AIChE

Enhancement of the Liquid Feed Distribution in Gas-Solid Fluidized Beds by Nozzle Pulsations (Induced by Solenoid Valve)

Rana Sabouni, Aidan Leach, Cedric Briens, and Franco Berruti
Faculty of Engineering, Institute for Chemical and Fuels from Alternative Resources (ICFAR),University of Western Ontario, London, ON, Canada N6A 5B9

DOI 10.1002/aic.12538
Published online February 28, 2011 in Wiley Online Library (wileyonlinelibrary.com).

In this work, it was found that spray nozzles pulsations greatly improved the liquid feed spray distribution on fluidized bed particles. Pulsating a spray nozzle doubled its nozzle performance index at various operating conditions. The objective of this study was to impose fluctuations of well-defined frequency and amplitude on the liquid spray to investigate potentially beneficial effects of fluctuations on the liquid feed distribution on the particles in the fluidized bed. Three sets of experiments were conducted to study the quality of the spray jet-bed interaction using a conductance probe method. The jet penetration for each experiment was calculated theoretically. © 2011 American Institute of Chemical Engineers *AIChE J*, 57: 3344–3350, 2011
Keywords: pulsations, liquid and gas flowrates, nozzle performance index, air to liquid ratio (ALR), fluidized bed

Introduction

Many industrial applications use liquid injection into fluidized beds of solid particles, such as fluid catalytic cracking, fluid coking, and gas phase polymerization. In these applications, the reactor yield depends on the effectiveness of the liquid distribution on the bed particles. Therefore, it is of crucial importance to study the mechanism of liquid injection into fluidized beds to minimize the formation of undesired agglomerates, and thus, prevents mass and heat transfer limitations and maximize the yield of valuable product.

In the above processes, liquid feed is injected into the fluidized bed with gas atomization nozzles. Ariyapadi et al.[1] and Bruhns and Werther[2] demonstrated that liquid sprayed into a gas-solid fluidized bed typically forms liquid-solid agglomerates. Using X-ray imaging showed that agglomerates formed at the tip of the spray jet cavity.[1] Agglomerates survivability is affected by fluidized bed hydrodynamics and material properties.[3,4] Heat and mass transfer are influenced by agglomerates formation and survivability and, if the fluidized bed mixing is not intense enough, agglomerates survive for a relatively long time. As a consequence, a portion of the injected liquid becomes trapped within such agglomerates, and its conversion is negatively affected by mass and heat transfer limitations.[5]

Many researchers focused on studying the parameters affecting the interaction between gas-liquid jets and fluidized beds to minimize the undesired agglomerates and maximize mass and heat transfer, thus making the unit more efficient and profitable. Knapper et al.[6] showed that the quality of the interaction between the gas-liquid jet and the fluidized bed is strongly impacted by nozzle performance. Portoghese et al.[7] studied the use of triboelectric probe to characterize the performance of gas atomization nozzles injecting liquid into a gas-solid fluidized bed. However, using triboelectric probes measure the current generated by the collisions of bed particles with the electrodes and are too sensitive to the local bed hydrodynamics. Portoghese et al.[8] developed another method that is much less sensitive to the local hydrodynamics to evaluate the nozzle performance. It is based on

Correspondence concerning this article should be addressed to C. Briens at cbriens@uwo.ca.

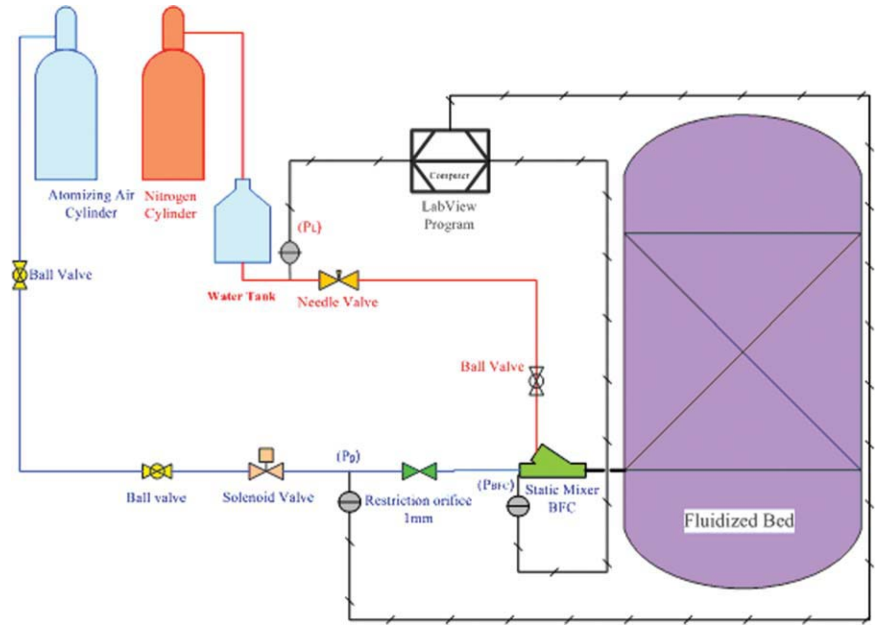

Figure 1. Schematic diagram of experimental apparatus.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

measuring the electrical conductance of the bed solids after completing the liquid injection and defluidizing the wetted particles. If most of the injected liquid is concentrated in a few agglomerates, most of the bed is dry and the bed conductance is small. Conversely, if the liquid is well distributed on the particles, forming a liquid film on the particles surface that connects all the particles, the bed conductance is large.

Leach et al.[9] improved both methods from Portoghese et al.[7,8] Their study showed that increasing the liquid flow rate or reducing the nozzle size enhanced its spraying performance in the fluidized bed. Moreover, House et al.[10] demonstrated that both the nozzle internal geometry and internals have a strong impact on the quality of the liquid-solid contact.

Ariyapadi et al.[11] developed a correlation to predict the horizontal jet penetration of gas-liquid sprays jets in a gas-solid fluidized beds by combining both a theoretical model to predict the momentum flux of two phase sprays with a correlation from Benjelloun et al.[12] for the penetration of gas jets. They found that their correlation predicted values that were in a good agreement with the experimental data.

The objective of this study was to impose fluctuations of well-defined frequency and amplitude on the liquid spray, and measure the resulting effect on the interactions between the gas-liquid jet and the fluidized particles and, consequently, on the effectiveness of the liquid feed distribution throughout the bed. Chan et al.[13] assumed that stable, non-pulsating sprays are required for optimal reactor operation and showed that, in a pilot plant fluid coker, a stable spray provided higher liquid yields and lower sulfur dioxide emissions than a strongly pulsating spray. McDougall et al.[3] found that a pulsating spray reduced bed fluidity and promoted the formation of agglomerates. The basic assumption of the current study is that, contrarily to those preliminary findings, well-designed spray pulsations may actually enhance the liquid-solid contact, by disrupting the region, near the tip of the jet, where the wet agglomerates form. Investigating the application of pulsating nozzles can, thus, be used to improve fluid bed coking operations through the enhancement of the contact of injected liquid bitumen with hot fluidized coke particles.

Apparatus

The experimental apparatus, shown in Figure 1, consists of:

(1) A fluidized bed with a rectangular cross-section of 1.2 m by 0.15 m. It was filled with 250 kg of silica sand particles with a Sauter mean diameter of 190 μm and an apparent particle density of 2600 kg/m^3 (Group B of the Geldart's powder classification). Air at a superficial gas velocity of 0.24 m/s was used to fluidize the bed.

(2) The air stream was supplied from a medical air cylinder, and regulated by a pressure transducer, solenoid valve and 1 mm restriction orifice. A pressure transducer was used to measure the pressure (P_g) upstream of the 1 mm restriction orifice. To induce pulsations in the liquid spray, a solenoid valve was introduced in the air stream, just upstream of the restriction orifice (Figure 1). A 70 mm long section of 6.4 mm diameter line between the solenoid valve and the restriction orifice provided a volume that acted as a capacitance, to dampen the gas flow fluctuations induced by the opening and closing of the valve. This solenoid valve was controlled by a function generator using the circuit shown in Figure 3. By opening and closing the gas line (because of the opening and closing of the solenoid valve), the gas-to-liquid ratio is no longer held constant, and the fluctuations in gas pressure in the line cause the water flowrate to also change. This induces the pulsations whose effects were

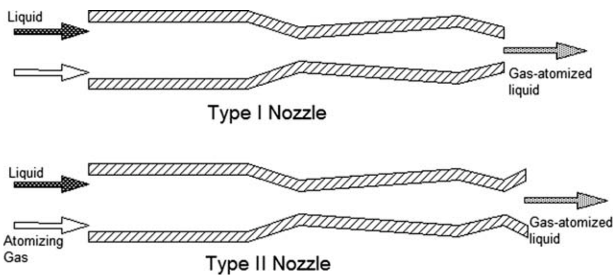

Figure 2. Internal geometry of Type I nozzle and Type II nozzle.

investigated in this study. The frequency of pulsation was fast enough that the gas flowrate never decreased to zero, as there was still a release of gas from the region between the solenoid valve and the restriction orifice governing the gas flowrate.

(3) The injected liquid stream was deionized water. The water tank was pressurized by a nitrogen cylinder and a pressure transducer measured the pressure (P_L) upstream of the needle valve.

(4) A premixer of the gas and liquid streams, where the pressure (P_{BFC}) was measured with a pressure transducer.

(5) A spray nozzle. Two spray nozzles were used for comparison in this study (Type I nozzle and Type II Nozzle) as illustrated in Figure 2. The first one had throat diameters of 1.6 mm. The second one had the same internal geometry as Type I, except for a deviated section located downstream of the second throat. Both types of nozzles were developed Portoghese et al.[14] The spray nozzle was located 0.6 m above the fluidization gas distributor and protruded into the bed for 0.05 m from the wall. Past studies showed that the spray jet did not interact with the column walls.[15]

All pressure transducers were calibrated and connected to a data acquisition system to measure the pressure drops across the air restriction orifice (P_g-P_{BFC}), and across the liquid needle valve (P_L-P_{BFC}), from which the instantaneous gas and liquid flowrates to the premixer could be determined.

The time-averaged liquid flowrate was controlled by using a pressure regulator placed on the nitrogen cylinder to adjust the liquid tank pressure. In most of the experiments of this study, the time-averaged liquid flowrate was held constant at 0.022 kg/s. The time-averaged air flowrate was controlled using the pressure regulator placed upstream of the restriction orifice.

The temperature of the bed was measured using four thermocouples, placed in the bed to ensure that the bed temperature was 20°C at the start of each injection. All the thermocouples were type J and placed in the bed at heights of 15, 35, 55, and 75 cm above the gas distributor.

A function generator was used to control the solenoid valve frequency (0–10 Hz) and to create a sinusoidal waveform with a 6.7 RMS voltage. Figure 3 shows the circuit diagram used in the experiments.

Based on the previous work of,[8] the bed conductivity can be measured by applying a sinusoidal current to the fluidized bed and measuring the voltage drop across the fluidized bed. This particular technique was also used in the current work. The conductivity of the bed was measured using an electrode which was placed at the centre of the bed, 0.37 cm above the gas distributor and penetrated 0.65 m into the bed. The electrode was made of a stainless steel hollow tube with an outer diameter of 7 mm. It was connected to a 51 kΩ resistor. Figure 4 shows the schematic diagram of the electrode circuit. The voltage imposed by the signal generator was used with the voltage measured across the resistor to calculate the bed conductance using Ohm's law:

$$G_{\text{bed}} = \frac{1}{R_{\text{bed}}} = \frac{1}{R_m} * \left[\frac{V_2}{V_1 - V_2}\right] \tag{1}$$

A data acquisition system was used to measure the voltage V_1 imposed by the signal generator, the voltage V_2 across the resistor, and the temperature of the four thermocouples, at a frequency of 1000 Hz.

Experimental Procedure

The objective of the conducted experiments was to study the effects of spray nozzle pulsations on the jet-bed interaction, which was characterized by a nozzle performance index (NPI). The NPI characterized the quality of the interaction between injected liquid and bed solids.[9,10]

A common experimental procedure was used for all experiments:

(1) The fluidization air velocity was set to 0.25 m/s. The bed was fluidized for several minutes to reach steady-state.

(2) The needle valve opening was set fully open in all the experiments.

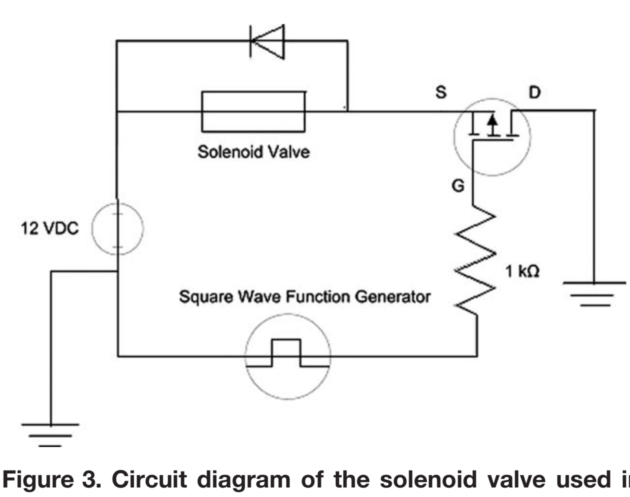

Figure 3. Circuit diagram of the solenoid valve used in the experiments.

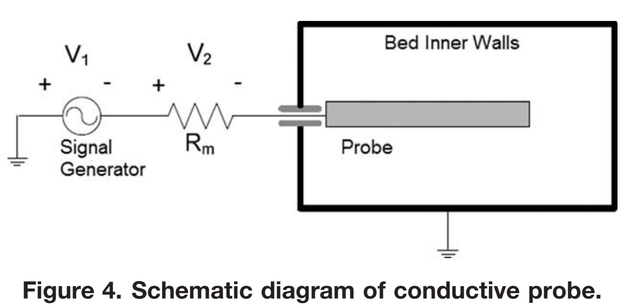

Figure 4. Schematic diagram of conductive probe.

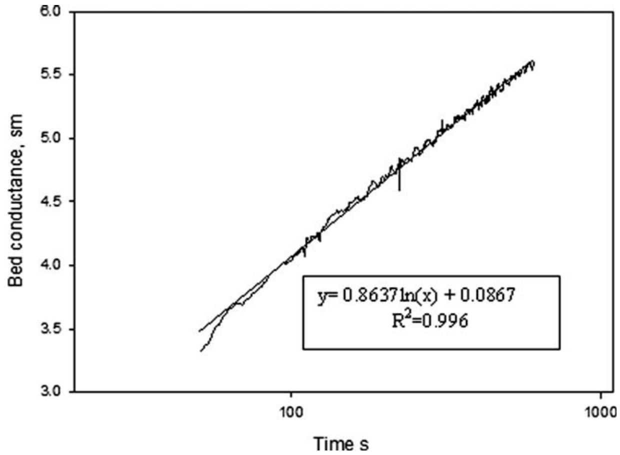

Figure 5. Conductance method, 1 Hz, fully open needle valve, Type I nozzle D = 1.66 mm, F_L = 0.022 kg/s, 1 mm restriction orifice, 1.7 ALR%, V_{air} = 14 cm^3.

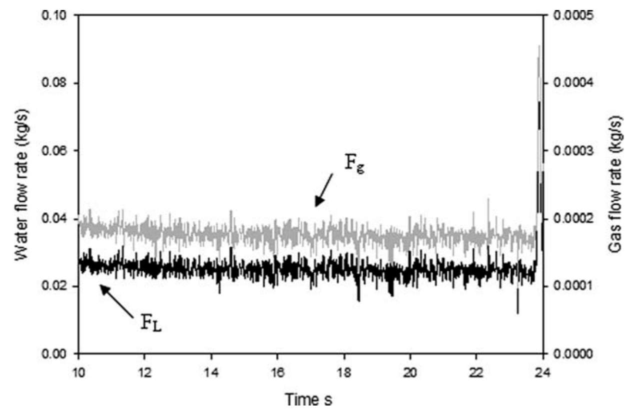

Figure 6. Liquid flowrate and gas flowrate as function of time, 0 Hz, fully open needle valve, Type I Nozzle D = 1.66 mm, F_L = 0.022 (kg/s), 1 mm restriction orifice, 1.7 ALR%, Air, V_{air} = 14 cm^3.

(3) At t = 0, the data acquisition was started using the LabView program (version 8, National instruments)

(4) Simultaneously, the solenoid valve was switched on and pulsated at the desired frequency for 15 s.

(5) At t = 10 s, water was injected into the bed through the spray nozzle. The duration of the water injection was 15 s.

(6) At t = 25 s, the liquid injection, fluidization air, and solenoid valve were stopped, and the bed was defluidized for 7 minutes. Conductivity measurements were performed during these 7 minutes. The conductance of the fluidized bed solids were measured by the conductance probe during the 7 minutes of defluidizing as developed by Leach et al.[9] Taking the conductivity measurements during defluidization gave better results because of reduced signal fluctuations and electrical noise.

(7) At t = 7 min the bed was refluidized again to dry it by vaporizing the injected water and to ensure that the bed temperature returned to its initial value of 20°C before starting a new experiment. In addition, refluidizing the bed caused the agglomerates to break up and, therefore, facilitated the drying.

The injection time was kept constant at 15 seconds in all of the experiments to ensure that the mass of injected liquid was always the same, since the liquid mass flowrate was maintained at 0.022 kg/s. The air to liquid ratio (ALR) was maintained constant for each run. The tests were repeated for different frequencies, using the same conditions. The pressure values for the premixer (P_{BFC}), liquid (P_L), and air (P_g) streams were recorded during each experiment.

As a last step, a plot of bed conductance vs. time was used to estimate the NPI, which is defined as the slope of the trend-line of that plot, using a logarithmic scale for time. This method was developed by Leach et al.[9] A high NPI value means that water diffuses quickly through the defluidized bed, increasing the bed conductance quickly. A high NPI therefore corresponds to a good original distribution of the liquid on the bed particles, just before defluidization. To ignore any irregularities in the start-up of the defluidization, only data subsequent to t = 50 s were used. Figure 5 shows an example of the change with time of the conductance of the defluidized bed. In the case corresponding to Figure 5, the NPI was 0.8637.

Result and Discussion

Effect of frequency

Figures 6 and 7 show the variations with time of the liquid and gas flowrates for two different operating conditions as follows: the data illustrated in Figures 6 and 7 have the same liquid flowrate of 0.22 kg/s but different frequencies of 0 and 1 Hz, respectively. The jet penetration was calculated using the model from Ariyapadi et al.,[11] using the measured instantaneous liquid and gas flowrates (Figures 6 and 7).

Figure 8 demonstrates the effect of changing the nozzle fluctuation frequency on the NPI. Each point in the figure represents an average of three replicates under the same conditions (1.7% ALR and F_L = 0.022 kg/s) and the 95%

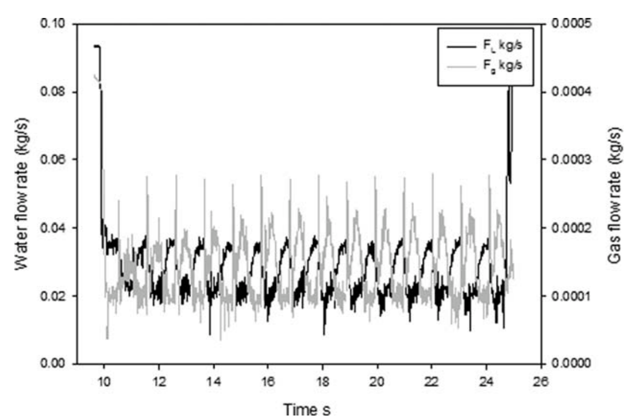

Figure 7. Liquid flowrate and gas flowrate as function of time, 1 Hz, fully open needle valve, Type I Nozzle D = 1.66 mm, F_L = 0.022 (kg/s), 1 mm restriction orifice, 1.7 ALR%, Air, V_{air} = 14 cm^3.

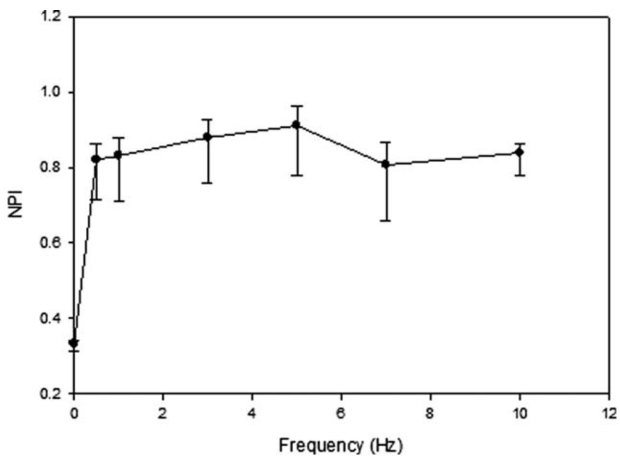

Figure 8. Effect of frequency on NPI, fully open needle valve, Type I nozzle D = 1.66 mm, 1.7% ALR, F_L = 0.022 kg/s, Air, V_{air} = 14 cm^3, 1 mm orifice restriction, 95% Confidence intervals.

confidence intervals are shown. It is obvious that there is a huge positive impact of pulsations on the NPI, with pulsations more than doubling the NPI. The detailed explanation for this phenomenon is discussed later in this article.

Figure 9 shows the effect of changing the ALR on the NPI as a function of frequency of the nozzle pulsations. Each point is obtained from the average of three tests performed under the same operating conditions. Standard deviation error bar was used to show the error for the three different runs. The error bars of Figure 9 show that one can not differentiate the effect of frequencies above 1 Hz because of the small number of experimental replicates. However, in all cases it is clear that pulsations always improve the NPI.

Figure 10 shows that, as a result of the pulsations, the jet penetration moves rapidly back and forth. Since the wet agglomerates form at the jet tip, this back and forth motion

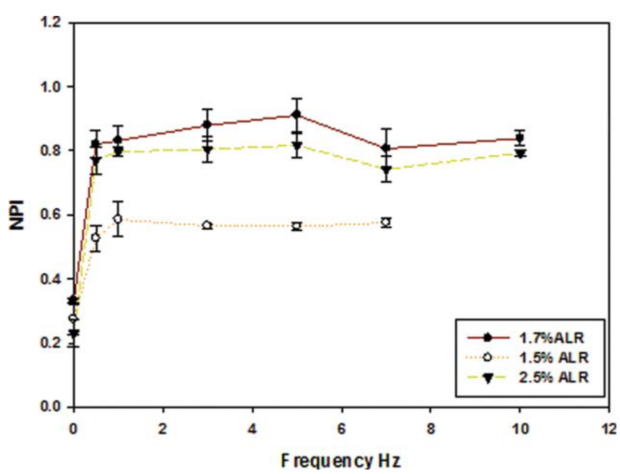

Figure 9. Effect of frequency on NPI, fully open needle valve, Type I nozzle D = 1.66 mm, F_L = 0.022 kg/s, Air, V_{air} = 14 cm^3, 1 mm orifice restriction.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

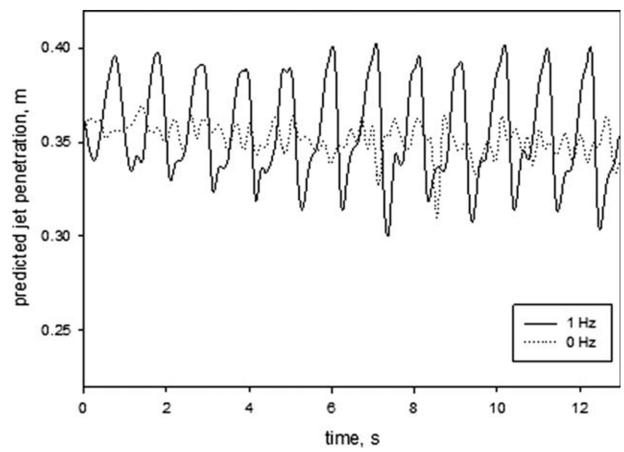

Figure 10. Predicted jet penetration for both no imposed pulsation and imposed pulsation effect., F_L = 0.022 kg/s, 1.7% ALR, fully open needle valve, Type I nozzle D = 1.66 mm, 1 mm restriction, air, V_{air} = 14 cm^3.

has two impacts: it distributes the liquid over more bed solids than a stable jet and it disrupts the agglomerates. When compared to a stable jet, a pulsating jet thus creates dryer and weaker agglomerates that are more likely to break up, which promotes further dispersion of the liquid on the bed particles.

Figure 11 illustrates the effect of changing the ALR on the NPI for various solenoid valve frequencies. Each point in the figure is the average of three tests under the same operating conditions. It is clear that the ALR of 1.7% corresponds to the highest NPI values, with and without pulsations. Below an ALR of 1.7%, the spray quality improved with increasing ALR, as expected. Above ALR of 1.7%, the nozzle flow regime changed and increasing the ALR did not bring any further benefit. For all ALRs and flow regimes, imposing pulsations greatly improved the NPI.

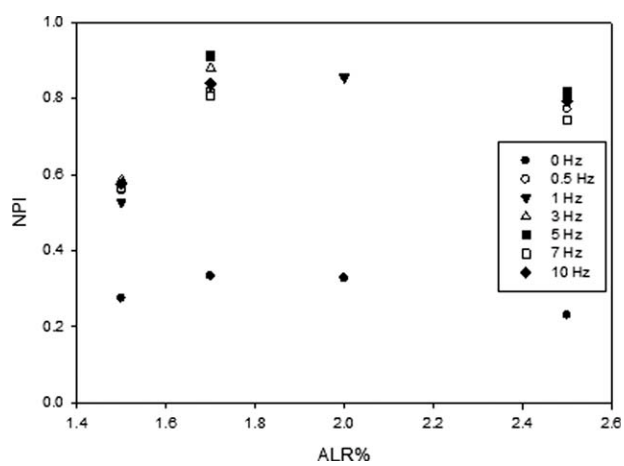

Figure 11. Effect of changing ALR% on NPI, fully open needle valve, F_L = 0.022 (kg/s), Type I nozzle D = 1.66 mm, air, V_{air} = 14 cm^3, 1 mm restriction orifice.

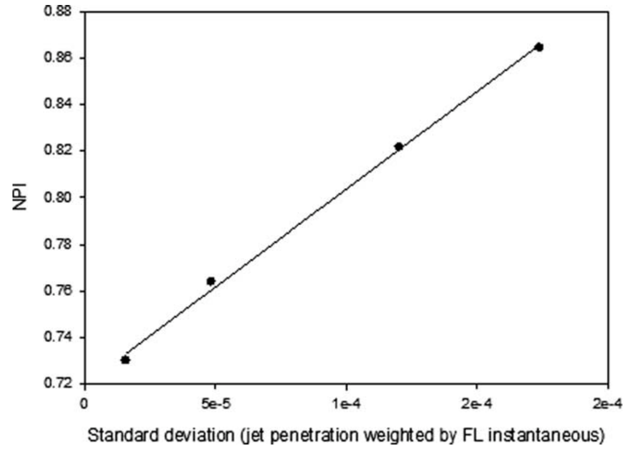

Figure 12. Effect of changing air line volume on NPI, 1 Hz, fully open needle valve, Type I nozzle D = 1.66 mm, F_L = 0.022 (kg/s), 1 mm restriction orifice, 1.7% ALR, air, V_{air} = 14 cm^3.

Optimizing the pulsation amplitude

The air line volume, between the solenoid valve and the restriction orifice (Figure 1) was changed to study the effect of pulsation amplitude on the NPI. The average liquid and gas flowrates were held constant. The effects of four different air line volumes are compared in Figure 12. To characterize the impact of the air line volume on the pulsations, the instantaneous jet penetration was calculated from the measured instantaneous air and liquid flowrates, using the method from.[11] To attain a better understanding of the effect of these pulsations, the standard deviation of the jet penetration weighted with the instantaneous liquid flow rate was calculated. According to Figure 12, there is a linear relationship between the standard deviation of the jet penetration weighted with the instantaneous liquid flow rate and the NPI, with $R^2 = 0.9977$.

Other conditions

The effect of pulsations on the interaction between gas-liquid jet and fluidized bed particles was studied under three different conditions to establish whether pulsations were beneficial over a wide range of conditions.

Effect of Liquid Flow Rate. To study the effect of changing liquid flowrate on the NPI, six experiments were conducted under different liquid flow rates but at the same ALR (1.7%) and air line volume (14 cm^3). For three different liquid flowrates (0.019, 0.022, and 0.026 kg/s), experiments were conducted with pulsations of 1 Hz and with no pulsations. The results of these experiments are summarized in Figure 13. It is clear that pulsations have a dramatic impact on NPI for all liquid flowrates.

Effect of Nozzle Geometry. The effect of changing the nozzle geometry on NPI was investigated using both the Type I nozzle and the Type II nozzle. Several experiments were conducted for the two types of spray nozzles at constant liquid flowrate of 0.022 kg/s and (ALR) of 1.7%. Figure 14 confirms that pulsations are beneficial with different spray nozzle geometries.

Effect of Atomization Gas Properties. Two atomization gases were utilized to determine how gas properties affect the impact of pulsations on NPI. These two gases were air and a mixture of 18 mol % helium and 82 mol % nitrogen (this composition of mixed gas was used in the course of

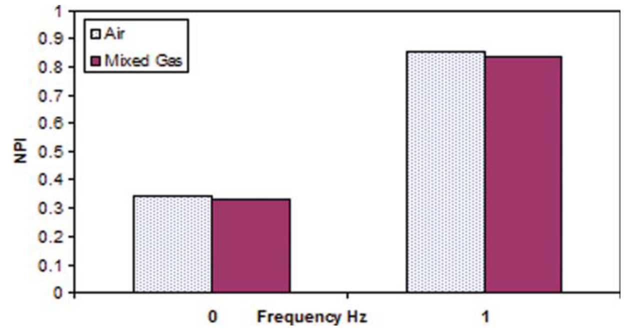

Figure 14. Effect of nozzle geometry on NPI, fully open needle valve, F_L = 0.022 kg/s, 1.7%, V_{air} = 14 cm^3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

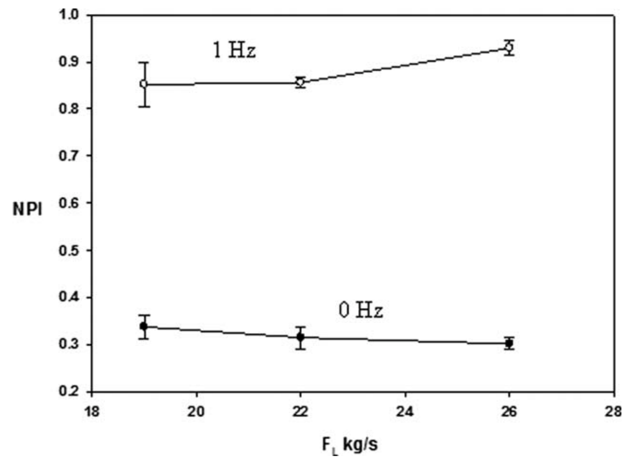

Figure 13. Effect of liquid flowrate on NPI, fully open needle valve, Type I nozzle D = 1.66 mm, 1.7% ALR, Air, V_{air} = 14 cm^3.

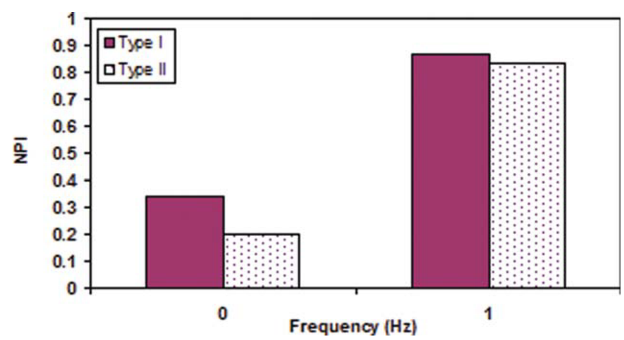

Figure 15. Effect of gas properties on NPI, fully open needle valve, TEB nozzle D = 1.6 mm, V_{air} = 14 cm^3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

experiments because it has the same viscosity of steam at 300°C used in fluid coker and to match the density and the speed of sound). Figure 15 shows that pulsations greatly improved the NPI with both gas types.

Conclusions

This study investigates the effect of imposing fluctuations of well-defined frequency, on the interactions between a gas-liquid spray jet and fluidized particles. It was found that pulsations doubled the value of a NPI for three different ALR. Changing the amplitude of the pulsations showed that the pulsations improve the liquid-particles contact through complex mechanisms that require further investigation. The strong, beneficial effect of pulsations on liquid-particles contact was confirmed over a variety of operating conditions such as different liquid flow rates, gas properties and spray nozzle geometry.

Acknowledgments

The authors wish to express their appreciation to Syncrude Canada Ltd. and the Natural Science and Engineering Research Council (NSERC) of Canada for financial support and technical advice. They also would like to acknowledge the assistance of the Engineering Stores and the University Machine Services (UMS) at the University of Western Ontario.

Notation

ALR = air to liquid mass ratio
d_{sm} = Sauter mean diameter of droplets (μm)
G_{bed} = electrical conductance of fluidized bed (mS)
i = electrical current traveling through probe/bed (A)
NPI = nozzle performance index (-)
P_g = pressure of upstream restriction orifice (Psi)
P_L = pressure of the upstream needle valve (Psi)
R_{bed} = electrical resistance of fluidized bed (Ω)
R_m = resistance of resistor (kΩ)
t = elapsed time of test
V_1 = voltage measured across function generator (V)
V_2 = voltage measured across resistor (V)
V_g = voltage of the air pressure transducer (V)
V_{BFC} = voltage of the BFC pressure transducer (V)
V_L = voltage of the liquid pressure transducer (V)

Literature Cited

1. Ariyapadi S, Holdsworth D, Norley C, Berruti, F, Briens C. Digital X-ray imaging technique to study the horizontal injection of gas-liquid jets into fluidized beds. *Int J Chem React Eng*. 2003; 1.
2. Bruhns S, Werther J. An investigation of the mechanism of liquid injection into fluidized beds. *AIChE J*. 2005;51:766–775.
3. McDougall SL, Saberian M, Briens C, Berruti F, Chan EW. Characterization of fluidization quality in fluidized beds of wet particles. *Int J Chem React Eng*. 2004; 2.
4. Weber S, Briens C, Berruti F, Chan E, Gray M. Agglomerate stability in fluidized beds of glass beads and silica sand. *Powder Technol*. 2006;165:115–127.
5. House PK, Saberian M, Briens C, Berruti F, Chan E. Injection of a liquid spray into a fluidized bed: particle-liquid mixing and impact on fluid coker yields. *Ind Eng Chem Res*. 200;43:5663–5669.
6. Knapper BA, Gray MR, Chan EW, Mikula R. Measurement of efficiency of distribution of liquid feed in a gas-solid fluidized bed reactor. *Int J Chem React Eng*. 2003; 1.
7. Portoghese F, Berruti F, Briens C, Chan E. Novel triboelectric method for characterizing the performance of nozzles injecting gas-atomized liquid into a fluidized bed. *Chem Eng Process: Process Intensification*. 2007;46:924–934.
8. Portoghese F, House P, Berruti F, Briens C, Adamiak K, Chan E. Electric conductance method to study the contact of injected liquid with fluidized particles, *AIChE J*. 2008;54:1770–1781.
9. Leach A, Portoghese F, Briens, C, Berruti F. A new and rapid method for the evaluation of the liquid-solid contact resulting from liquid injection into a fluidized bed. *Powder Technol*. 2008;184:44–51.
10. House PK, Briens C, Berruti F, Chan E. Effect of spray nozzle design on liquid-solid contact in fluidized beds. *Powder Technol*. 2008;186:89–98.
11. Ariyapadi S, Berruti F, Briens C, McMillan J, Zhou D. Horizontal penetration of gas-liquid spray jets in gas-solid fluidized beds. *Int J Chem React Eng*. 2004; 2.
12. Benjelloun F, Liegeois R, Vanderschuren J. Penetration length of horizontal gas jets into atmospheric fluidized beds. In: Large J-F, Laguerie C, editors. *Proceedings of the Fluidization-VIII*, Engineering Foundation, NY, 1995:239–246.
13. Chan EW, Base TE, McCracken T. Design and development of syncrude coker feed nozzles: a coker 2000 initiative. Syncrude Canada Technical Report. 2001.
14. Portoghese F, Ferrante L, Berruti F, Briens C, Chan E. Effect of injection-nozzle operating parameters on the interaction between a gas-liquid jet and a gas-solid fluidized bed. *Powder Technol*. 2008;184:1–10.
15. Berruti F, Dawe M, Briens C. Study of gas-liquid jet boundaries in a gas-solid fluidized bed. *Powder Technol*. 2009;192:250–259.

Manuscript received July 14, 2010, revision received Sept. 26, 2010, and final revision received Dec. 21, 2010.