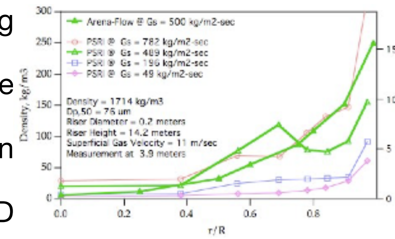
Applying the Fundamentals

PSRI Research Programs

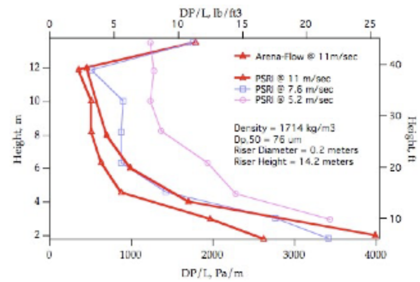
PSRI has been researching multiphase flow systems for over 45 years. In that time, PSRI has amassed 32 terabytes of data on fluidized beds, circulating fluidized beds, cyclones, slurries, feeders, and conveying systems. From those systems, PSRI has developed state of the art methods, procedures, correlations, tools and design guides covering all aspects of granular-fluid unit operations including entrainment, elutriation, classification, attrition, jet penetration, segregation, mixing and back mixing.

PSRI Particulate Solid Research, Inc.

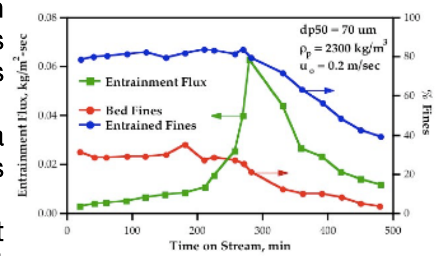
PSRI being first in granular-fluid concepts[1]



- 1988: PSRI reveals a core-annulus profile in large circulating fluidized bed risers
- 1991: PSRI accounts for particle clustering with the estimation of particle entrainment rates in fluidized beds
- 1994: PSRI develops and validates jet penetration correlations for gas-solid and high-pressure jets
- 1995: PSRI presents its first challenge problem for CFD validation of an 8-inch (0.15-m) diameter by 72-feet (22-m) tall riser with FCC powder and glass beads



- 1998: PSRI shows that particle segregation in a riser is possible with larger particles migrating to the wall
- 1999: PSRI Joins the Multiphase Fluid Dynamics Consortium (MFDRC). A five-year program designed to develop better CFD codes for granular-fluid systems consisting of five national labs, seven universities, and eleven companies
- 2000: PSRI develops a fiber-optic probe for measuring solids concentrations in circulating fluidized bed risers
- 2000: PSRI presents its second challenge problem for CFD validation of an 8-inch (0.15-m) diameter by 72-feet (22-m) tall riser
- 2001: PSRI reveals streaming flow in cyclone diplegs and how to prevent such flow
- 2001: PSRI demonstrates the benefits of trickle-valve aeration on a large secondary cyclone
- 2002: PSRI demonstrates that the core-annulus profile in a circulating fluidized bed riser can have upflow or downflow at the wall depending on the superficial gas velocity and the solids circulation rate



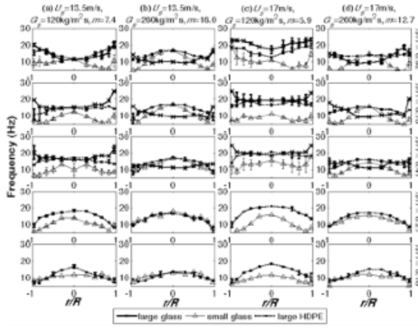
- 2004: PSRI documents the presence of gas bypassing in deep or dense fluidized beds that is independent of the gas distributor design, but highly dependent on the fines concentration
- 2006: PSRI documents that the additions of fines to a fluidized could reduce entrainment if particle clustering is present
- 2007: PSRI reveals limitations with the Davison Attrition Jet Cup method and develops a conical jet cup design that provides consistent results that mirror attrition rates measured on large fluidized bed units

PSRI Current Membership-Based Research

- Cyclone operation, efficiency and reliability
- Cyclone termination with L-valves, trickle valves and flapper valves
- Fluidized bed gas-solid hydrodynamics with bed internals
- Stripper internals design criteria
- Particle attrition, testing and models
- Particle drag in fluidized beds with application to CFD modeling

[1] Publicly disclosed concepts

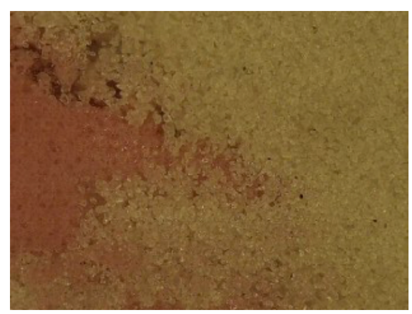
Applying the Fundamentals

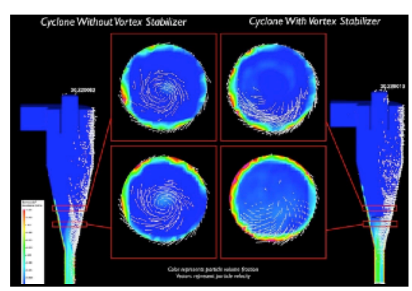


- 2008: PSRI reveals images of particle clusters above and in a fluidized bed during operation
- 2009: PSRI, with NETL, quantify granular temperature in a riser from the core to the wall with an order-of-magnitude difference
- 2010: PSRI documents the intrusiveness of using a fiber optic probe in a riser and develops a second generation design to minimize its effect on the gas-solid flow
- 2011: PSRI quantifies the stability and frequency of large clusters in a riser using wavelet decomposition
- 2012: PSRI images particle behavior with gas-liquid atomization into a fluidized bed which revealed a mechanism for the formation of agglomerates
- 2012: PSRI discerns the mechanism of increase standpipe performance due to proper aeration in terms of amount and location
- 2014: PSRI develops a dynamic force sensor for quantifying hydrodynamic forces imposed on fluidized bed internals
- 2015: PSRI quantifies erosion pattern and wear rates in a secondary cyclone based on using a cyclone dust hopper or vortex stabilizer
- 2016: PSRI reveals the role vent holes have in disk and donut stripping elements with reducing flooding in large-scale strippers
- 2017: PSRI quantifies the change in bed densities and discerns the mechanics of bubble flow with fluidized bed internals in a large-scale fluidized bed

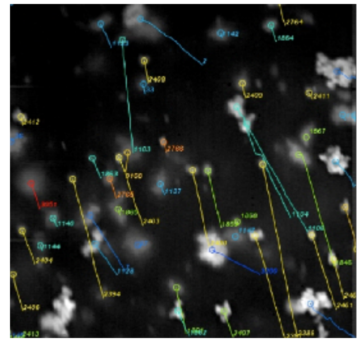
Past Selective PSRI Research Programs[2]

- 1970: Entrainment and bubble sizes in fluidized beds
- 1971: Particle attrition in fluidized beds
- 1973: Grid design and its effect on bed entrainment and particle attrition
- 1974: Grid design guidelines for proper gas distribution and low particle attrition
- 1974: Breakage mechanism due to attrition for FCC particles
- 1975: Pneumatic conveying of glass beads and polystyrene pellets in a 4-inch (0.05-m) diameter conveying loop
- 1976: Acceleration loss in the elbows of pneumatic conveying lines of dense flow suspensions
- 1976: Pressure drop in cyclone separators
- 1977: Development of a pressure drop correlation for cyclone separators
- 1978: Further development of particle entrainment rate correlations for fluidized beds
- 1979: The role of moisture retention on the hydrodynamics of FCC particles in a fluidized bed and riser
- 1980: Saltation velocities in a horizontal dilute-phase conveying line
- 1982: Particle hold up at and above the choking velocity

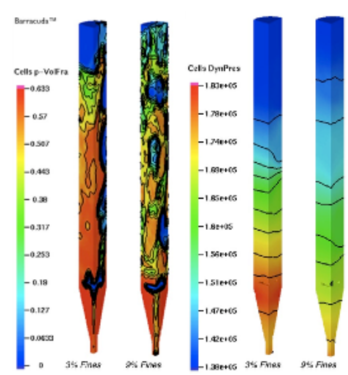


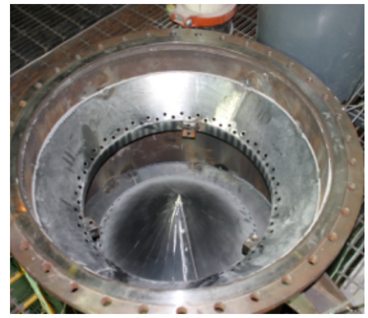


[2] Membership research projects only



in a vertical pneumatic conveying line
- 1984: Saltation velocity of granular polymers and glass spheres
- 1986: The hydrodynamics of FCC powder in a 3-inch (0.03-m) diameter standpipe
- 1987: Particle attrition in reverse flow cyclones
- 1987: Particle attrition of gas jets submerged in a fluidized bed
- 1988: Flow profile of FCC catalyst, lignite char, and FCC fines in a dense phase conveying loop
- 1988: Development of a cyclone collection efficiency correlation with dependencies on solids loading and cyclone design
- 1988: The effects of fines level on standpipe performance for Geldart Group A particles
- 1989: Measuring bulk solids viscosity
- 1989: Particle attrition in the elbows of dilute-phase conveying lines
- 1990: Air classification of ultra-fine powders
- 1990: Jet penetration for upwardly, downwardly and horizontally directed jets
- 1990: Effect of grid type and the direction of gas jets on particle attrition
- 1991: Effects of system pressure on particle attrition from grid plates
- 1992: Development of a second generation entrainment and particle cluster-size correlations
- 1992: Correlations for choking and saltation velocities with dilute-phase pneumatic conveying
- 1993: Staging of fluidized beds
- 1994: Countercurrent contacting in multistage fluidized beds
- 1995: The effect of solids-gas mixtures on jet penetration for upwardly, downwardly and horizontally directed jets in fluidized beds
- 1995: Design aspects of various bends in dilute-phase pneumatic conveying
- 1998: High-pressure cyclones and their effect on collection efficiencies
- 1999: Predicting streaming flow in cyclone diplegs
- 2000: Role of shrouds on gas distributors with respect to particle attrition
- 2000: Dipleg splash plate design and operation
- 2001: Effect of particle size and gas velocity on fluidized bed densities
- 2002: Role of bed internals in deep fluidized beds
- 2003: Parametric study of cyclone performance at low and high solids loadings
- 2004: Hydrodynamics of a circulating fluidized bed riser with Geldart Group A powders of varying polydispersity
- 2006: Developed and implemented a new jet cup attrition testing method
- 2007: Gas bypassing in deep or dense fluidized beds
- 2009: Effects of grating trays on the staging of deep fluidized beds
- 2011: Revealed factors affecting cyclone reliability
- 2012: Revisiting particle entrainment in fluidized beds
- 2013: Hydrodynamics and stripper efficiency of a large stripper with disk and donut internals
- 2014: Hydrodynamics and stripper efficiency of a large stripper with grating tray internals
- 2014: Hydrodynamics of a circulating fluidized bed riser with Geldart Group B powders of varying polydispersity





- 2014: Development of a dynamic force probe for fluidized bed applications
- 2015: Quantifying particle attrition from gas jets and cyclone separators
- 2015: Hydrodynamics of a fluidized bed with bed internals
- 2015: Development of a second generation solids tracer technique for quantifying solids dispersion and mixing
- 2016: Development of a population balance model for the prediction of particle attrition in large commercial units
- 2016: Design of axial cyclones for very low solids loading applications
- 2017: Development of a drag model for CFD applications
- 2017: Hydrodynamics and stripper efficiency of a large stripper with chevron internals
- 2018: Hydrodynamics in an angled standpipe

Selected List of PSRI Research Publications

1. R.A. Cocco, S.R. Karri, T.M. Knowlton, J. Findlay, T. Gauthier, J.W. Chew, et al., Intrusive Probes in Riser Applications, AIChE J. 0 (2017) 1–14. doi:10.1002/aic.15892.
2. A. Anantharaman, A. Issangya, S.B.R. Karri, J. Findlay, C.M. Hrenya, R.A. Cocco, et al., Annulus flow behavior of Geldart Group B particles in a pilot-scale CFB riser, Powder Technology. (2016) 1–45. doi:10.1016/j.powtec.2016.11.007.
3. A.S. Issangya, S.B.R. Karri, T. Knowlton, R. Cocco, Use of pressure to mitigate gas bypassing in fluidized beds of FCC catalyst particles, Powder Technology. 290 (2016) 53–61. doi:10.1016/j.powtec.2015.08.043.
4. S. Tebianian, K. Dubrawski, N. Ellis, R.A. Cocco, R. Hays, S.B.R. Karri, et al., Investigation of particle velocity in FCC gas-fluidized beds based on different measurement techniques, Chemical Engineering Science. 127 (2015) 310–322. doi:10.1016/j.ces.2015.01.049.
5. A. Cahyadi, A.H. Neumayer, C.M. Hrenya, R.A. Cocco, J.W. Chew, Comparative study of Transport Disengaging Height (TDH) correlations in gas–solid fluidization, Powder Technology. 275 (2015) 220–238. doi:10.1016/j.powtec.2015.02.010.
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10. J. McMillan, F. Shaffer, B. Gopalan, J.W. Chew, C. Hrenya, R. Hays, et al., Particle Cluster Dynamics During Fluidization, Chemical Engineering Science. 100 (2013) 39–51. doi: 10.1016/j.ces.2013.02.047.
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12. C.B. Solnordal, K.J. Reid, L.P. Hackman, R. Cocco, J. Findlay, Modeling Coke Distribution above the Freeboard of a FLUID COKING Reactor, Ind. Eng. Chem. Res. 51 (2012) 15337–15350. doi:10.1021/ie3010176.

13. R. Cocco, S.B.R. Karri, T. Knowlton, B. Gopalan, F. Shaffer, J.W. Chew, et al., Particle and Particle Cluster Hydrodynamics in a Circulating Fluidized Bed Riser, in: U. Arean, R. Chirone, M. Miccio, P. Salatino (Eds.), Napoli, Italy, 2012: pp. 1–8.
14. J.W. Chew, R. Hays, J.G. Findlay, T.M. Knowlton, S.B.R. Karri, R.A. Cocco, et al., Reverse core-annular flow of Geldart Group B particles in risers, 221 (2012) 1–12. doi:10.1016/j.powtec.2011.12.019.
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