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Shantanu Roy

Jinwen Chen

Sailesh B. Kumar

M. (Muthanna) H. Al-Dahhan
Missouri University of Science and Technology, aldahhanm@mst.edu

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/che_bioeng_facwork/1383

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Tomographic and Particle Tracking Studies in a Liquid−Solid Riser

Shantanu Roy, Jinwen Chen, Sailesh B. Kumar, M. H. Al-Dahhan,* and M. P. Duduković

Chemical Reaction Engineering Laboratory (CREL), Department of Chemical Engineering, Washington University, St. Louis, Missouri 63130

A liquid−solid circulating fluidized bed is a potential reactor of interest in a variety of industrial processes, such as petroleum refining, and in the synthesis of fine chemicals, petrochemicals, and foodstuffs. Rapid deactivation of the solid catalyst in these processes necessitates regeneration and recirculation of the solids into the riser section in which the principal reaction is accomplished. In this study we show that computer-automated radioactive particle tracking (CARPT) can be used to obtain solids velocity patterns in the riser and that backflow of solids exists at the tested liquid velocities. γ-ray computed tomography (CT) reveals slightly higher solids concentrations in the center of the column. This is in contrast to gas−solid riser reactors in which the concentration of solids is higher at the walls.

Introduction

Liquid−solid circulating fluidized beds are rapidly gaining popularity as reactors of choice in a variety of industrial processes like the synthesis of fine chemicals and petrochemicals and in petroleum refining (Liang et al., 1995). The process requirements that motivate the use of such reactors are the presence of a liquid-phase reactant, which is typically a hydrocarbon under high pressure and low temperature (Thomas, 1970), and a solid-phase catalyst, which gets deactivated rapidly (Corma and Martinez, 1993). The principal reaction is accomplished in a vertical riser column of high *L*/*D* ratio (in which the solids are fluidized and transported by the liquid phase). Regeneration of the deactivated catalyst is done in a separate process, which is coupled to the principal reaction in the riser by circulating the solids continuously in a closed loop.

The design and scaleup of such continuous-flow liquid−solid systems require knowledge of the flow pattern of each of the phases and the phase holdup distribution. The goal of this work is to study experimentally the velocity and holdup distribution of the solid phase in the riser of a laboratory-scale cold flow model of a circulating liquid−solid system.

Experimental Section

A schematic of the laboratory-scale liquid−solid circulating fluidized-bed setup is shown in Figure 1. The riser section is a 15 cm (6 in.) diameter Plexiglass column, with a height of about 210 cm (7 ft.). Glass beads (diameter 2.5 mm) are fluidized with ordinary tap water in the riser section and circulated back into the system through the hopper and eductor. The solids mass flux in the riser is maintained by controlling the liquid flow rate through the eductor (which was precalibrated for solids flow rate as a function of motive water flow rate). The overall desired solids/liquid flow ratio is obtained by supplying the remaining liquid through the distributor plate at the bottom of the column. A constant high flow rate and head of water in the column and at the eductor inlet is maintained by circulating it through a pump and storage tank, in a closed loop.

Experiments were performed using the CARPT (computer-automated radioactive particle tracking) and CT (computer tomography) facilities developed at the Chemical Reaction Engineering Laboratory, Washington University, St. Louis, MO (Devanathan, 1991; Kumar, 1994). It may be noted that the system under study is very dense and turbulent, and only noninvasive flow-monitoring methods like CARPT and CT are capable of accurately measuring solids velocity and concentrations.

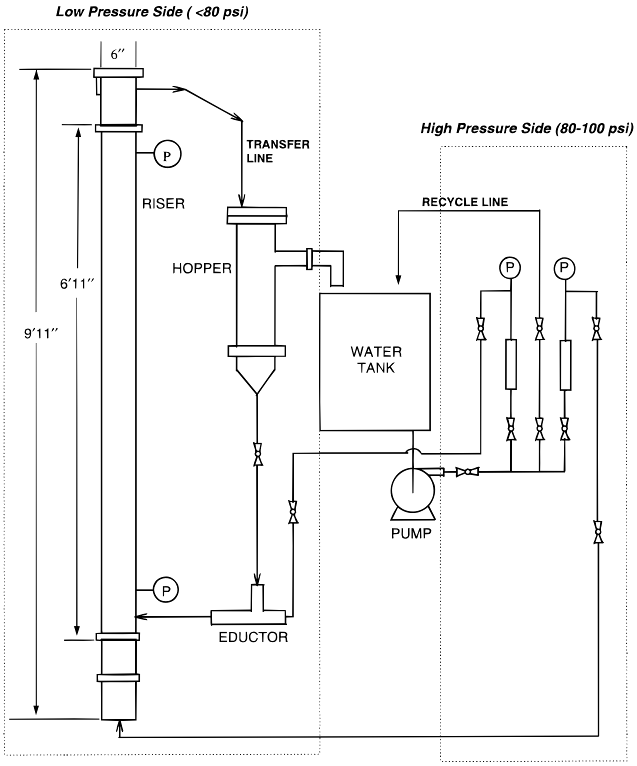

Figure 1. Schematic of the liquid−solid riser setup.

The present setup was designed so that the riser section could be installed for study in the CARPT−CT platform.

Prior to study of the solid-phase hydrodynamics, residence time distribution measurements were conducted in the liquid phase. Conductivity of the liquid phase was monitored at strategic locations after a pulse injection of KCl solution. Results of this study were reported elsewhere (Roy et al., 1996). It was found that the liquid phase flows practically in plug flow, with small dispersion effects. Dimensionless variance of the liquid tracer E-curve was always bounded below 0.1.

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* Author to whom all correspondence should be addressed.

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For the CARPT study (Devanathan, 1991; Yang et al., 1992), a tracer particle was prepared by introducing a radioactive Sc-46 particle (of strength 350 μCi and half-life of 83 days) in a hollow aluminum sphere whose size and density were matched with the glass particles being fluidized. Through an elaborate calibration procedure used in the CARPT method (Yang et al., 1992), the particle was placed in around 200−300 known locations in the test section and a calibration map was obtained for the distance−intensity of the radiation relationship for each detector. Once the calibration was complete, the desired liquid superficial velocity was set and maintained, and the particle was allowed to move freely in the flow field, simulating the motion of a typical glass particle. The position of the tracer particle was recorded as a function of time, in the form of photon counts from the detectors, over a long period of time (8 h). Mean and fluctuating velocity components, turbulence parameters, and kinetic energy of solid particles could be subsequently calculated by filtering and processing the raw data (Devanathan, 1991; Larachi et al., 1997). This is the first time that the use of CARPT has been demonstrated successfully in a system where the tracer particles periodically leave and re-enter the section being interrogated by the detectors.

The CT scanner at CREL, Washington University, St. Louis, MO, uses a fan-beam geometry for measurement of attenuation of γ-radiation as it passes through the given object, in this case the riser section. The raw attenuation measurements are then used to reconstruct the cross-sectional time-averaged holdup distribution of the phases. The source is an encapsulated 100 mCi Cs-137 isotope, and an angular array of 11 NaI detectors (maximum) is used for attenuation measurement. The estimation−maximization algorithm, based on maximum likelihood principles (Lange and Carson, 1984), is used for image reconstruction from the projection measurements. Details of the software and hardware aspects of the CREL scanner are discussed by Kumar et al. (1995) and Kumar and Duduković (1997).

In the present study, the test section (liquid−solid riser) was scanned at four strategic axial locations along the column.

Results and Discussion

Experiments were performed in a range of liquid superficial velocities, from 12 to 23 cm/s. In this study, typical results obtained by running the system at a liquid superficial velocity of 20 cm/s are reported. All experiments were performed with glass particles of 2.5 mm diameter, with an eductor water flow rate of 25 gal/min. A water flow rate of 33 gal/min was maintained at the bottom of the riser to maintain an overall liquid superficial velocity of 20 cm/s in the column.

Figure 2 is a plot of azimuthally averaged and time-averaged radial solids holdup (solids concentration) distribution, measured at four axial locations, at a liquid superficial velocity of 20 cm/s. It is observed that the magnitude of the solids holdup does not vary very significantly (maximum variation is 4%) with increasing radial position but decreases slightly with axial position (maximum 4%). The solids holdup, at any given axial position, is slightly higher at the center of the column as compared to the wall. This is an interesting result, for it is widely reported that in gas−solid risers the opposite trend is observed (Rhodes and Geldart, 1989; Rhodes, 1990). The radial gradient in the solids holdup distribution is also much smaller here.

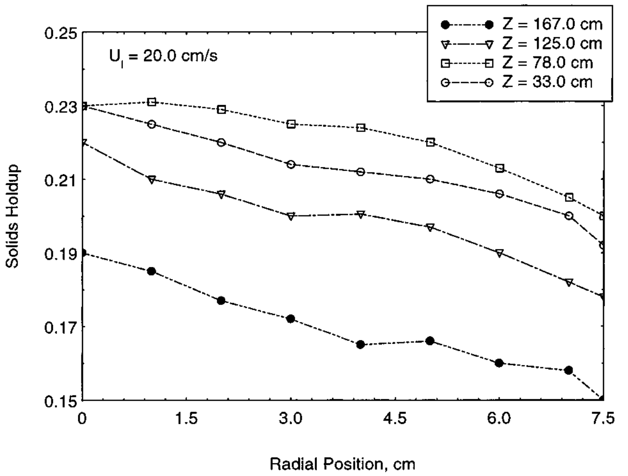

Figure 2. Solids holdup (concentration) distribution at different axial locations (liquid superficial velocity = 20 cm/s).

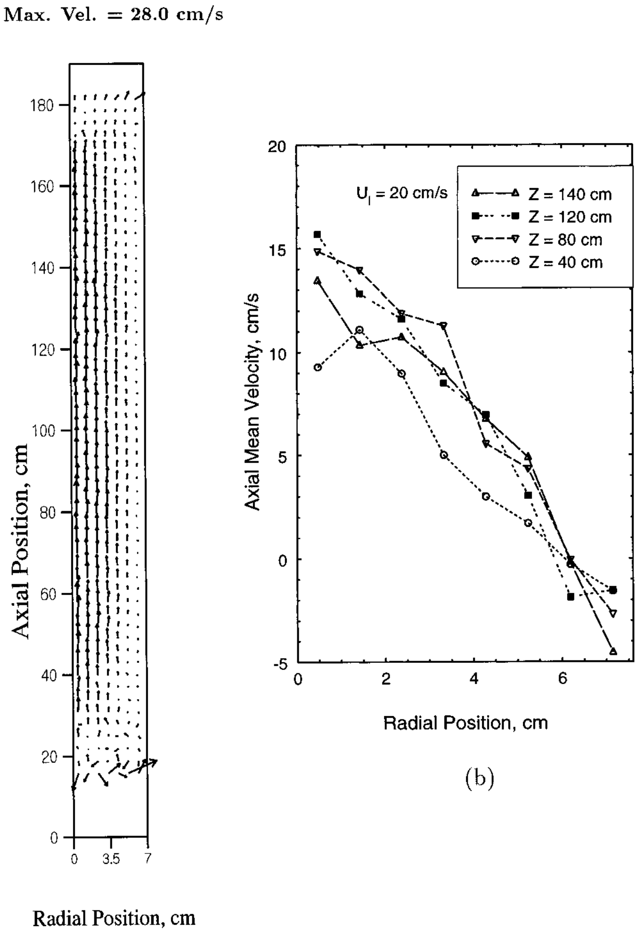

Figure 3. Solids velocity field at a liquid superficial velocity of 20 cm/s: (a) velocity vector plot; (b) axial mean velocity profile.

Figure 3 shows the solids velocity field as evaluated from the CARPT experiment. Figure 3a is a velocity vector plot, which clearly shows that, in a time-averaged sense, the solids phase has one circulation loop: solids ascending at the center of the column and descending at the wall. Figure 3b shows the same fact quantitatively in terms of the time-averaged axial component of solids velocity, at four locations at the middle of the column. It may be noted that while the downflow velocities of solids at the wall are of small magnitudes as compared to the upflow velocities, the total mass of solids in downflow is still appreciable (9.6% in this case)

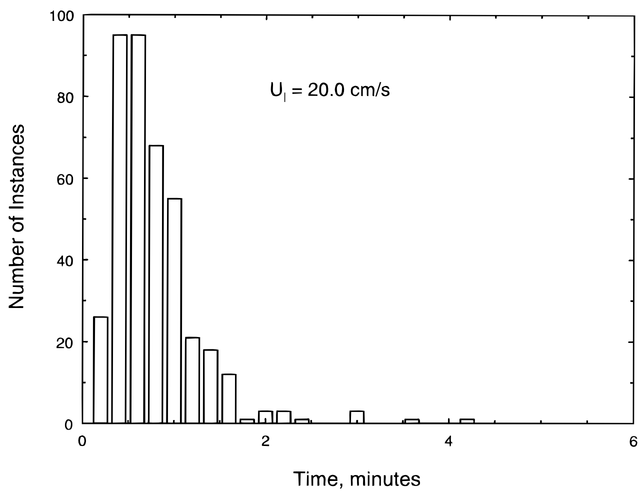

Figure 4. Residence time distribution of the solid phase at a liquid superficial velocity of 20 cm/s (from CARPT experiment).

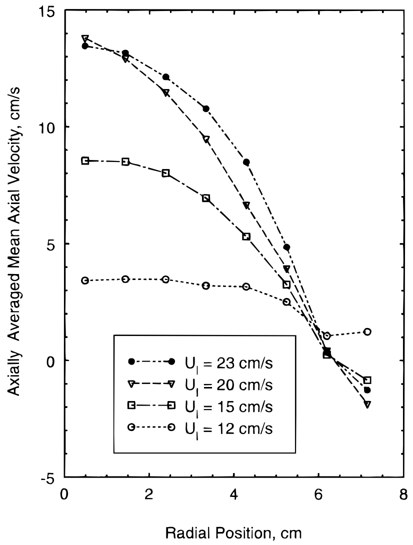

Figure 5. Axially averaged axial mean solids velocity as a function of liquid superficial velocity.

owing to a higher sectional area of flow at a greater radial location.

A comment about the solids holdup profile at the level of 33 cm in the column is in order. This level, just above the distributor and eductor in the column (Figure 1), is part of a mixing zone, and apparently shows an anomalous lower holdup profile than the 78 cm level. This is also confirmed by the CARPT results: Figure 3a clearly shows the solids velocity vectors are randomly directed at that level, while higher up in the column a clear circulation loop can be identified. Thus, the flow at 33 cm in the column is still developing and shows an apparently deviant behavior when compared to the rest of the column.

Using a novel approach, the solids residence time distribution (RTD) in the riser section was calculated indirectly from the CARPT data. Since the tracer particle is deemed to be a typical dispersed phase entity which gets repeatedly circulated back into the riser section, the distribution of times spent by it in the riser section during each of its visits is a measure of its RTD. These "residence times" during successive visits are plotted as a histogram in Figure 4. Evoking the ergodic hypothesis, this gives the RTD of the solid phase.

Finally, in Figure 5, the axially averaged mean axial velocity of solids is presented as a function of liquid superficial velocity. Experiments done at the different conditions indicate an overall increase in magnitude of the centerline as well as wall (downflow) velocity. This is, of course, to be expected since a higher momentum of the liquid phase would impart more momentum to the solid phase through the interphase drag, leading to a higher mean velocity of the solids. Purely based on these experiments, the results seem to suggest that the solid-phase velocity reaches some kind of a "saturation-profile" with increasing liquid superficial velocity. However, rigorous verification of such results awaits future experimentation.

Concluding Remarks

Design practice of fluidized beds and risers even today rests on conventional "rules-of-thumb". The actual phenomena in such systems are much more complex than captured by the heuristic approaches used as the basis of the design equations. Hence, the users and designers of liquid−solid risers should ultimately profit from an improved fundamental understanding of the hydrodynamics in such systems. The present study was intended to be a first step in the experimental quantification of the same.

At CREL, work is in progress in studying the riser setup under a variety of operating conditions and using a spectrum of particle sizes. Investigation of transient phenomena in such systems is also planned for in the future. Further processing of the data will be done in order to calculate the kinetic energy, turbulent shear stresses, and turbulent dispersion coefficients in the solid phase. The overall goal of this research effort is to develop an understanding of the key variables affecting the performance of the liquid−solid riser and develop more fundamentally-based scale-up rules. The experimental data are also expected to act as benchmarks for computational fluid dynamic modeling of the liquid−solid riser flow.

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Nomenclature

U_l = superficial liquid velocity, cm
Z = level in the riser, cm

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