The 14th International Conference on Fluidization – From Fundamentals to Products

Refereed Proceedings

2013

Liquid Injection into Fluidized Beds

Ray Cocco
Particulate Solid Research, Inc., USA

Jennifer McMillan
Syncrude Canada Ltd., Canada

Roy Hays
Particulate Solid Research, Inc., USA

S.B. Reddy Karri
Particulate Solid Research, Inc., USA

Recommended Citation

Ray Cocco, Jennifer McMillan, Roy Hays, and S.B. Reddy Karri, "Liquid Injection into Fluidized Beds" in "The 14th International Conference on Fluidization – From Fundamentals to Products", J.A.M. Kuipers, Eindhoven University of Technology R.F. Mudde, Delft University of Technology J.R. van Ommen, Delft University of Technology N.G. Deen, Eindhoven University of Technology Eds, ECI Symposium Series, (2013). http://dc.engconfintl.org/fluidization_xiv/125

Liquid Injection into Fluidized Beds

Ray Cocco[1], Jennifer McMillan[2], Roy Hays[1], S.B. Reddy Karri[1]
[1]Particulate Solid Research, Inc.
4201 W 36th Street, Suite 200
Chicago, IL 60632
ray.cocco@psrichicago.com

[2]Syncrude Canada Ltd.
Edmonton Research Centre
9421 17th Avenue
Edmonton, Alberta T6N 1H4

ABSTRACT

Many of our fluidized bed unit operations involve liquid injection. Yet, how the liquid and solids interact in these units and how the hydrodynamics change because of the liquid injection is not well understood. High-speed video imaging suggests that two types of particle clustering are prevalent when using a standard type of liquid atomizer in a fluidized bed. Smaller clusters tend to be formed near the nozzle region, whereas large agglomerates are formed further downstream from the nozzle. These large agglomerates appeared to form an almost impenetrable membrane that further stabilized the jet while allowing little distribution of the liquid into the fluidized bed.

INTRODUCTION

Liquid injection into a fluidized bed or circulating fluidized bed is a part of a wide range of chemical processes including oxychlorination, catalytic oxidization, condensed-mode polyethylene, oil cracking with fluidized catalytic cracking units and bitumen upgrading with Fluid Cokers™. Despite the fact that some of these processes have been in service for decades, little is known about liquid hydrodynamics in a fluidized bed especially for horizontal injection. Bruhns and Werther (1) investigated the mechanism of liquid injection into fluidized beds and found that the injected liquid formed agglomerates with the bed particles at the nozzle exit and were transported into the bed interior by mixing of the bed solids.Ariyapadi et al. (2,3) investigated jet penetration and jet stability with a wide variety of nozzle designs and found that jet penetration was inconsistent with gas injection into a fluidized bed. Pougatch, et al. (4) was able to capture this discrepancy with a two-fluid Eulerian-Eulerian model. Liquid-particle interactions were captured with empirical correlations, but it was the refinement of the heat transfer that provided good agreement with measured data. Droplet size is another factor that needs further study. If liquid droplets are too large or a large layer of liquid resides on the particles, mass transfer is limited and excessive coking and agglomeration ensue (5). This is certainly true in the operation of converting bitumen to gas oils using a fluidized bed Coker™. As a result, operational windows tend to be narrow and reliability tends to be problematic.

House et al. (6) injected a sucrose solution into a small scale bed of coke particles. The sucrose solution binds to the particles with the injected liquid, and the liquid-solid contact was evaluated after the bed was dried and the water was evaporated. Their results suggested that an addition of a cylindrical tube coaxially downstream from the nozzle may improve the uniformity of liquid distribution. McMillan et al. (7) also investigated a similar tube and came to similar conclusions.

This study examined liquid and particle interaction of a liquid jet stream injected into a fluidized bed using high-speed video and a specially modified borescope. Video results show that the liquid quickly provides an encapsulated region that limits additional particle migration. In addition, two forms of agglomeration were revealed, with one resulting from the formation of this encapsulated region.

EXPERIMENTAL

Fluidized Bed

Experiments were carried out in a circulating fluidized bed (CFB) at the lab facility of Particulate Solid Research, Incorporated (PSRI) in Chicago, IL. Figure 1 shows a schematic drawing of the CFB. The unit consists of a 30-cm diameter by 22-m tall riser connected to a 2.1-meter wide by 0.3-meter deep by 6.2-meter tall fluidized bed. The fluidized bed face is constructed of a Plexiglas™ window to allow macroscopic views of the liquid jet hydrodynamics.

The fluidized bed unit was filled with sand (Agsco 50-80) having a particle density of 2600 kg/m^3 and a median particle size of 237 microns with a sphericity of 0.72. Humidified air was used as the gas medium throughout all the studies. Larostat−519 from BASF, an ammonia quaternary salt, was added to the powders to further eliminate electrostatic effects. The superficial gas velocity in the bed was 3.0 m/sec. Superficial air velocity was measured using an orifice flow meter. The fluidized bed unit was operated at room temperature and at near ambient pressures.

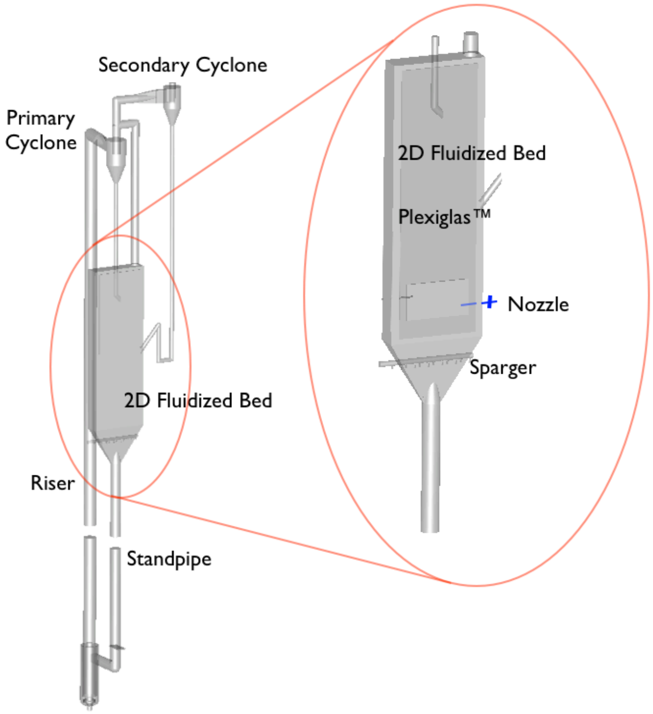

Figure 1: Schematic of the CFB and fluidized bed portion of the CFB used for the liquid injection studies.

Nozzle Design and Operation

The nozzle was a fifth-scale atomizer of a design similar to that used on the Syncrude Canada, Ltd. Coker™ units (8). Studies with the atomizer outside of the fluidized bed suggest that atomization capabilities were limited, with periodic pulsing observed.

The nozzle was located on one side of the fluidized bed about 0.6-meters above the gas sparger. For the macroscopic videos, the nozzle was angled towards the Plexiglas™ wall such that the jet was just impinged onto the Plexiglas™ face. For the video imaging with the borescope, the nozzle was adjusted to be parallel to the wall to minimize the wall effect on the jet hydrodynamics. The nozzle was operated with a liquid (water) to gas (air) ratio by weight of 66 with superficial velocities at the external orifice of 80 m/sec for the gas and 11 m/sec for the liquid. The liquid was stored in an external tank pressurized to 414 kPa gauge.

A magenta fluorescent dye (RiskReactor DFWB-K10-50) was added to the water at a concentration of 40 ppm. The dye provided added contrast for the liquid phase even without using UV lighting.

High-Speed Video

High-speed video images were obtained using a Vision Research Phantom v7.2 color camera. Although the camera is capable of operating at 150,000 fps, only frame rates ranging from 3000 to 10,000 fps were used. The camera was fitted with a F-mount or C-mount connector which allowed connection to standard Nikon lenses or to the modified boroscope.

Imaging was done in two modes: broad view through the face plate on the fluidized bed using a Nikon macro lens and micro view using a modified borescope through one of several ports in the fluidized bed. An Olympus R10003800050 Industrial Rigid Borescope was modified to allow imaging of particles and clusters in the freeboard and in the bed. This boroscope has a depth of field of 5 mm to infinity and was outfitted with a 6-mm diameter optical spacer (Melles Griot) to account for the distance between the boroscope face and the focal length. This prevented particles closer than the focal length from blurring the images or reducing the lighting for the imaged particles. The spacer was further secured using a stainless steel guard collar to protect the instrument when in the bed. A sleeve was fitted over the borescope to allow a sweeping gas across the borescope window face. This prevented particles closer than the focal length from blurring the images or reducing the lighting for the imaged particles. A sweeping gas consisting of air was set at 0.06 SCMH (standard cubic meters per hour) in order to keep the face clean of particles and liquid while minimizing its intrusion effect. Furthermore, the jet was directed away from the faceplate or any other wall during studies using the borescope in order to minimize other forms of intrusion on the hydrodynamics.

The Olympus borescope allows for internal lighting. A Xenon light source with an Olympus Liquid-Filled Light Guide was used to supply lighting through the borescope probe. External lighting was used whenever possible (8). Rottier, et al (9) has used a similar method for particle tracking in furnaces.

Particle concentrations and tracking were done using Mathematica version 8. Concentrations were determined from area ratios of light and dark regions after dilation, erosion, and binarization of the images. Particle and cluster velocities were obtained by masking disks on particle clusters after the image enhancement. Liquid velocities were determined by assuming the gas bubbles were traveling at the same speed as the liquid and disk masking the gas bubbles.

RESULTS AND DISCUSSION

Video images of the gas-liquid jet from the nozzle/atomizer in the fluidized bed were collected using two different methods. The first method was to use a macro lens connected to the Phantom VII camera via an F-mount adapter which captured the jet hydrodynamics at the Plexiglas™ face. The second method was to use a modified borescope with a c-mount adapter and the Phantom VII camera. Although the second method eliminates wall effects since the jet no longer needs to be near the wall, lighting issues limit the frame rates and resolution.

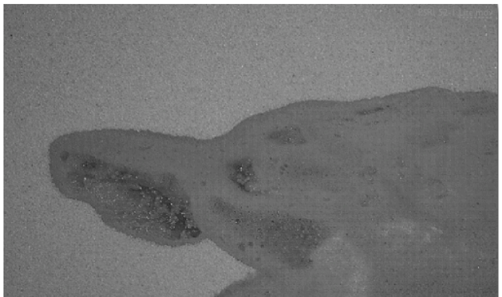

Figure 2: Image of gas-liquid jet penetration into a fluidized bed of sand particles using a macro lens at 9900 fps with a 20 microsecond shutter speed.

Figure 2 shows one gray-scale frame from a set of capture video images. The liquid (water) was observed to penetrate about 20-cm into the bed. Two features were notable. First, the liquid jet seems to push the solids in the fluidized bed away than encapsulating and incorporating the solids into the jet. Second, large sections of wet sand seem to shed off the bottom of the jet into the fluidized bed. Once separated from the jet, these regions seem to stay fairly intact in the lower shear regions of the fluidized bed compared to the jet.

Figure 3 shows gray-scale close up images representing the hydrodynamic behavior of the videos represented in Figure 2. Figure 3a shows the end of the jet at 20 cm from the nozzle face. The video clearly shows how the liquid penetration pushed the solids from the jet and allowed little incorporation of the solids at the boundary layer. In contrast, Figure 3b shows a

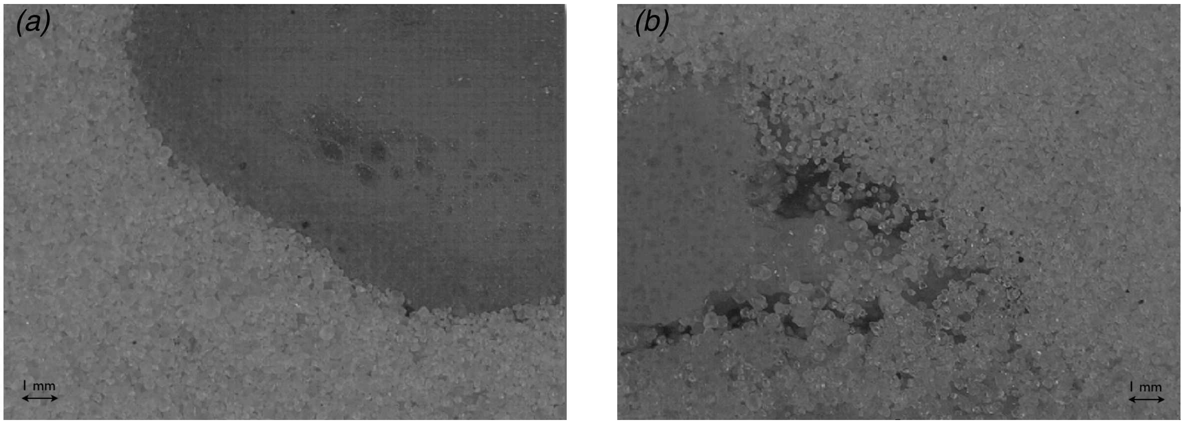

Figure 3: Close up images of gas-liquid jet 20 cm from nozzle face (a) and 5 cm from nozzle face (b) at 9900 fps with a 20-microsecond shutter speed.

significant amount of solids being incorporated into the gas-liquid jet. This figure is one gray-scale image of a video captured at 5 cm from the nozzle face or orifice. Clearly, these images suggest that solids incorporation into the jet is predominately near the nozzle face. Beyond that region, a liquid boundary layer, presumably stabilized by surface tension, prevents any significant amount of solids from being incorporated into the jet.

Figure 4 shows a further magnification of the image in Figure 3a. This boundary layer can be clearly seen and appears to be approximately 0.4 mm in thickness and appears to form near the nozzle face but not at the nozzle face (i.e., 5 to 10 cm from the nozzle face). Two features of this boundary layer were striking. First, as noted above, the particles in the fluidized bed-side of the jet seem to be pushed from the jet rather than be incorporated into the jet. Second, the gas in the jet, as gas bubbles, seems to be absent in this boundary layer.

The ramifications of this boundary layer may be significant. Both House et al. (6) and McMillan et al. (7) propose adding a cylindrical tube coaxially downstream from the nozzle. Results in Figures 3 and 4 suggest that the location of the coaxial tube may be a critical design parameter. If placed too far from the nozzle face, it would serve little purpose other than to further stabilize the boundary layer. If located closer to the nozzle face, a coaxial tube may enhance particle integration into the jet. Figure 3b suggests that the coaxial tube needs to be close to the jet. A coaxial tube could enhance particle elutriation much like a draft tube or inductor, as well as enhance the mixing between the liquid and the solids and disrupt the boundary layer.

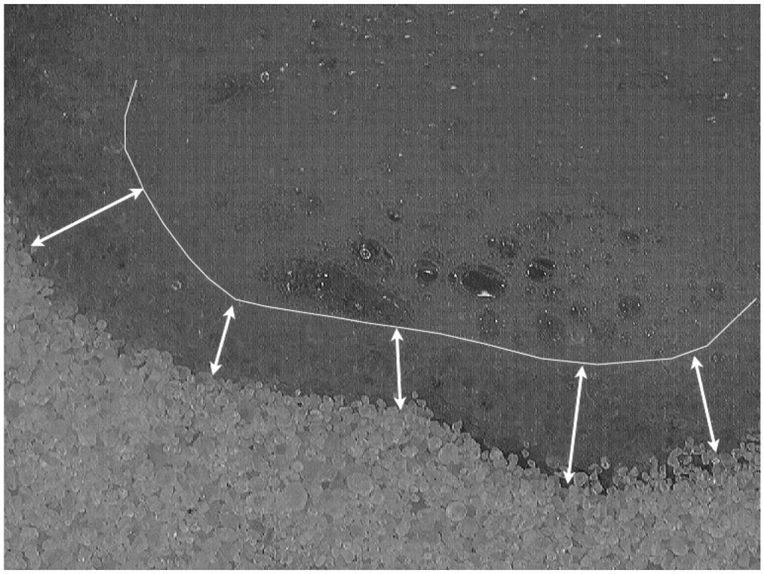

Figure 4: Estimate of jet boundary layer thickness 20 cm from nozzle face.

Figure 5 suggests that there may be an opportunity for increasing the particle concentration in the jet near the nozzle face. Figure 5 shows two sections of the image in Figure 3b which represents the series of images (10,000 images total) that were enhanced using Mathematica's dilation, erosion,

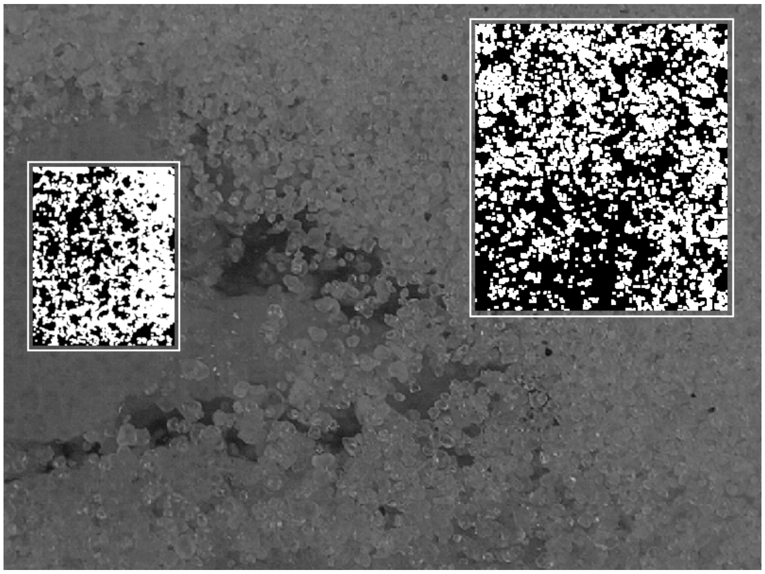

Figure 5: Contrast enhancement and subsequent digitalization in order to depict the approximate solids volume fraction inside the jet and outside the jet.

and binarization imaging features. After this enhancement, the area corresponding to the dark regions and representing the liquid and gas were compared to the area of the light regions representing the particles. This analysis indicates that the solids volume fraction of the fluidized bed region, outside the jet, was approximately 0.54. Inside the jet, near the nozzle face, the solids volume fraction was determined to be 0.30, suggesting that room is available for the incorporation of solids in the jet stream.

The video, represented by the image in Figure 5, also highlights that liquid injection into a fluidized bed should not be modeled in a similar fashion used to simulate jets in risers. Models by Okasha and Miccio (11) and Nayak et al. (12) were able to capture liquid jet hydrodynamics in a riser by focusing more on evaporation and heat transfer than on the motion of the individual phases. In the relatively dilute phase of a riser, this perhaps is realistic. However, in the more dense fluidized bed, the liquid and solid phase seem to not interact except in the region near the nozzle face. Presumably, the surface tension of the liquid phase could be controlling with liquid injection in fluidized beds, more so than expected, especially at a distance from the nozzle face. Even the multiphase models of Gao et al (13) and Li et al. (14) neglected surface tension, which limited their application to the low solids loadings of a riser. Pougatch et al. (4), however, did add surface tension as a coalescence term to a similar multiphase model. Their results were in

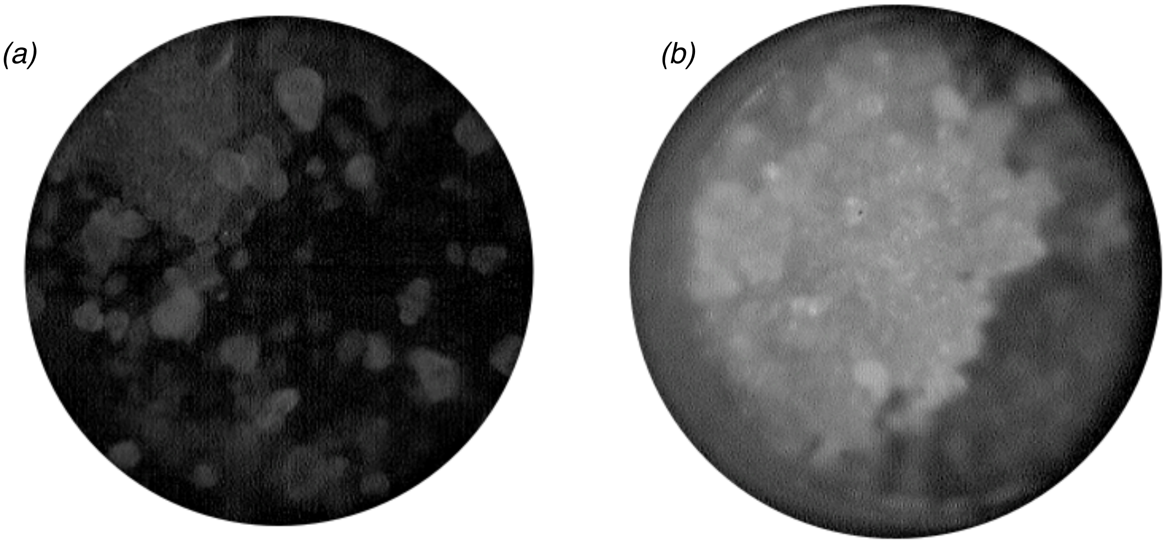

Figure 6: High-Speed video imaging using a modified borescope for agglomerates located 20 cm (a) and 5 cm (b) from nozzle face. Image collected at 1000 fps with a 990 microsecond shutter speed.

good agreement with the liquid injection data of McMillan et al. (7) with and without the coaxial cylindrical insert.

Particle tracking was also done in the near nozzle region that is represented in Figure 5. Particle velocities were measured to be approximately 6 m/sec with a standard deviation of 2 m/sec. The liquid velocity, tracked by the gas bubbles, was determined to be approximately 9 m/sec with a standard deviation of 2.1 m/sec. This is consistent with the calculated liquid jet with a nozzle velocity of 11 m/sec. The particle-liquid slip velocity appears to be on the order of 3 m/sec although this region could be influenced by the developing flow of the jet. Assuming any light region that exceeded the medium particle size by more than six particles denotes clusters, cluster velocities could also be determined. Cluster velocities were measured to be approximately 3.3 m/sec with a standard deviation of 1.7 m/sec.

Figure 6 provides black and white images from video captured in the jet using a modified borescope. Figure 6a shows a particle agglomerate or cluster captured approximately 20 cm from the nozzle face. Figure 6b shows a cluster capture at about 5 cm from the nozzle face. The clusters shown in Figure 6 are representative of clusters observed during the studies. However, a statistically significant collection of clusters was not achieved due to data acquisition limitations. It did appear that clusters near the nozzle were on order of 20 to 30 particles in size which reduced to 5 to 10 particles in size further away from the nozzle. Clusters near the nozzle also appear to contain more liquid than clusters present further downstream from the nozzle tip.

Figures 2 and 6 suggest that there may be a clustering and agglomeration mechanism involved with liquid injection into a fluidized bed. As shown in Figure 2, the boundary layer around the jet is not completely stable as large regions of liquid and solids shed off (due to the hydrodynamics of the bed), which could be a precursor to large agglomerates. Inside the jets, smaller clusters form but seem to break up as they progress along the jet. It did not appear that these smaller clusters were responsible for the larger agglomerates observed in Figure 2. Hence, the distinction in terminology with cluster and agglomerates.

The larger agglomerates from the destabilization of the boundary layer may pose a challenge in fluidized bed operation. Such agglomerates could collect at the bottom of the bed (perhaps causing defluidization), or in the case of Fluid Coker™, cause fouling of the downstream stripper at the bottom of the bed. There are two possible methods for reducing the formation of the large agglomerates: (i) stabilize the boundary layer, or (ii) completely destabilize the boundary layer. A stabilized boundary layer does not seem realistic in the dynamic environment of a fluidized bed, especially commercial fluidized beds. Thus, complete destabilization of the boundary layer appears to be the most promising option. Fortunately, this may be possible by increasing the solids volume fraction in the jet such that more particles are coated by the liquid. In that case, the jet hydrodynamics would be due more to particle dynamics than liquid dynamics.

The coaxial tube or draft tube designs noted in McMillan et al. (7) may promote the required lower liquid to solids ratio. McMillan et al. (7) experimentally showed that a draft tube could lead to a 20% reduction in the liquid-solid ratio in a jet. The Paugatch et al., model (14) with surface tension also showed this trend but to a lesser degree. The high-speed images captured in this study suggest that the placement of this draft tube is a key parameter and that it should be located closer to the nozzle face in order to enhance the entrainment of solids into the liquid jet and provide optimal mixing. Imagine analysis data of the near jet region suggest that almost 50% solids can be incorporated into the jet, assuming that the jet can handle emulsion densities similar to that in a fluidized bed.

SUMMARY

A high-speed video study with a modified borescope was used to study the jet hydrodynamics for liquid injection into a fluidized bed. Both a macroscopic view and a microscopic view of the jet were employed. Video images revealed that liquid injection into a fluidized bed, at least that from a fifth-scale nozzle used in this study, is dominated by liquid motion resulting from surface tension. Atomization did not seem to have an impact unlike the behavior typically reported (9,10) for the leaner particle concentrations of a riser. Individual liquid droplets were not observed in this study, and the images captured most closely resemble the mechanism described by Bruhns and Werther (1). Thus, it is unlikely that the models used for describing jet hydrodynamics or penetration for liquid injection into a riser are applicable in a fluidized bed unless surface tension, in some form, is captured.

The role of surface tension seems to be that it promotes an almost impenetrable boundary layer around the jet beyond the nozzle face. If particles are not incorporated into the jet near the nozzle face, it is unlikely that additional particles are going to be incorporated into the jet due to this boundary layer. Instabilities in this boundary layer seem to lead to shedding of relatively large regions of liquid and solids, which in a commercial system could result in significant agglomeration issues. Smaller agglomerates were observed in the jet but, at least in the cold flow study, and break up into smaller size as the agglomerates traveled along the jet. These smaller agglomerates did not appear to be linked to the larger agglomerates shedding from the boundary layer.

The nozzle improvements proposed by House et al, (6) and later by McMillan (7) appear to have merit. However, the location of this coaxial tube or draft tube appears to be a key design parameter. The high-speed video images in this study suggest that such a tube should be located close to the nozzle face to promote more particle entrainment into the jet and to provide optimal liquid-solid mixing. Image analysis results of the solids volume fraction in the jet and in the bed suggest additional entrainment may be possible.

ACKNOWLEDGEMENTS

The authors would like to thank Alexander Mychkovsky and Steve Ceccio of the University of Michigan for their help with consultation in the development of the borescope. The authors also thank Frank Shaffer from the National Energy Technology Lab and the Department of Energy for his guidance in high-speed video operation.

REFERENCE

1. Bhruns, S., Werther, J., 2005. An Investigation of the Mechanism of Liquid Injection into Fluidized Beds. AIChE J. 51, 766-775.
2. Ariyapadi, S., Berruti, F., Briens, C., McMillan, J., Zhou, D., 2004. Horizontal penetration of gas–liquid spray jets in gas–solid fluidized beds. Int. J. Chem. Reactor Eng. 2, A22.
3. Ariyapadi, S., Berruti, F., Briens, C., Knapper, B., Skwarok, R., Chan, E., 2005. Stability of horizontal gas–liquid sprays in open-air and in a gas–solid fluidized bed. Powder Technology. 155, 161–174.
4. Pougatch, K., Salcudean, M., McMillan, J., 2012, Three-dimensional numerical modeling of interactions between a gas-liquid jet and a fluidized bed, Chem. Eng. Sci., 68, 258-277.
5. Gray, M.R., Le, T., McCaffrey, W.C., Berruti, F., Soundararajan, S., Chan, E., Huq, I., Thorne, C., 2001. Coupling of mass transfer and reaction in coking of thin films of an Athabasca vacuum residue. Ind. Eng. Chem. Res. 40, 3317–3324.
6. House, P.K., Saberian, M., Briens, C.L., Berruti, F., Chan, E., 2004. Injection of a liquid spray into a fluidized bed: particle–liquid mixing and impact on fluid coker yields. Ind. Eng. Chem. Res. 43, 5663–5669.
7. McMillan, J., Zhou, D., Ariyapadi, S., Briens, C., Berruti, F., 2005. Characterization of the contact between liquid spray droplets and particles in a fluidized bed. Ind. Eng. Chem. Res. 44, 4931–4939.
8. Base, T., Chan, E., Kennett, R., Emberley, D., 1999. Nozzle for Atomizing Liquid in Two Phase Flow. United States Patent # 6003789.

9. Cocco, R., Shaffer, F., Hays, R., Karri, S. & Knowlton, T., 2010, Particle clusters in and above fluidized beds. Powder Technology 203, 3–11.
10. Rottier, C., Godard, G., Corbin, F., Boukhalfa, A. M. & Honoré, D., 2010, An endoscopic particle image velocimetry system for high−temperature furnaces. Meas. Sci. Technology. 21, 115404.
11. Okasha, F., Miccio, M., 2006. Modelling of wet jet in fluidized bed. Chem. Eng. Sci. 61, 3079–3090.
12. Nayak, S.V., Joshi, S.L., Ranade, V.V., 2005. Modeling of vaporization and cracking of liquid oil injected in a gas–solid riser. Chem. Eng. Sci. 60, 6049–6066.
13. Gao, J., Xu, C., Lin, S., Yang, G., Guo, Y., 2001. Simulations of gas–liquid–solid 3-phase flow and reaction in FCC rise reactors. AIChE J. 47, 677–692.
14. Li, T., Pougatch, K., Salcudean, M., Grecov, D., 2010. Numerical simulation of an evaporative spray in a gas–solid crossflow. Int. J. Chem. Reactor Eng. 8, A43.