Jet Hydrodynamics Around Fluidized Bed Spargers

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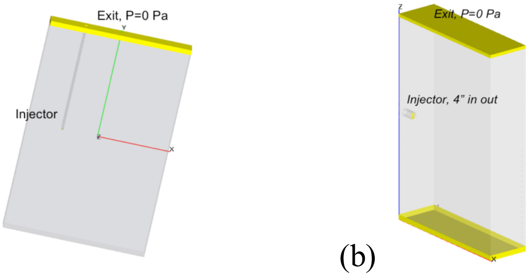
I. Introduction

Many of the problems encountered in fluidized bed operations can be linked to injectors, spargers and grid plates. Gas maldistribution and high attrition related to injectors spargers and grid plates issues often result in frequent and premature shutdown of the unit and replacement of some, if not all, of the components. Fortunately, these failures can be managed. Understanding the jet hydrodynamics from spargers and grid plates is critical in designing and operating a reliable sparger. Jet penetration, jet/initial bubble evolution, and bubble hydrodynamics all contribute to the performance and reliability of fluidized beds. Using criteria such as pressure drop, orifice pitch and jet penetration length are a good start, but computational fluid dynamics (CFD) models could be an effective way to understand, improve and optimize injectors, spargers and grid plates, especially for the implement of less common applications such as those in high-temperature, highly-corrosive fluidized beds and risers and other systems with very limited experimental data.

II. Methodology

Two systems were examined with cold-flow units and a computational fluid dynamics (CFD) software. The first system was a vertical diffuser immersed in a packed bed of polyethylene powder with a particle density of 720 kg/m3 and dp50 of 500 μm. Air at 98 m/sec (320 ft/sec) was used to generate a downward jet following by bubbling up to the surface. The second system consisted of a horizontal jet in a bubbling fluidized bed filled with a FFC powder with a particle density of 1200 kg/m3 and dp50 of 67 μm. The superficial gas velocity of the bed was 0.1 m/sec (0.3 ft/sec) with the jet velocity being 30.5 m/sec (100 ft/sec) or 61 m/sec (200 ft/sec).



(a) (b)

Figure 1: Grid domains used in the Arena-Flow modeling for (a) downward jet in a packed bed and (b) horizontal jet in a bubbling fluidized bed.

Simulations were performed using the Arena-Flow™ 5.0 Computational Particle Fluid Dynamics (CPFD) software package. Arena-Flow is a CFD base code employing the multiphase particle-in-cell (MP-PIC) numerical method, which has been formulated for

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dense particle flows[1,2]. The carrier gas is treated as a continuum in an Eulerian flow field. The particle phase is treated as discrete entities with particle friction and stresses defined as three dimensional sub-grid forces. Gas and particle phases are two-way coupled through the drag term. In order to track a large number of particles (millions to billions), particles of specific sizes are treated as parcels or "clouds." Parcels of N particles are assumed to have a drag force of one similar particle times N. Arena-Flow models the entire particle size distribution, not just a single representative particle size.

Figure 1a shows the grid domain used to model the first system of a downward jet in a packed bed. A (7.8 mm) 0.31" ID x 0.3 m (12") diffuser extended into a "2D" cold-flow unit that was 0.61 m (24") x 0.20 m (7.75") x 25.4 mm (1") in size. Arena-Flow gridding matched the dimensions of the unit used in the cold-flow studies. The second system was done by Dr. Ted Knowlton at Particulate Solids Research Inc. (PSRI™) and consisted of a 50 mm (2") ID nozzle that extended 100 mm (4") into a 1.6 m (5') diameter semicircular column. In this case, Arena-Flow gridding did not match the experimental unit. Instead, a 50 mm (2") ID nozzle that extended 100 mm (4") into a 0.61 m (2') deep x 1.1m (40") wide box was used, as shown in 1b. This allowed a representative domain to be modeled while minimizing computational requirements.

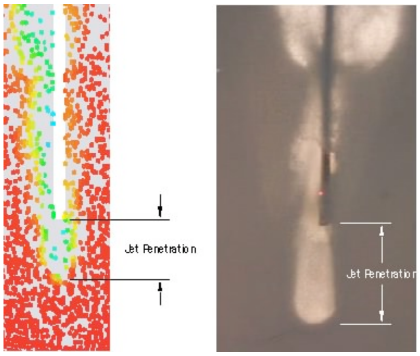

Figure 2: Method for determining the jet penetration length for a downward jet in a packed bed with experimental results (right) and Arena-Flow simulations with particles/clouds artificially enlarged (post processing) to better visualize gas-solid interface simulation (left).

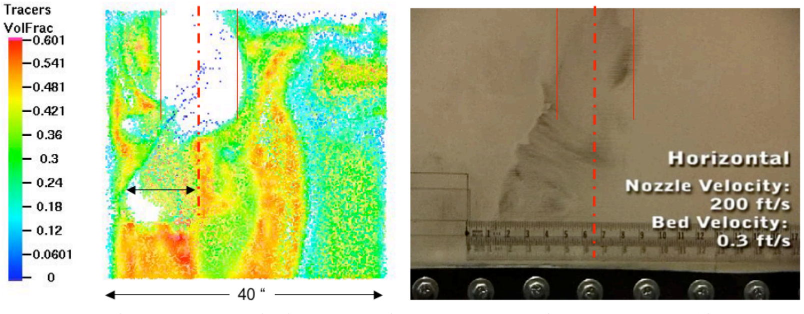

Figure 3: Method for determining the jet penetration length (from the wall) of a horizontal jet in a bubbling fluidized bed in PSRI's cold-flow fluidized bed (right) and in an Arena-Flow (left).

Jet penetration lengths were measured by comparing the highest region of contrast in the recorded video from the experimental studies and the resulting movie from Arena-Flow simulations. For the downward jet in a packed bed, the jet penetration was the distance from the tip of the diffuser to the maximum penetration of the downward flowing gas into the bed, as shown in Figure 2. For the horizontal jet into a bubbling fluidized bed, jet penetration was measured as the distance from the tip of the nozzle to the centerline of the upward flow of the jet or bubble, after horizontal penetration into the bed, as shown in Figure 3. This centerline measurement was taken in similar location above the horizontal nozzle for both experimental data and simulation results.

III. Results and Discussion

Figure 4 shows a sequence of frames captured from the video used in the cold-flow study of a downward air jet in an initially packed bed of polyethylene powder. The jet appeared to dominate towards one side, but then the upward flowing bubbles migrated back to the diffuser and periodically shifted from one side to the other side of the diffuser. Bubble formation occurred relatively close the diffuser tip after the gas turned around and flowed upwards. Most of the bubbles near the diffuser were elongated in shape.

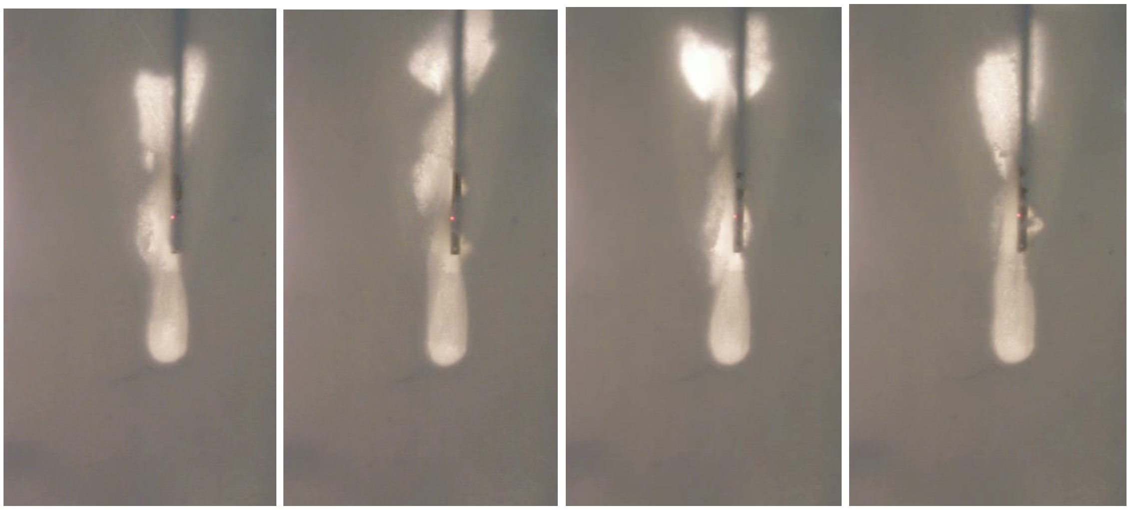

Figure 4: Frame capture from video taken of cold-flow studies of a downward jet into a packed bed.

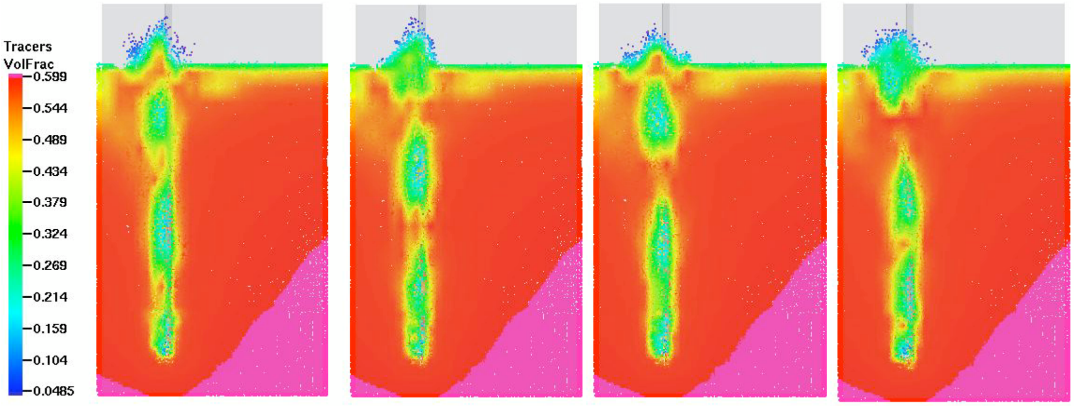

Figure 5: Front view of Arena-Flow simulations for a downward jet into a packed bed.

Arena-Flow simulations of the same system in Figure 4 showed similar qualitative results. Figure 5 shows this with bubble formation occurring near the diffuser tip. Similarly, Arena-Flow showed the same elongated bubbles as that observed in the cold-flow study.

Figure 6 shows the same simulation results as that shown in Figure 5 except the viewing domain has been sliced to the thickness of the diffuser. This provides a slice of the bubble behavior around the diffuser. As shown in Figure 6, the formations of bubbles near the diffuser tip are more apparent. As with the experimental results, Arena-Flow also predicted the bubbles migrating back to the diffuser, but the bubbles appear to dominate one side over the other. The periodic motion of the bubbles for one side to another side of the diffuser was less noticeable in the simulations. It is possible that this periodic motion observed in the cold-flow studies is the result of an external effect (pressure instabilities or small-scale fluctuation) that is not being captured in the Arena-Flow model.

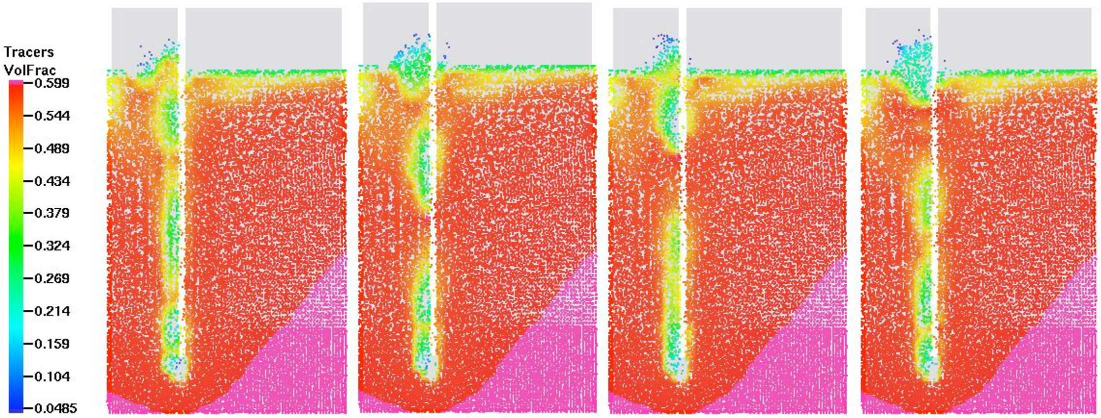

Figure 6: Sliced view of Arena-Flow simulations for a downward jet into a packed bed. View was reduced to a thickness of the diameter of the nozzle (0.31")

Jet penetration lengths were measured from the results of the cold-flow study and from the Arena-Flow simulations. Figure 7 shows the time dependent results for both studies. Arena-Flow results show the transient behavior of a jet from time zero to 1 second when steady state is reached. Upon starting up, the jet penetration reached a maximum at 0.4 seconds then decrease to a steady state value. Experimental data of this transient effect were not collected, and Figure 7 shows only the steady state behavior of the jet penetration. Arena-Flow simulations appear to somewhat under predict the jet penetration length as ~59 mm (2.3"). From the experimental data, the jet penetrations were observed to be ~72 mm (2.8").

Figure 8 shows the video capture of a horizontal jet in an 1.6 meters (5') ID semicircular cold-flow fluidized bed for a jet velocity of ~30.5 m/sec (100 ft/sec). Similar experiments were also done with jet velocities of 61 m/sec (200 ft/sec). The bed was fluidized using air at a superficial gas velocity of 0.061 m/sec (0.3 ft/sec), which suggest this is in the bubbling fluidized bed regime for this FCC powder.

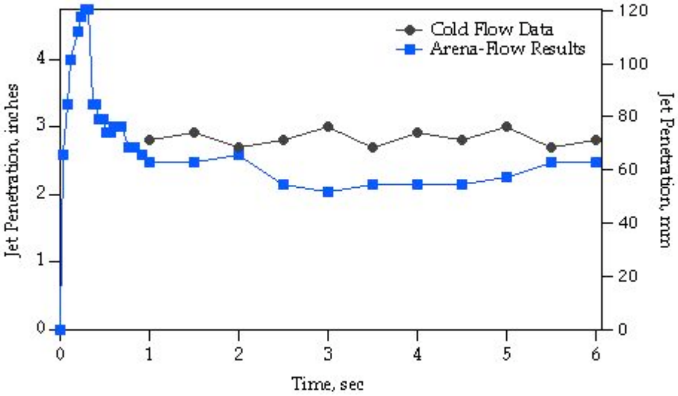

Figure 7: The jet penetration length for a downward jet in a packed bed via cold-flow studies and Arena-Flow simulations.

Figure 9 shows the solids volume fraction of this system using Arena-Flow. Simulation results of the jet and bubble hydrodynamics appear to be in good agreement with the experimental results indicated in Figure 8. For 31.5 m/sec jet velocity, the gas protruded only 2.5 inches into the bubbling fluidized bed. After which, the jet directed to an upward flow breaking up into large bubbles. This upward jet periodically moved from close to the wall to 4.5 inches from the wall.

Figure 8: Frame capture from video taken of cold-flow studies of a horizontal jet into a bubbling fluidized bed.

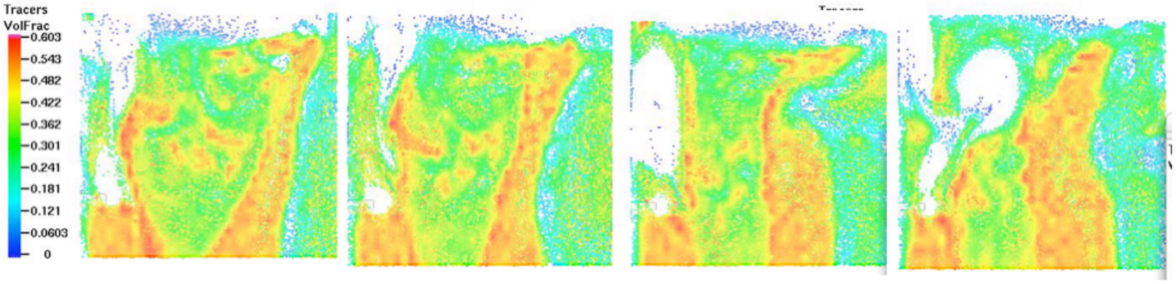

Figure 9: Front view of Arena-Flow simulations for a horizontal jet into a bubbling fluidized bed.

Sampling the video and simulations at 0.2 seconds intervals, the centerline of the jet or bubble plume moving upward in the fluidized bed was collected. The distance from the nozzle tip to this centerline was assumed to be the jet penetration length. Figure 10 shows the average value of this jet penetration measurement with a jet velocity of 30.5 m/sec (100 ft/sec). As shown in this t-test, Arena-Flow was in good agreement with experimental data within a 95% confidence level.

Similarly, these measurements were also taken for the same system with a jet velocity of 61 m/sec (200 ft/sec). As shown in Figure 10, jet penetration into the fluidized bed reached 7.5 inches for this jet velocity. The same bubble hydrodynamics were observed, and Arena-Flow simulations were in good agreement with these results as well.

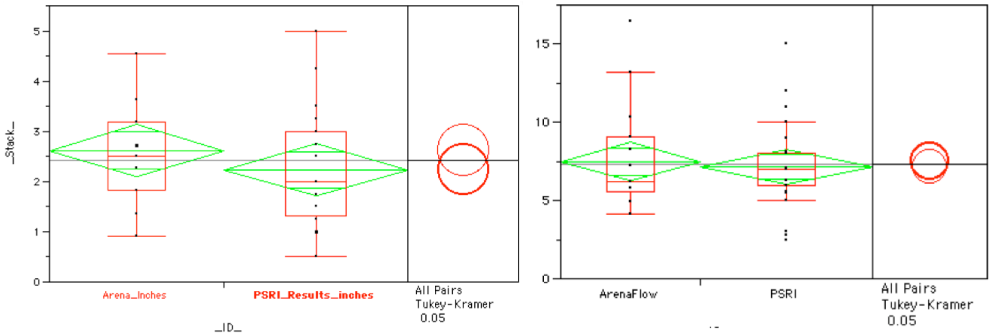

Figure 10: Tukey-Kramer Student T-Test of jet penetration lengths obtained from experiments at PSRI and corresponding Arena-Flow simulation for a horizontal injector with jet velocities of 30.5 m/sec (100 ft/sec) and 61 m/sec (200 ft/sec).

IV. Conclusions

One of the issues in predicting jet penetration lengths is that available correlations[3,4,5] tend to show significant differences with each other. These correlations are not incorrect; it is that they are system and operating conditions specific. Particle and gas properties, temperature, pressure, vessel design and scale and interpretation of the jet boundary all play a roll in predicting jet penetrations. For example, many of these correlations work well in fluidized beds with horizontal or upward jets; but, few correlations work well for downward jets and even fewer can work for other fluidized systems beyond bubbling fluidization regime, such as turbulent fluidized beds and risers.

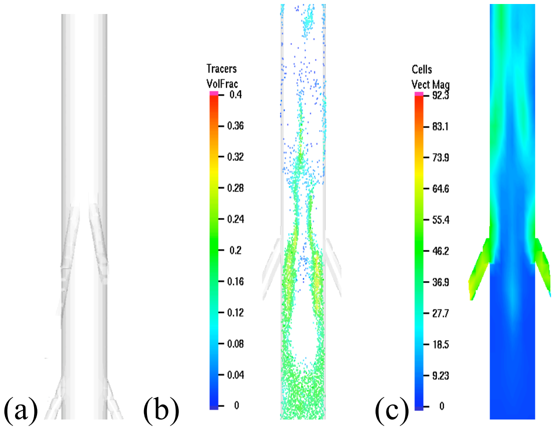

Figure 11: (a) Grid domain, (b) solids volume fraction and (c) gas velocity magnitude for an Arena-Flow simulation of an 8" ID riser with four injectors (two below, two above) at a gas injection velocity of 46 m/sec (150 ft/sec).

The results shown here suggest that Arena-Flow models may be able to bridge the gap between your system and the actual jet penetration. For downward jet into a packed bed, Arena-Flow was within 15% of the measured jet penetration data. In a fluidized bed with a horizontal jet, Arena-Flow results where in excellent agreement (within 95% confidence level) with the experimental data. Thus, such a model may be useful in predicting the jet penetration in a more complex system such as a riser reactor, as shown in Figure 11.

V. Acknowledgement

The authors would like to thank Dr. Ted Knowlton of PSRI for sharing their bubbling fluidized bed data.

VI. References

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