operational parameters on improving the solid circulation would be very useful for the optimization of biomass gasification in dual fluidized-bed systems.

In the present work, a three-dimensional (3D) CFD model using the multiphase particle-in-cell (MP-PIC) method (Snider *et al.*, 2011) was established to simulate the hydrodynamics of a dual fluidized-bed gasification system. A grid resolution study was implemented to examine the accuracy of the CFD model. A series of case studies were also conducted to examine how the solid circulation rate was influenced by the factors such as the steam supply to the gasifier, the 1st, 2nd, and 3rd air supplies to the combustor, and the bed material height. The ultimate goal of the present work is to explore the effective ways to improve the solid circulation in the dual fluidized-bed gasification system.

MODEL DESCRIPTION

In the model, the gas phase is simulated by Large Eddy Simulation (LES) and the particle phase is described by the particle acceleration equation.

Governing Equations

The continuity and momentum equations for the gas phase are shown as follows:

$$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g u_g\right) = \delta m_p \tag{1}$$

$$\frac{\partial(\alpha_g \rho_g u_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g u_g u_g\right) = -\nabla p + F + \alpha_g \rho_g g + \nabla \cdot \tau \tag{2}$$

$$\tau = \mu \left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i} \right) - \frac{2}{3} \mu \delta_{ij} \frac{\partial u_k}{\partial x_k} \tag{3}$$

$$\mu = \mu_{lam} + \mu_{eddy} \tag{4}$$

μ_{eddy} is calculated by the sub-grid scale (SGS) model (Smagorinsky, 1963) as shown below:

$$\mu_t = \frac{1}{2} C \rho_g \Delta^2 \sqrt{\left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i}\right)^2} \quad (5)$$

$$\Delta = \sqrt[3]{V} \quad (6)$$

The particle acceleration equation is applied to calculate the particle velocity as follows (O'Rourke and Snider, 2010):

$$\frac{du_p}{dt} = D_p\left(u_g - u_p\right) - \frac{\nabla p}{\rho_p} - \frac{\nabla \tau_p}{\rho_p \alpha_p} + g + \frac{\overline{u_p} - u_p}{2\tau_D} \quad (7)$$

The solid stress tensor, τ_D, is modeled by the following equation:

$$\tau_p = \frac{10 P_s {\alpha_p}^{\beta}}{max\left[(\alpha_{cp} - \alpha_p), \varepsilon(1 - \alpha_p)\right]} \quad (8)$$

The solid volume fraction, α_p, is calculated as follows:

$$\alpha_p = \iiint f \frac{m_p}{\rho_p} dm_p du_p dT_p \quad (9)$$

The interphase force between the gas and particle phase is given by:

$$F = \iiint f \left\{ m_p \left[D_p\left(u_g - u_p\right) - \frac{\nabla p}{\rho_p} \right] + u_p \frac{dm_p}{dt} \right\} dm_p du_p dT_p \quad (10)$$

The drag coefficient, D_p, is calculated by the Wen-Yu (Wen and Yu, 1966) model:

$$D_p = \frac{6}{8} C_d \frac{\rho_g |u_g - u_p|}{\rho_p d_p} \quad (11)$$

$$C_d = \begin{cases} \frac{24 {\alpha_g}^{-2.65}}{Re}, Re < 0.5 \\ \frac{24 {\alpha_g}^{-2.65}}{Re}\left(1 + 0.15 Re^{0.687}\right), \ 0.5 \le Re \le 1000 \\ 0.44 {\alpha_g}^{-2.65}, \ Re > 1000 \end{cases} \quad (12)$$

Simulation Setup

The CFD model was built in Barracuda Virtual Reactor ® using the MP-PIC method to simulate the hydrodynamics of a dual fluidized-bed gasification system following the dimensions of the pilot plant (1MWth, 6tons/day) at Woodland Biomass Research Center, Woodland, California.

The dimensions of the dual fluidized-bed system and the model setup are shown in Figure 1. As seen in the figure, steam is injected into the gasifier and loop-seal to fluidize the bed material while air is introduced to the combustor at three locations.

For the base case the computation grid has 393,800 cells. The model is set to run for 50 seconds of simulation time to reach the pseudo steady-state. The calculation time for the simulation of 50-second operation is about 12 hours. The size of time step is in the range of 10^{-3} to 10^{-5} seconds and is automatically controlled by the Courant-Friedrichs-Lewy (CFL) scheme (Courant *et al.*, 1967) to achieve a converged solution. The model is computed using the GPU-accelerated computing on a computer with an Intel® i7 CPU @3.50 GHz and a GeForce GTX TITAN graphics card.

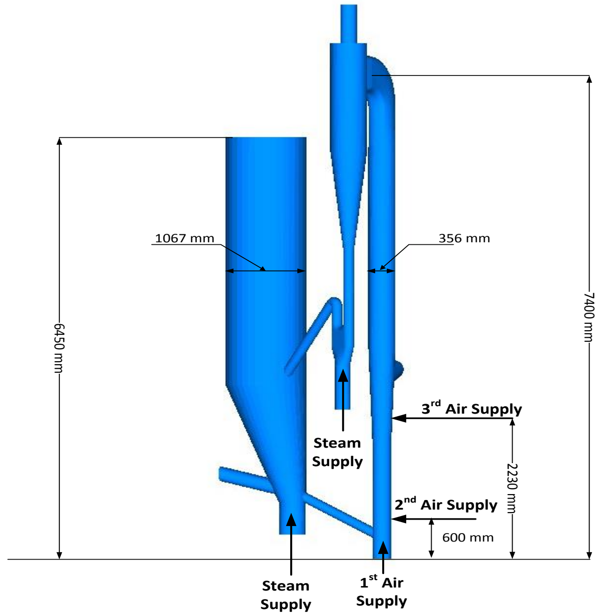

Figure 1: Dimensions of dual fluidized-bed system

Since the current model is primarily focused on the hydrodynamics of the gas and particle system, no reactions are included in the present work. In addition, for simplicity, the dual fluidized-bed system is considered isothermal. Accordingly, the system temperature is set as 850°C.

Description	Value
Bed material density (kg/m^3)	3560
Bed material diameter (μm)	488
Initial solid packing	0.56
Initial bed height (m)	2.50
Outlet pressure (atm, abs.)	1.0
Steam supply to the gasifier (kg/s)	0.0382
The 1st air supply to the combustor (kg/s)	0.0174
The 2nd air supply to the combustor (kg/s)	0.149
The 3rd air supply to the combustor (kg/s)	0.0638

Table 1: Base case settings

RESULTS

The particle circulation in the dual fluidized-bed system is shown in Figure 2. As seen in the figure, the particles are circulated between the gasifier, combustor, cyclone separator, and loop-seal.

As mentioned previously, this study is to investigate the solid circulation in the dual fluidized-bed gasification system. The solid mass flowrate at the height of 5.5 meters in the combustor was calculated from the simulation for this purpose.

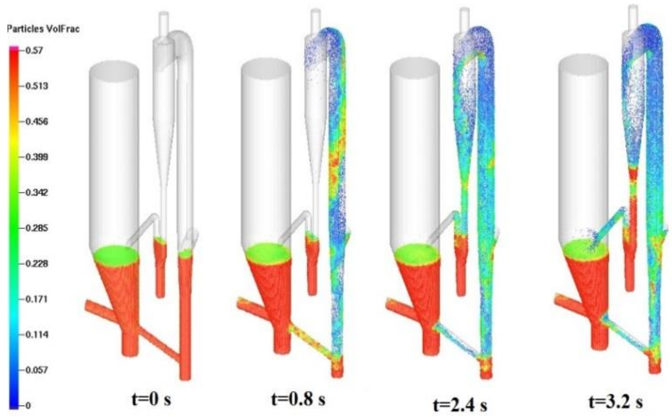

Figure 2: Particle volume fraction in the dual fluidized-bed gasification system as a function of time at star-up.

Grid Resolution Study

A grid resolution study was implemented to ensure that the solid mass flow rate calculated from the simulation was independent of the grid resolution. Four grids with 243,423-cell, 286,065-cell, 393,800-cell, and 489,834-cell were applied for the study. As observed in Figure 3, the solid mass flow rate dramatically decreases from the 243,423-cell to 286,065-cell grids. After that, the decrease of the solid mass flow rate becomes less significant. The solid mass flow rates from the three cases using the 286,065-cell, 393,800-cell and 489,834-cell grids are similar and the difference between the cases is less than 5 %. The 489,834-cell grid might be a good option for the current study; however, considering the fact that the current hydrodynamic model is mainly developed for our future modeling of biomass gasification in the dual fluidized-bed, the computational cost for the gasification model using such a grid (489,834 cells) can be expensive. Therefore, instead of the 489,834-cell grid, the 393,800-cell grid was chosen for the current study, due to the reduced computational cost and the acceptable accuracy.

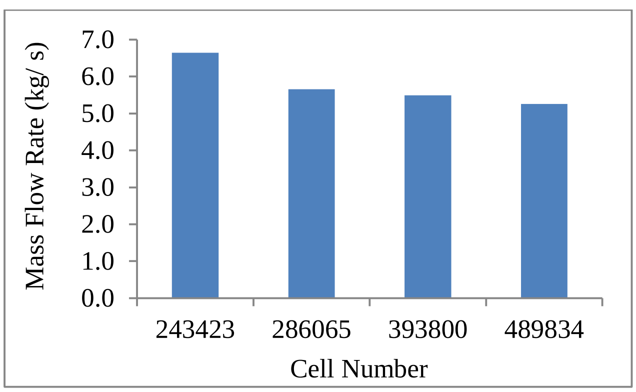

Figure 3: Comparison of the solid mass flow rates for the grid resolution study

In this work, the impact of three operating parameters on the solid circulation rate of the gasification systems was investigated to include: the steam supply to the gasifier, the bed height of the gasifier, and the air supplies (1st, 2nd, and 3rd).

Effect of the Steam Supply to the Gasifier

Cases 2 and 3 were built to investigate the impact of the steam supply to the gasifier. In cases 2 and 3, the steam to the combustor was increased to 0.0573 and 0.0764 kg/s, respectively. Figure 4 shows the comparison of solid circulation rates from cases 1-3. It can be seen that increasing the steam to the gasifier can improve the solid circulation in the dual fluidized-bed system.

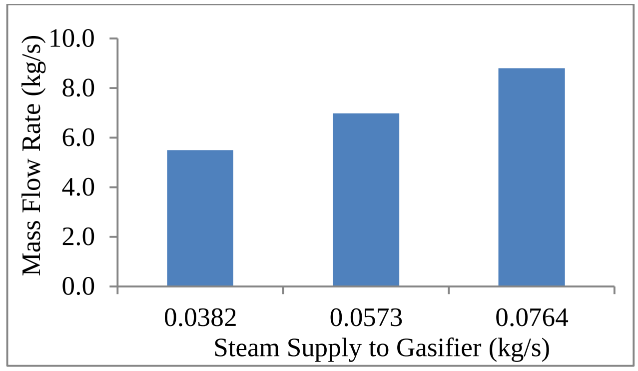

Figure 4: Comparison of the solid mass flow rates for the study of steam to the gasifier

However, as demonstrated in Figure 5, more steam escapes to the combustor while the steam increases in the gasifier. In the actual operation of the dual fluidized-bed gasification system, a large amount of leaking steam can cool down the combustor and consequently destabilize the whole process. Therefore, increasing the steam supply to the combustor may not be a preferable way to improve the solid circulation.

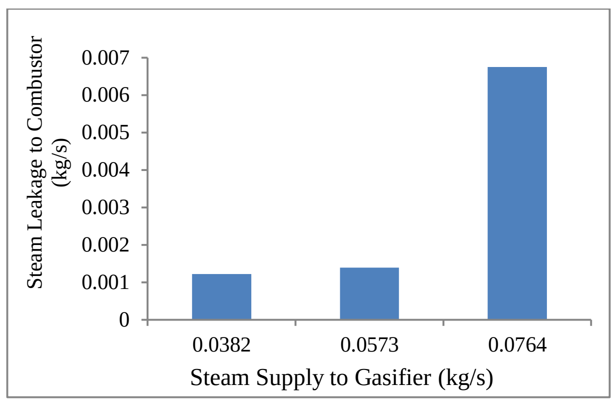

Figure 5: Steam leakage to the combustor

Effect of the Bed Height of the Gasifier

The impact of the bed height on the solid circulation was investigated. In case 4 the initial 2.5 meters of the bed height in the gasifier was decreased to 2.0 meters. As shown in Figure 6, the solid mass flow rate dramatically changes with the bed height in the gasifier, indicating that higher or lower bed height can lead to the faster or slower solid circulation rate, respectively.

Effect of the Air Supplies to the Combustor

The effect of the air supplies to the combustor was also examined. Cases 5 and 6 were established to study the impact of the 1st and 2nd air supplies while cases 7 and 8 were built to investigate the effect of the 3rd air supply.

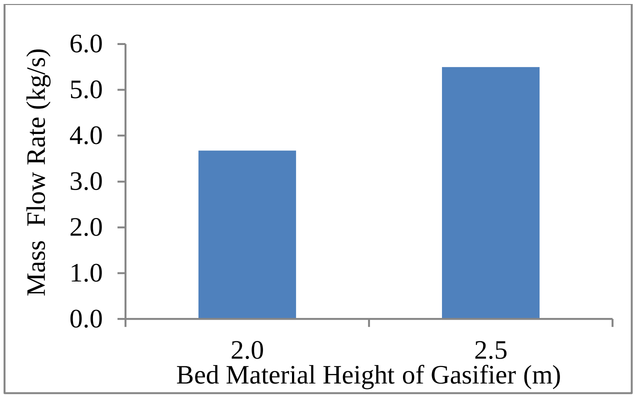

Figure 6: Comparison of the solid mass flow rates for the study of the bed height

The 1st and 2nd air supplies were totally increased to 0.1995 kg/s (the 1st air supply: 0.0209 kg/s; the 2nd air supply: 0.1786 kg/s) in case 5 and 0.2792 kg/s (the 1st air supply: 0.0292 kg/s; the 2nd air supply: 0.250 kg/s) in case 6. Figure 7 demonstrates the comparison of the solid mass flow rate between cases 1, 5, and 6. It can be seen that the solid mass flowrate dramatically increases with the 1st and 2nd air supplies.

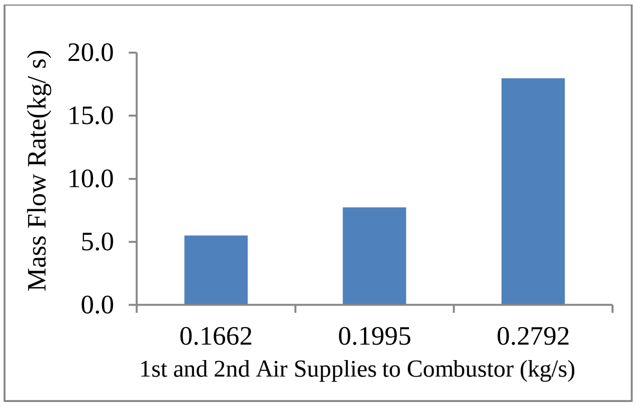

Figure 7: Comparison of the solid mass flow rates for the study of the 1st and 2nd air supplies to the combustor

Meanwhile, in cases 7 and 8 the amounts of the 1st and 2nd air supplies were unchanged from the base case (case 1). Instead, the increments applied in cases 5 and 6 to the 1st and 2nd air supplies were added to the 3rd air supply in cases 7 and 8, respectively. Thus the 3rd air supplies in cases 7 and 8 become 0.097 kg/s and 0.1768 kg/s.

As displayed in Figure 8, the solid mass flow rates from cases 1, 7 and 8 are compared to each other. It can be seen that the solid circulation can be improved by increasing the 3rd air supply.

However, Figure 9 shows that when the same amounts of air increments are applied to the 1st and 2nd air supplies, and 3rd air supply, respectively, the increases of solid mass flow rates by the 1st and 2nd air supply are much higher than those by the 3rd air supply, indicating that the impact of 1st and 2nd air supplies on the solid circulation is much stronger than that of the 3rd air supply. Therefore, it can be concluded that increasing the 1st and 2nd air supplies to the combustor is the most effective way to improve the solid circulation in the dual fluidized-bed gasification system.

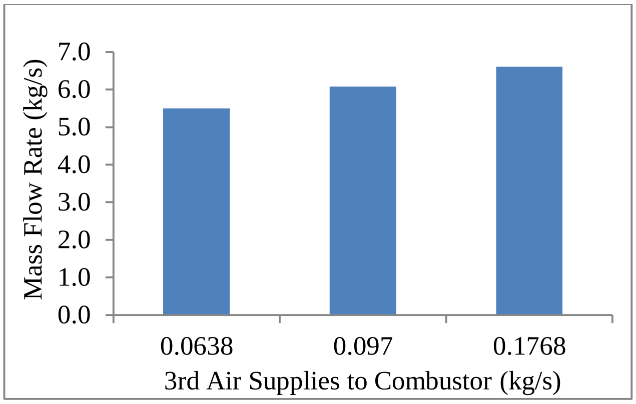

Figure 8: Comparison of the solid mass flow rates for the study of the 3rd air supply to the combustor

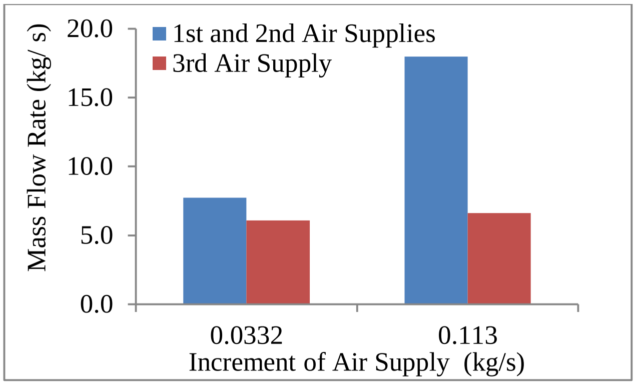

Figure 9: Comparison of the solid mass flow rates for the study of 1st, 2nd and 3rd air supplies

CONCLUSION

In this work, a 3D hydrodynamic model was established to investigate the solid circulation in the dual fluidized-bed gasification system. The grid independence study was conducted to determine the appropriate grid resolution for the simulation. The effects of the factors such as the steam to the gasifier, the bed height of the gasifier, and the air supplies to combustor on the solid circulation were investigated.

Among these factors, the air supplies to the combustor demonstrated the strongest impact on the solid circulation. Additionally, the 1st and 2nd air supplies showed more significant impact than that of 3rd air supply. The height of bed material in the gasifier can also facilitate the solid circulation. In practice, increasing the bed material can increase the residence time of biomass in the gasifier to improve biomass conversion. Finally, as shown in this work, the steam supply to the gasifier can help the solid circulation rate; however, increasing steam is not a preferable way to improve the solid circulation, because it may lead to more steam escaping to the combustor to destabilize the whole gasification process.

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