Spring 5-2-2011

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HIGH-RESOLUTION SIMULATIONS OF GAS-SOLIDS JET PENETRATION INTO A HIGH DENSITY RISER FLOW

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ABSTRACT

High-resolution simulations of a gas-solids jet in a 0.3 m diameter and 15.9 m tall circulating fluidized bed (CFB) riser were conducted with the open source software-MFIX. In the numerical simulations, both gas and solids injected through a 1.6 cm diameter radial-directed tube 4.3 m above the bottom distributor were tracked as tracers, which enable the analysis of the characteristics of a two-phase jet. Two jetting gas velocities of 16.6 and 37.2 m/s were studied with the other operating conditions fixed. Reasonable flow hydrodynamics with respect to overall pressure drop, voidage, and solids velocity distributions were predicted. Due to the different dynamic responses of gas and particles to the crossflow, a significant separation of gas and solids within the jet region was predicted for both cases. In addition, the jet characteristics based on tracer concentration and tracer mass fraction profiles at different downstream levels are discussed. Overall, the numerical predictions compare favorably to the experimental measurements made at NETL.

INTRODUCTION

Gasification is a process converting carbonaceous materials, such as coal, biomass, and waste to syngas, a mixture of CO and H_2 and other gases, which can be used for the production of liquid fuels and chemicals or for power generation. Recently, gasifier designs based on circulating fluidized bed-type technology have drawn attention from both academia and industries (1), as circulating fluidized beds (CFBs) possess a number of unique features that make them more attractive than other systems in energy industries.

In gasification processes, the fuel particles with high energy density are usually injected into the gasifier as gas-solids jets. It is thus of great practical importance to understand the manner in which fuel particles disperse and mix with the bed material upon entering the system. Only limited studies on particle-laden jets in fluidized beds can be found in the open literature. Glicksman et al. (2) studied the mixing characteristics of horizontally injected particles in a one-quarter scale model of a pressurized bubbling fluidized bed combustor using a thermal tracer technique. Shadle et al. (3) studied the jet penetration of a gas-solids jet into a circulating fluidized bed riser by tracking phosphorescent particles illuminated immediately prior to injection. Wang et al. (4) reported the dynamic phenomena of horizontal gas and gas/solid mixture jets in a bubbling fluidized bed with an electrical capacitance volume tomography (ECVT) technique. Recently, a challenge problem was generated by NETL in collaboration with PSRI, in which experimental measurements of a gas-solids jet into a riser flow will be reported for validation of mathematical models (5). However, the aforementioned knowledge is far from enough to fully understand the flow behavior of particle-laden jets in a gas-solids flow system.

In this study, CFD was employed to study the gas-solids jet penetration into a high density circulating fluidized bed riser flow (3). A gas-solids jet in a pilot-scale riser was simulated with the open-source Multiphase Flow with Interphase eXchanges (MFIX) code at https://mfix.netl.doe.gov. The general hydrodynamics of riser flow predicted by the numerical simulations were first compared against the available experimental data. Jet behaviors were studied through the numerical simulations and separation of jetting gas and particles was observed. Parameters characterizing the solids penetration were evaluated at different levels above the jet injection and comparison with the experimental data was reported.

NUMERICAL MODELING

In this study, the MFIX code was used to carry out the numerical simulations. MFIX is a multi-fluid, Eulerian-Eulerian code, with each phase treated as an interpenetrating continuum. Mass and momentum conservation equations are solved for the gas and solid (particulate) phases, with appropriate closure relations (6). The governing equations for the solid phase are closed by the kinetic granular theory Constitutive relations derived based on the kinetic theory for the solid phase stress tensor are used. More information on the code as well as detailed documentation can be found at the MFIX website.

The pilot-scale cold flow circulating fluidized system available at NETL with 0.305 m diameter 15.9 tall is schematically shown in Figure 1. To simplify the simulation, only the riser section indicated in Figure 1 was simulated. The solids enter the riser from a side port 0.23 m in diameter and 0.27 m above the gas distributor. Solids exit the riser through a 0.20 m side port about 1.2 m below the top of the riser. A gas-solids jet was introduced through a small tube of 1.59 cm diameter at 4.3 m above the bottom distributor in the same azmuthal direction as the bulk solids feed to the riser. Gas and particles injected through the jet were treated as species in the gas and solid phases, respectively. Transport equations were solved for the mass fraction of each species. The high density polyethylene (HDPE) beads with an averaged diameter of 750 microns and a density of 863 kg/m^3 used in the experiments were simulated. The material properties and operating conditions based on the experiments conducted at NETL were used in the simulation, as summarized in Table 1. Two cases with low and high jet gas velocities of 16.6 and 37.2 m/s, respectively, were simulated.

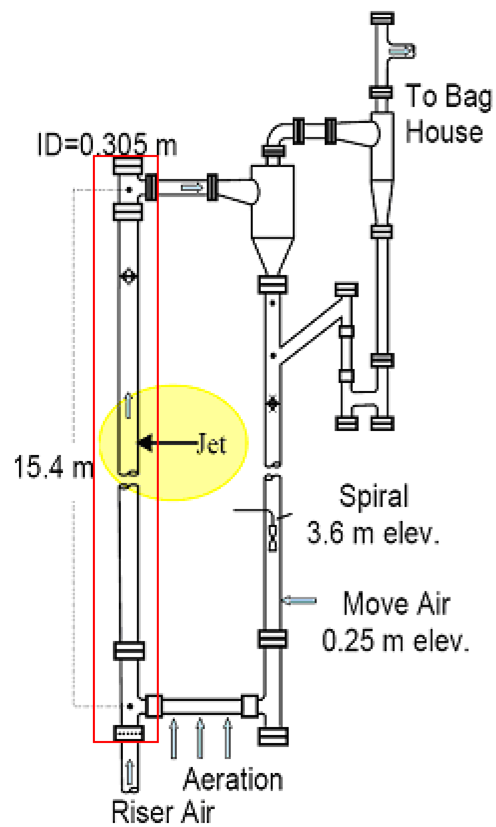

Figure 1. Schematic of NETL CFB with the gas-solids jet injection (Adapted from (3))

Table 1. Material properties and operating conditions.

Property	Value
Particle diameter (µm)	750
Solid density (kg/m^3)	863
Interparticle restitution coefficient -	0.8
Particle-wall restitution coefficient	0.7
Packed bed voidage -	0.346
Angle of internal friction (deg)_	30
Superficial gas velocity (m/s)	7.62
Solids circulation rate (kg/s)	11.34
Gas viscosity (Pa.s)	1.8E-5
Jet inlet diameter (cm)	1.59
Voidage at jet inlet (-)	0.97
Jet gas velocity (m/s)	16.6, 37.2
Jet solids velocity (m/s)	6.93, 15.5
Temperature (K)	298
Pressure at top exit (Pa)	101325
Pressure at bottom (Pa)	118000
Gas molecular weight (kg/kmol)	28.8

High-resolution 3D numerical simulations of the riser flow were performed. A cuboid domain was discretized with a uniform grid size of 7.5 mm except at the jet injection level where the grid was slightly refined. The current gird is believed to be fine enough according to 10-particle-diameter criterion for grid independence in gas-solids simulations (7, 8). To represent the cylindrical geometry of the riser, some cells were blocked so that a stair-step surface was used to represent the column boundary. A total of 3 million computational cells was used. To better resolve the transient flow behavior of riser flow and gas-solid jet, a second order Superbee discretization scheme was employed for all equations (9). The computation was conducted on a high performance computing (HPC) system with 192 Xeon quad-core CPU running at 2.83 GHz. More information on the numerical modeling was provided in (10).

The following boundary conditions were applied in the numerical simulations. At the bottom distributor, a uniform gas inflow was specified, with no particles entering the domain. While for the side solids inlet and the gas-solids jet inlet, constant inflow conditions were assumed. At the top abrupt exit, a constant pressure was used and particles were free to leave the system. At the wall, a no-slip boundary condition was adopted for both gas and solid phases for simplicity and it is believed to be appropriate for the stair-step boundary surface used in the current study.

RESULTS AND DISCUSSION

Approximately, a real time simulation of 25 seconds was completed for each case. Numerical results in the last 5 seconds were recorded at a frequency of 20 Hz for post-processing with the first 20 seconds simulation excluded to avoid the startup effect of such a large system. The flow was confirmed to be fully developed after 15 seconds by monitoring the overall pressure drop across the entire riser. The numerical results were visualized by an open-source, multi-platform data analysis and visualization application–Paraview.

General hydrodynamics of the riser flow were compared to the experimental measurements first to validate the numerical models. Figure 2 presents the comparison between numerical simulation and experimental data on the axial pressure gradient. The experimental data shown in the figure are average of 12 duplicated runs and the error bar indicated the standard deviation. Reasonable agreement between simulation and experiment was obtained though the pressure gradient was slightly over-predicted presumably because of the no-slip wall boundary condition and possibly due to the compressive nature of the superbee discretization scheme used in the simulations (7). From the axial pressure gradient profile, it can be observed that the apparent solids holdup first decreases with increasing height at the lower region (0-5 m) and remains fairly constant in the middle region (5-10 m) and then, increases with height at the upper region of the riser (10-15 m). This profile is consistent with the experimental measurements and the effects of solids side inlet and abrupt exit were reasonably predicted (11). In addition, comparison with the experimental data on the solid velocity was made and reasonable agreement between simulation and experiment was obtained (10).

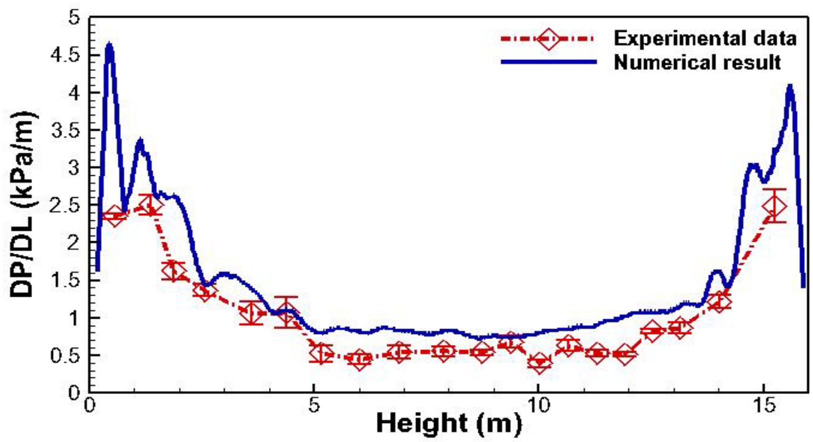

Figure 2. Axial profiles of pressure gradient for the case with low jet velocity (error bar indicates the standard deviation of 12 experimental data sets of duplicated runs).

In the numerical simulations, gas and particles injected through the jet were tracked as species in the gas and solid phases, respectively. Transport equations were solved for the mass fraction of each species. The tracer concentrations, $\varepsilon_{g,tr}$ and $\varepsilon_{p,tr}$, thus can be determined through

$$\varepsilon_{g,tr} = \varepsilon_g X_{g,tr} \tag{1}$$

$$\varepsilon_{p,tr} = \varepsilon_p X_{p,tr} \tag{2}$$

where ε_g and ε_p are volume fractions of gas and solid phases, and $X_{g,tr}$ and $X_{p,tr}$ are species mass fraction of tracer gas and particles, respectively.

Distributions of gas and solid tracers were calculated and the behavior of gas-solids jet was studied by analyzing the transient results. Snapshots of voidage, tracer concentrations close to the jet injection in the lengthwise cross-section are shown in Figure 3. Clusters phenomenon, prominent near the wall, can be clearly observed from the voidage distribution in Figure 3(a). The gas-solids jet penetrates into the riser flow and bends upward because of the crossflow. It was also found that the jet was very unstable due to the strong interactions between the jet and the non-homogeneous riser flow. The clusters in the dense riser flow played the most important role in the interaction. Occasionally, the large falling clusters close to the wall dragged the jet downward.

It is seen from the distributions of solid and gas tracer concentration in Figure 3 that the jetting particles with high momentum travel deeper into the crossflow and separate from the jetting gas flow. This is caused by the different dynamic responses of gas and particles to the crossflow. The separation of gas and solids from the jet flow was also observed when the mean tracer concentrations were examined for both low and high jet velocities. Hence, the penetration depths, which determine the length of the effective interaction zone of the jet and crossflow, are different for the jetting gas and particles. The gas-solids separation suggests that both jetting gas and particles need to be tracked in order to study the gas-solids jet behavior. In some gasifier processes, the air-coal mixture is expected to undergo combustion reactions to supplement the heat needed by endothermic gasification reactions and provide rapid release of volatile matter. Under such circumstances, the separation of coal particles from the air jet not only limits the desired combustion but also leads to a cool region of oxygen-rich gas. The cool oxygen-rich gas flow propagates upwards and might cause un-wanted combustion of the devolitization and gasification product gases. Hence, the separation of gas and solids should be taken into account in design and operation when they are injected together into the reactor crossflow (9).

The depth of tracer particles penetrating into the crossflow increases slightly at higher levels. It is difficult to define the jet boundary due to fast mixing of the jetting gas and solids with the riser flow. Here, the analyses were focused on the penetration of tracer particles into the cross-flow. The penetration depth of tracer gas can be studied in a similar way.

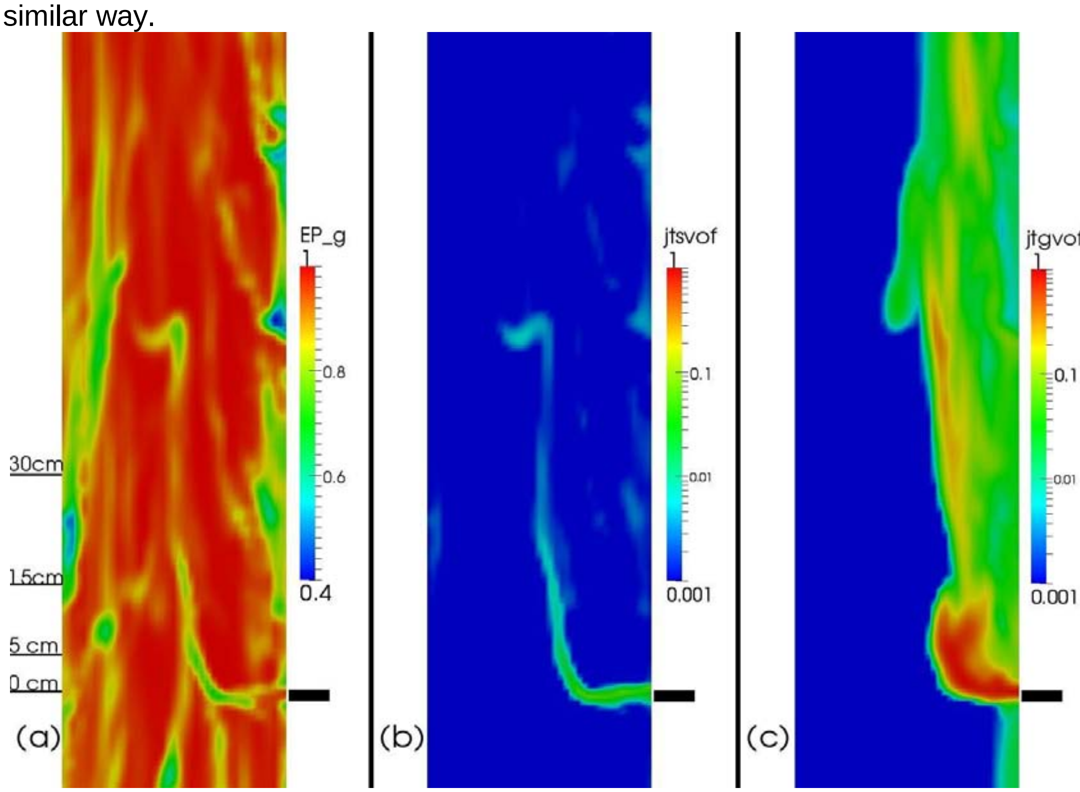

Figure 3. Snapshots of (a) voidage, (b) volume fraction of tracer particles, and (c) volume fraction of tracer gas in the length-wise cross-section for the case with a jet velocity of 37.2 m/s.

In the experiments, the solids particles were exposed to UV light before injection into the riser in form of gas-solids jet (3). The phosphorescent glow from the tracer solids was then detected by photo sensors at different radial positions along the jet direction within the riser 15 and 30 cm above the injection level. Relative concentration distribution of the jetting particles could be obtained through voltage signals of the photo detector probe. Each set of average radial voltage signals was normalized by dividing by the maximum voltage measured for that radial profile. Normalized concentration profiles of the phosphorescent particles ranged between 0 and 1 were then obtained by data fitting. The distance from the jet wall to the maximum peak and the width of the profile at half of the peak value were reported to characterize the jet-behavior as schematically shown in Figure 4.

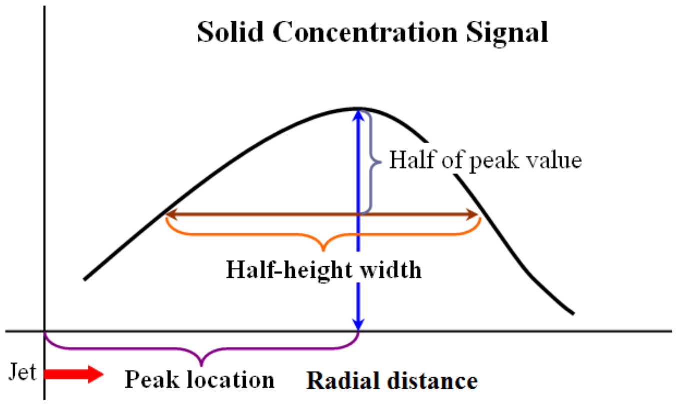

Figure 4. Schematic of experimental measurements on jet characteristics.

It was expected that the voltage signal from the photo sensor is proportional to the local concentration of the tracer particles. However, the light intensity of the glowing particles detected by the probe was also affected by the presence of opaque bulk particles which might block the light from glowing tracer particles. Hence, the concentration profile measured through this technique was an unknown combination of the absolute tracer concentration and the relative concentration of tracer in the solid phase. Without knowing the exact contributions of both concentrations to the final signal, it is necessary to compare the jet behaviors determined through the absolute and relative concentration profiles, which is straightforward in the numerical simulations. For this purpose, profiles of the tracer particles concentration, $\varepsilon_{p,tr}$, and the tracer particles mass fraction in the solid phase, $X_{p,tr}$, at different downstream levels are plotted against the radial distance from the wall in Figure 5 for the case with a jet velocity of 37 m/s. Regardless of the magnitude, similar shape of profiles are predicted with a single peak corresponding to the jet position. However, it is seen that the locations of peak are slightly different. From both profiles, the radial location of peak and half-height width can be determined as summarized in Tables 2 and 3 for cases with low and high jet velocities. The experimental measurements are listed for comparison. The radial peak locations based on the absolute tracer concentration profiles are higher than those based on the relative concentration profiles. While the half-height widths based on the absolute concentration are lower than those based on the relative concentration. The difference can be very significant, especially for the high jet velocity. From a practical point of view, the absolute tracer concentration should be used as it characterizes the distribution of the jetting particles in the riser. On the other hand, it is important to make sure the numerical simulations and the experimental measurements are equivalent in order to interpret experimental finding and validate numerical models. In Figure 5, obvious differences between these profiles can be observed near the wall. The high tracer concentration is resulted from the strong solids backmixing and the dense solids flow close to the wall.

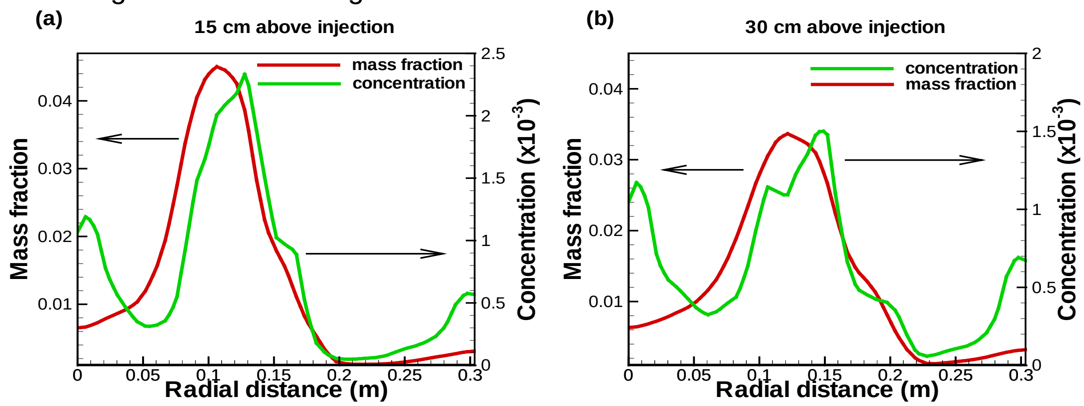

Figure 5. Radial profiles of tracer particle mass fraction in the solid phase and tracer particle concentration at (a)15 and (b) 30 cm above jet inlet for high jet velocity.

Table 2. Jet characteristics at 15 and 30 cm above injection for low jet velocity.

15 cm above injection	**peak location (cm)**	**half-height width (cm)**
Relative concentration	6	5.4
Absolute concentration	6.2	5.2
Experiment (3)	8	13
30 cm above injection	**peak location (cm)**	**half-height width (cm)**
Relative concentration	6.4	6.7
Absolute concentration	6.4	4.8
Experiment (3)	8	15

Table 3. Jet characteristics at 15 and 30 cm above injection for high jet velocity.

15 cm above injection	**peak location (cm)**	**half-height width (cm)**
Relative concentration	10.8	7
Absolute concentration	12.8	6.4
Experiment (3)	13	18
30 cm above injection	**peak location (cm)**	**half-height width (cm)**
Relative concentration	12.3	9.1
Absolute concentration	15	7.2
Experiment (3)	14	17

Generally, the current numerical predictions compare favorably to the experimental measurements. However, the half-height width is greatly under-predicted in the simulations. The main reason might be the unstable gas-solids flow through the feed nozzle. In the experiments, the solids concentration and gas and solids velocities subject to strong fluctuations, which tend to increase the lateral fluctuations of jet movement, leading to a wide concentration profile with low peak value. This was not considered in the current numerical simulations where a stable jet inflow with constant velocity and solids concentration was assumed.

CONCLUSIONS

High resolution numerical simulations were conducted to study the gas-solids jet penetration into a high density riser flow. General flow hydrodynamics of a pilot-scale riser were predicted and behaviors of a gas-solids jet were studied. The gas-solids jet was found to be very unstable because of the strong interactions between the jet and the non-homogeneous riser flow. There existed a significant separation of the jetting gas and solids when they entered the crossflow. Since experimental measurements of the absolute tracer concentration was difficult to obtain, the jet characteristics based on the radial profiles of absolute tracer concentration and relative concentration to the solids phase were compared against the experimental data. Generally, reasonable agreement between numerical simulations and experimental measurements on the gas-solid jet characteristics were obtained.

ACKNOWLEDGMENTS

The authors would like to thank Drs. Lawrence Shadle, Christopher Ludlow, and James Spenik for providing detailed experimental data and useful discussions. This research was supported in part by an appointment to the National Energy Technology Laboratory Research Participation Program, sponsored by the U.S. Department of Energy and administrated by the Oak Ridge Institute for Science and Education.

NOTATION

$X_{g,tr}$ mass fraction of tracer gas

$X_{p,tr}$ mass fraction of tracer particles

ε_g volume fraction of gas

ε_p volume fraction of particles

$\varepsilon_{g,tr}$ concentration of tracer gas

$\varepsilon_{p,tr}$ concentration of tracer particles

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