Numerical Simulations of PSRI Cold-Flow FCC Stripper Experiment with Subway Grating Baffles

Session 751: Industrial Application of Computational and Numerical Approaches to Particle Flow II

Sam Clark, CPFD Software, LLC, sam.clark@cpfd-software.com
Peter Blaser, CPFD Software, LLC, peter.blaser@cpfd-software.com
Allan Issangya, Particulate Solid Research, Inc. (PSRI), allan.issangya@psri.org
Ray Cocco, Particulate Solid Research, Inc. (PSRI), ray.cocco@psri.org

Table of Contents

Abstract

Industrial fluid catalytic cracking units (FCCUs) employ fluidized bed strippers to recover hydrocarbons carried away with the downward flowing spent catalyst particles from the reactor, preventing these valuable hydrocarbons from entering and combusting in the regenerator. In the stripper, steam (the "gas") flows upward, counter-current to the catalyst flow direction, stripping the hydrocarbon vapors from and around the catalyst particles before the particles enter the regenerator. Effective stripper operation requires intimate contact between the gas and particle phases. Commercial stripper designs often use internals, such as subway grating trays, chevrons (also called sheds), disk-and-donut baffles, structured packing or other configurations, to promote better mixing of gas and particles and improve stripping efficiency.

Numerical simulations were performed of a PSRI cold-flow FCC stripper experiment with subway grating baffles. The experimental unit had an internal diameter of 3 feet (0.9 m), and a height of 25 feet (7.62 m). The subway grating baffles within the vessel were intended to promote more uniform fluidization of particles by preventing the formation of large bubbles as well as preventing gas bypassing in the stripper. The commercial computational fluid dynamics (CFD) software Barracuda Virtual Reactor®, which implements the multi-phase particle-in-cell (MP-PIC) numerical method, was used to perform the simulations. Simulation results were compared with experimental measurements of apparent bed density over a wide range of solids flux conditions, at superficial gas velocities typical of industrial FCC stripper operation. The simulation results were in good agreement with the experimental bed density measurements, and matched the experimentally observed trends of bed density variation as a function of gas superficial velocity and catalyst mass flux through the stripper vessel.

Experiment

Full details of the experimental work for the system under consideration are given in PSRI's *Research Report No. 88* (Issangya et al, 2014), which is available to PSRI member companies. Permission has been granted by PSRI to provide sufficient details from *Research Report No. 88* to describe the geometry and operating conditions of the experiment used for creating the numerical models which are the main subject of the current work.

Physical Geometry

A schematic diagram of the experimental system is shown in Figure 1. The system consisted of a 3 ft (0.9 m) diameter fluidized bed with subway grating baffles; a 14 in (0.36 m) diameter standpipe below the fluidized bed; two 12 in (0.3 m) diameter risers lifting particles back to the top of the system; and a two-stage cyclone system to direct particles from the risers into the fluidized bed. The circulation rate of solids through the system was controlled by two pneumatically operated slide valves positioned before each riser. The gas distributor for the 3 ft (0.9 m) diameter stripper column was a 24 in diameter ring sparger, photographs of which are shown in Figure 2.

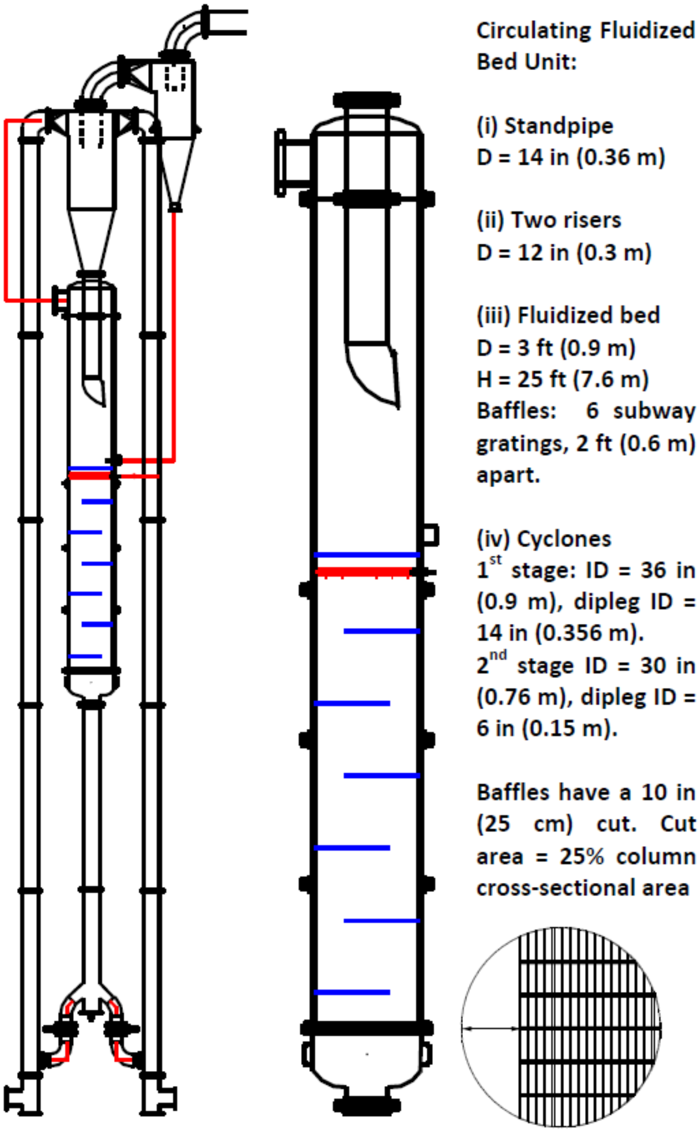

Figure 1. 3-ft (0.9-m)-diameter fluidized bed stripping unit equipped with subway grating internals.

Figure 1: Experimental unit geometry. Reproduction of Figure 1 from Research Report No. 88 (Issangya et al, 2014)

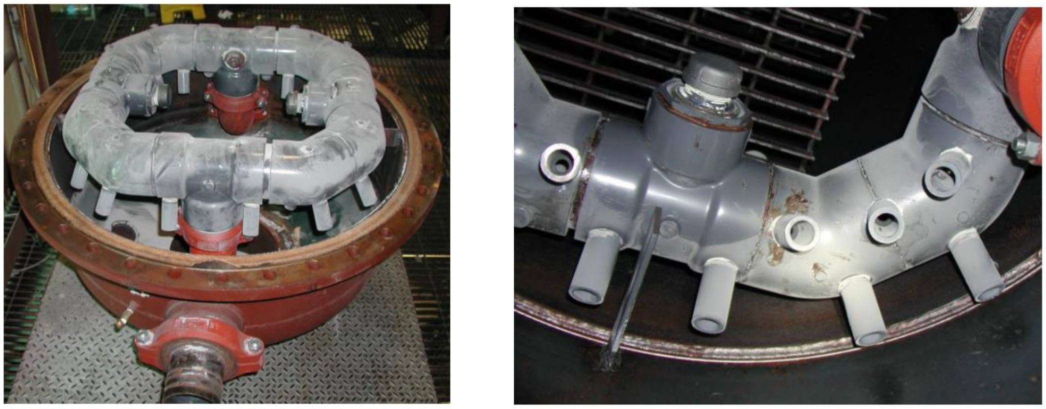

Figure 6a. Photograph of the ring sparger gas distributor installed in the 3-ft (0.9-m)-diameter stripper.

Figure 6b. Photograph of gas distributor as seen from below

Figure 2: Photographs of fluidized bed ring sparger. Reproduction of Figure 6 from Research Report No. 88 (Issangya et al, 2014)

Particle Properties

FCC catalyst particles with an 8% fines content were used in the experimental system. The particle size distribution (PSD) of these particles is shown in Figure 3, and particle properties are listed in Table 1.

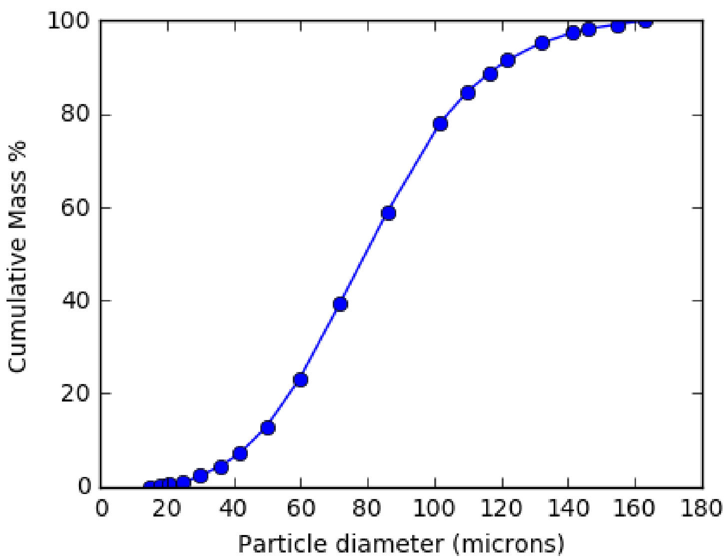

Figure 3: Particle size distribution of FCC catalyst particles

Table 1: FCC catalyst particle properties

Parameter	Value
Particle density	93 lb/ft^3 (1490 kg/m^3)
Sauter mean diameter	70.3 microns

Experimental Results

Over a range of operating conditions, PSRI reported the apparent bed density in the baffled section of the fluidized bed stripper, based on the pressure drop over an 11.2 ft (3.42 m) section of the bed. The apparent bed density is calculated from the measured pressure drop by the formula:

$$\rho_{bed} = \frac{\Delta P}{gL} \tag{1}$$

where:

ρ_{bed} is the apparent bed density (kg/m^3)

ΔP is the measured pressure drop (Pa)

g is the gravitational constant, 9.81 m/s^2

L is the length over which the pressure drop is measured (m)

The experimental results are shown in Figure 4. The apparent bed density was found to be inversely proportional to the superficial gas velocity, and also inversely proportional to the solids flux.

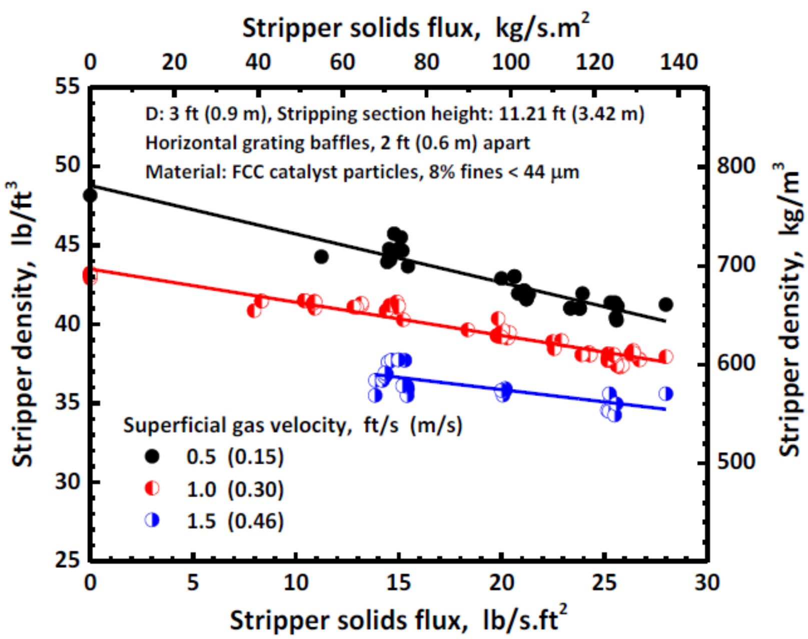

Figure 21. Stripper density as a function of solids flux for three superficial gas velocities in the 3-ft (0.9-m)-diameter fluidized bed stripper with subway gratings using 8% fines FCC catalyst particles.

Figure 4: Experimental results of apparent bed density over the baffled section of the fluidized bed stripper. Reproduction of Figure 21 from Research Report No. 88 (Issangya et al, 2014)

Simulations

Computational models of the stripper section of the experimental unit were set up and run using Barracuda Virtual Reactor version 17.1. Barracuda Virtual Reactor is a commercial multiphase CFD code based on the multiphase particle-in-cell (MP-PIC) numerical method (Snider, et al, 1998; Snider, 2001). It has been used to simulate fluidized bed systems such as FCC regenerators (Singh, et al, 2017), coal gasifiers (Snider, et al, 2011), circulating fluidized bed (CFB) combustors (Blaser, et al, 2012), polysilicon reactors (Parker, 2011), polymerization processes (Kashyap, 2016), and chemical looping combustors (Parker, 2014).

Multiple simulations of the PSRI 3 ft (0.9 m) diameter stripper with subway grating baffles were run, corresponding to various gas superficial velocities and various solids fluxes. The purpose was to simulate a wide range of operating conditions and compare with the experimental data reported by PSRI, enabling model validation and providing confidence in the use of simulation for scale-up and troubleshooting.

Domain and Boundary Conditions

A 3-dimensional CAD model of the fluidized bed stripper section was created and used in the simulations. The standpipe, risers, and external cyclones were not considered as part of the computational domain. A computational grid consisting of 727,000 real cells was used to resolve the geometry. Virtual Reactor™ uses cut cells to represent walls and internal structures. In the current model, the cyclone dipleg, fluidized bed ring sparger, helium pipe sparger (used in stripping efficiency tests) and subway grating baffles were captured by the computational grid.

Figure 5 shows the boundary conditions (BCs) used in simulations with non-zero particle flux through the stripper section; cases with zero particle flux used the same BCs, except that they did not include the bottom particle withdrawal flow BC. In all cases, particles were allowed to exit the system through the top pressure BC if they were entrained with the gas flow. All particles entrained from the system were returned via a BC Connector through the cyclone dipleg flow BC. This particle return was assumed to be 100% efficient, in order to maintain a constant particle mass in the simulation.

In cases with non-zero solids flux, a particle withdrawal flow BC was defined and the solids mass flux was specified. All particles withdrawn at this flow BC were returned via a second BC Connector to the cyclone dipleg flow BC. Again, this return was assumed to be 100% efficient, in order to keep the particle mass in the system constant. The particle withdrawal rates used for the flux values (Gs) considered in this work are listed in Table 2. Interstitial air was allowed to exit with the particles at the withdrawal flow BC, mimicking standpipe behavior.

Table 2: Particle mass flow rates, for solids mass flux values considered

Gs ($lb/ft^2/s$)	Gs ($kg/m^2/s$)	Particle mass flow rate (kg/s)
0	0	0
15	73.4	48
20	97.9	64
30	146.8	96

Fluidizing air was supplied via 28 discrete injection BCs placed near the fluidized bed ring sparger. The inner injection BC locations were moved inward from the physical nozzle locations (toward the center of the vessel), approximating a 4-inch jet penetration length. The total mass flow rate of air through these injection BCs was specified to match the superficial gas velocity used in the experimental system (either 0.5, 1.0, or 1.5 ft/s, depending on the condition being simulated). The air entering the system through the ring sparger was assumed to be at a temperature of 299.8 K, and a pressure of 140 kPa, resulting in a gas density of 1.63 kg/m^3. The resulting gas mass flow rates used for the superficial velocities considered in the current work are listed in Table 3.

Table 3: Gas mass flow rates from air ring, for superficial gas velocities considered

Ug (ft/s)	Ug (m/s)	Gas mass flow rate (kg/s)
0.5	0.15	0.163
1.0	0.30	0.326
1.5	0.46	0.489

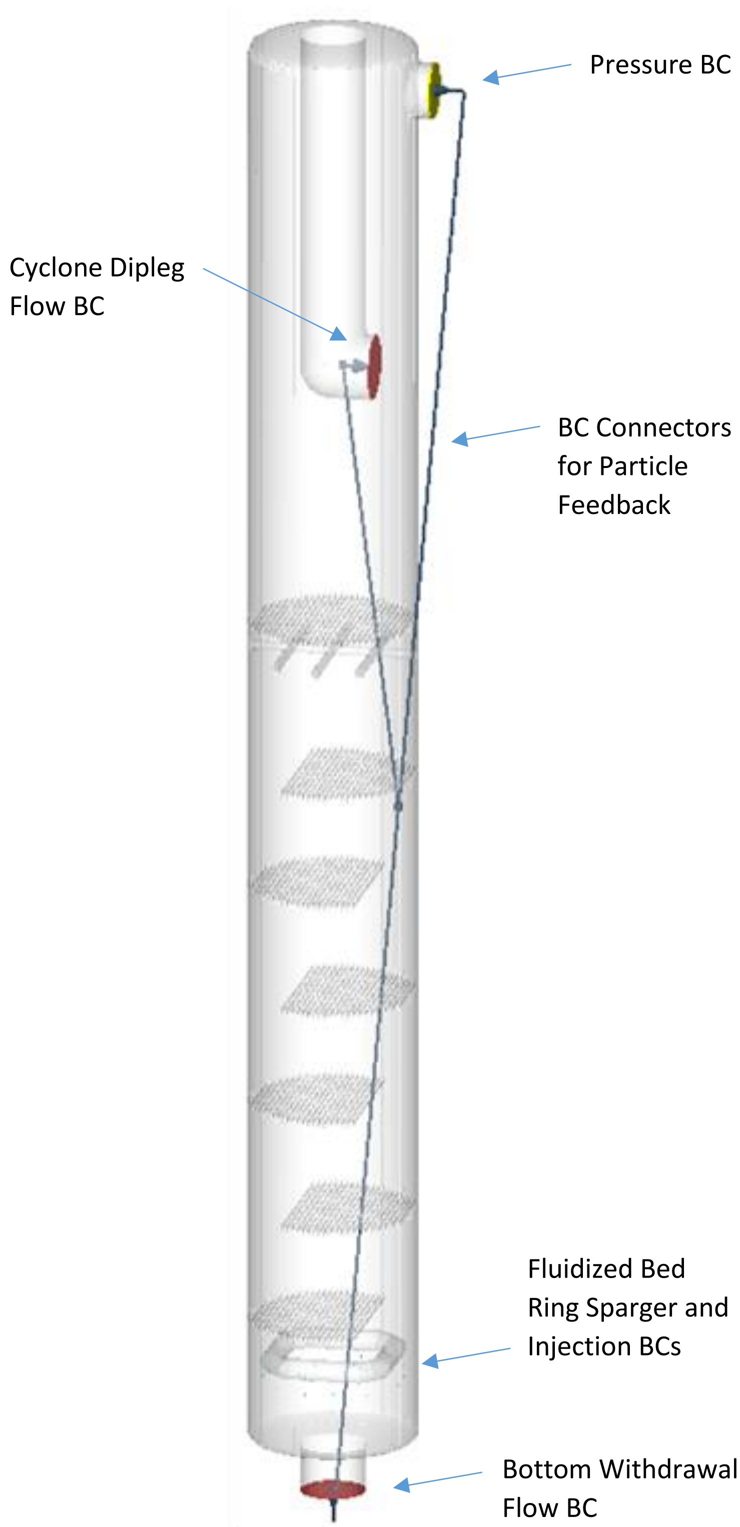

Figure 5: Computational model boundary conditions

Model Parameters

Simulations of fluid and particle dynamics are based on a combination of fundamental physics concepts, such as conservation laws, supplemented with empirical models. In this simulation, as in many multiphase simulations of fluidized bed systems, one of the most influential empirical models was the drag used to couple the particle and fluid phases. So-called “drag laws” are not physical laws, but rather models used by necessity to describe the forces exchanged between the particle and fluid phases.

The drag model used in this work was a blend of the drag model proposed by Ergun (1949) and that proposed by Wen and Yu (1966), with Sauter-mean diameter used as a basis for the drag calculation. A multiplier of 0.7 was applied to the Wen and Yu portion of the drag model, which reduced the drag force applied to particles when they were not near the close-pack particle volume fraction. This multiplier was chosen based on a calibration process in which various multiplier values were explored and compared with available test data. While calibration is standard practice for fluid-particle simulations, it should be noted that the model calibration was performed for a single operating condition, with all subsequent simulations using the identical empirical and numerical model settings.

Simulation Results

A visual representation of the simulation results for Ug = 1 ft/s, and various solids flux values, is shown in Figure 6. This is a half-slice view of the system at its center plane. Quantitatively, the Virtual Reactor simulation results are compared with experimental data for superficial gas velocities of 0.5 ft/s, 1.0 ft/s, and 1.5 ft/s in Figure 7, Figure 8, and Figure 9, respectively. In general, the simulation results compared very well with the experimental data. The inverse relationship between solids flux and apparent bed density was captured, as was the inverse relationship between gas superficial velocity and apparent bed density.

The largest deviation between simulation results and experimental data was observed in the solids flux range of 15 to 20 lb/ft^2/s for the lowest superficial velocity (0.5 ft/s), as shown in Figure 7. These are cases where the amount of gas withdrawn at the bottom exit BC was approaching the amount of gas being introduced by the fluidizing ring sparger. However, even in the low gas flow case, the trend was captured by the simulation results.

Discussion

Scale-up and troubleshooting of fluidized bed processes remains challenging due to non-linear process scalability combined with the limited data available at full scale, industrial facilities. Large scale test facilities enable the exploration of concepts and designs with strong industrial applicability. However, the large scale tests also provide data useful for calibration of numerical and empirical models used in CFD simulation.

In this work, the model calibration was performed for a single operating condition (Gs = 0 lb/s/ft^2, and Ug = 1.0 ft/s) before being verified to capture the experimentally-observed behavior at ten other combinations of gas and solids flux. This provides a modeler confidence in the applicability of the model to capture the general fluidization trends, rather than precise agreement for a single case. For cases where large scale test data is inaccessible, model calibration can be performed using available operational data. Ideally a computational model can be calibrated and verified using fundamental test data as well as operational data, but this work demonstrates the power of a single operational point to inform model settings with a significant range of applicability.

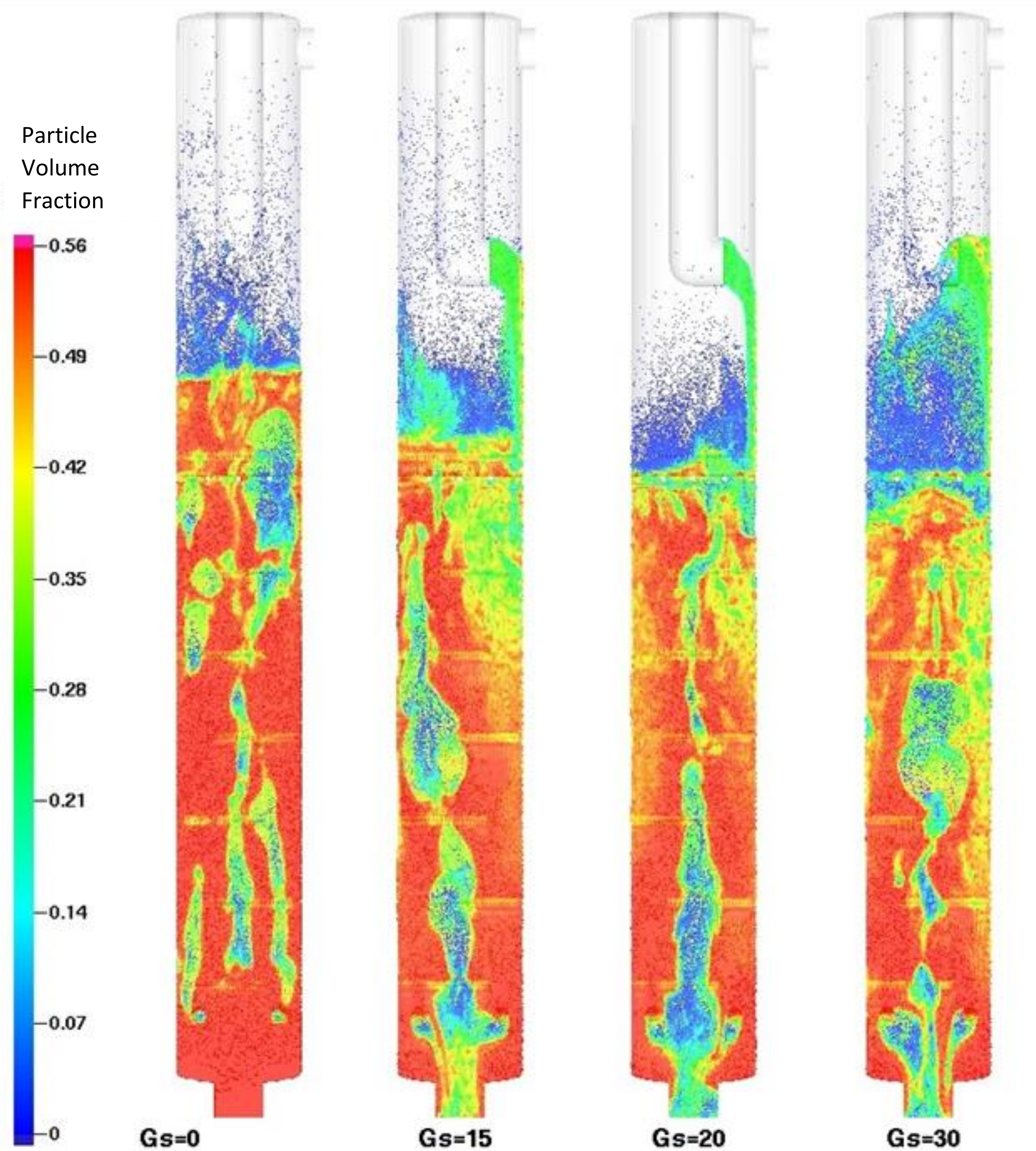

Figure 6: Half-slice view of particles colored by volume fraction, for simulations with Ug = 1 ft/s

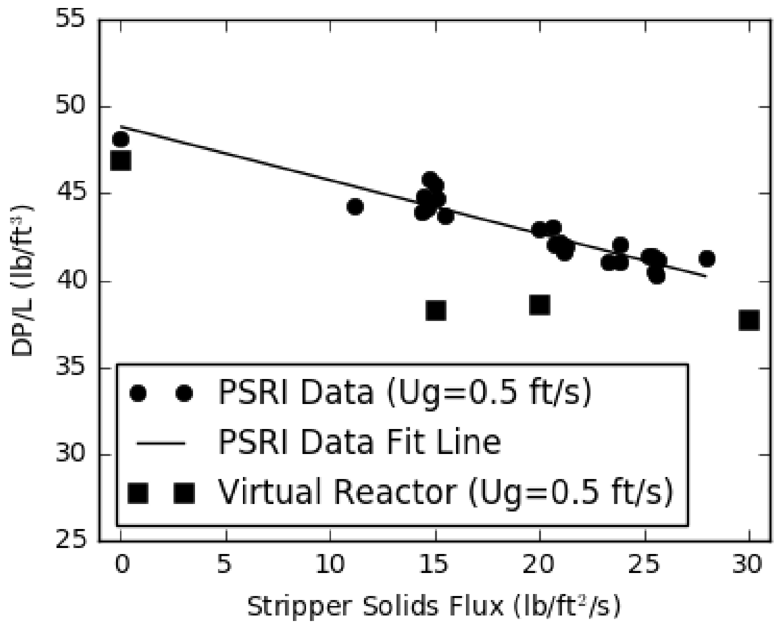

Figure 7: Simulation results compared with experimental data for Ug = 0.5 ft/s

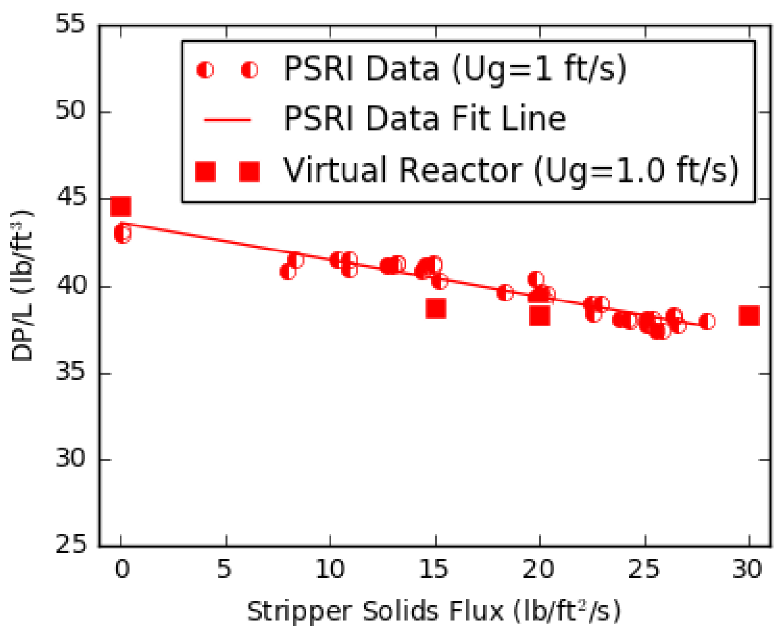

Figure 8: Simulation results compared with experimental data for Ug = 1.0 ft/s

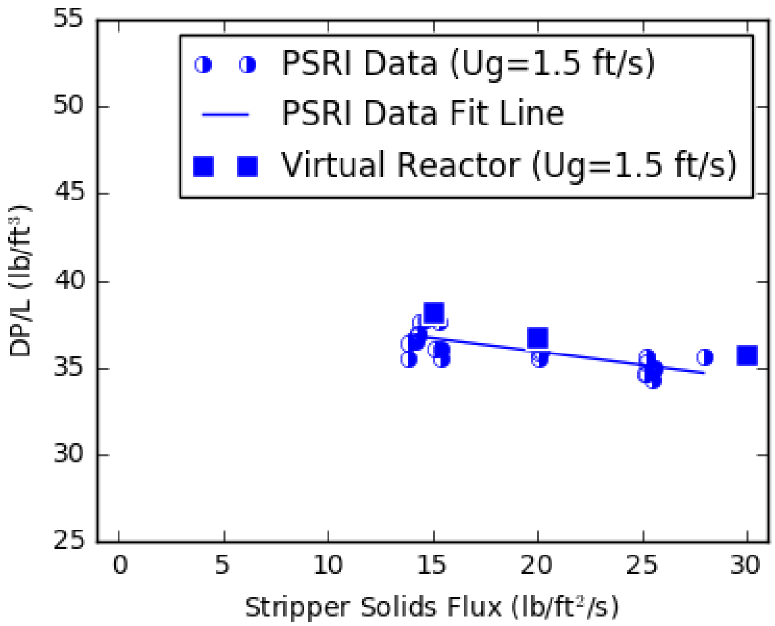

Figure 9: Simulation results compared with experimental data for Ug = 1.5 ft/s

Conclusions

Numerical simulations have been performed of a PSRI cold-flow FCC stripper experiment with subway grating baffles. The experimental unit had an internal diameter of 3 feet, and a height of 25 feet. The subway grating baffles within the vessel were intended to promote more uniform fluidization of particles by preventing the formation of large bubbles as well as preventing gas bypassing in the stripper. The commercial computational fluid dynamics (CFD) software Barracuda Virtual Reactor, which implements the multi-phase particle-in-cell (MP-PIC) numerical method, was used to perform the simulations. Simulation results were compared with experimental measurements of apparent bed density over a wide range of solids flux conditions, at superficial gas velocities typical of industrial FCC stripper operation. The simulation results were in good agreement with the experimental bed density measurements, and matched the experimentally observed trends of bed density variation as a function of gas superficial velocity and catalyst mass flux through the stripper vessel.

References

1. Issangya, A. S., Karri, S. B. R., and Cocco, R. A., 2014. "PSRI Research Report No. 88: Performance of Subway Grating Baffles in a 3-ft (0.9-m)-Diameter Fluidized Bed Stripper Using FCC Catalyst Particles." Particle Solid Research, Inc. Full report available to PSRI member companies only. Figures and data referenced in the current work have been used with permission from PSRI.
2. Snider, D.M., P.J. O'Rourke, and M.J. Andrews. 1998. "Sediment Flow in Inclined Vessels Calculated Using a Multiphase Particle-in-Cell Model for Dense Particle Flows." *International Journal of Multiphase Flow* 24 (8): 1359–82. doi:10.1016/S0301-9322(98)00030-5.

3. Snider, D.M. 2001. “An Incompressible Three-Dimensional Multiphase Particle-in-Cell Model for Dense Particle Flows.” *Journal of Computational Physics* 170 (2): 523–49. doi:10.1006/jcph.2001.6747.
4. Singh, Raj, and Eusebius Gbordzoe. 2017. “Modeling FCC Spent Catalyst Regeneration with Computational Fluid Dynamics.” *Powder Technology* 316 (July): 560–68. doi:10.1016/j.powtec.2016.10.058.
5. Snider, Dale M., Samuel M. Clark, and Peter J. O’Rourke. 2011. “Eulerian–Lagrangian Method for Three-Dimensional Thermal Reacting Flow with Application to Coal Gasifiers.” *Chemical Engineering Science* 66 (6): 1285–95. doi:10.1016/j.ces.2010.12.042.
6. Blaser, Peter J., and Giorgio Corina. 2012. “Validation and Application of Computational Modeling to Reduce Erosion in a Circulating Fluidized Bed Boiler.” *International Journal of Chemical Reactor Engineering* 10 (1). doi:10.1515/1542-6580.3001.
7. Parker, James M. 2011. “Validation of CFD Model for Polysilicon Deposition and Production of Silicon Fines in a Silane Deposition FBR.” *International Journal of Chemical Reactor Engineering* 9 (1). doi:10.1515/1542-6580.2549.
8. Mayank Kashyap, "Application of multiphase flow CFD in the gas phase polymerization process" in "Fluidization XV", Jamal Chaouki, Ecole Polytechnique de Montreal, Canada Franco Berruti, Wewstern University, Canada Xiaotao Bi, UBC, Canada Ray Cocco, PSRI Inc. USA Eds, ECI Symposium Series, (2016). http://dc.engconfintl.org/fluidization_xv/65
9. Parker, James M. 2014. “CFD Model for the Simulation of Chemical Looping Combustion.” *Powder Technology* 265 (October): 47–53. doi:10.1016/j.powtec.2014.01.027.
10. Ergun, S. 1949. “Fluid flow through packed columns.” *Chemical Engineering Progress, 48:89*,
11. Wen, C.Y., and Yu, Y.H. 1966. “Mechanics of fluidization.” *Chemical Engineering Progress Symposium*, pages 100–111.