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The Effects of Liquid Properties and Bed Hydrodynamics on the Distribution of Liquid on Solid Fluidized Particles in a Cold-Model Fluidized Bed

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ABSTRACT

Uniform distribution of liquid feed on fluidized particles increases the yield of valuable products and improves operability in processes such as Fluid Coking™ and Fluid Catalytic Cracking. The liquid properties and local bed hydrodynamics have a strong impact on the contact between the injected liquid and the bed particles. Several publications addressed parameters which affect the formation of undesired solid-liquid agglomerates, such as fluidization velocity, nozzle geometry, ratio of atomization gas to liquid. In this study, the effect of viscosity, wettability, fluidization velocity and atomization gas flowrate on the distribution of liquid feed sprayed into a fluidized bed was investigated with a reliable and fast response capacitance meter. This method was extended to monitor the gradual agglomerate breakup kinetics.

INTRODUCTION

In Fluid Coking™, heavy oil is injected with a gas-atomization nozzle into a solid-gas fluidized bed of hot coke particles, where it cracks thermally. Improving the contact between injected liquid and fluidized particles boosts the yields of valuable products in these reactors by minimizing the formation of agglomerates (1). The liquid properties and local bed hydrodynamics have a strong impact on the contact between the injected liquid and the bed particles. Changing liquid properties or the local bed hydrodynamics can improve the contact between the liquid and the bed solids to minimize agglomerate formation, which is detrimental to Fluid Coking™. It is essential to increase the free liquid, i.e. the proportion of injected liquid that is not trapped within liquid-solid agglomerates. It is also preferable that the liquid trapped within agglomerates be freed rapidly through agglomerate breakup, before it can have a detrimental effect on the process. Several publications reported that liquid injected into a gas-solid fluidized bed with spray nozzles is present in 2 forms: liquid forming a thin layer around individual particles, which was called “free liquid”, liquid trapped within “agglomerates” (2, 3, and 4). Bruhns et al. (2) and Knapper et al. (4) showed that agglomerates form near the tip of jet cavity of the spray. Knapper et al. (4) also studied the impact of spray nozzle performance on the quality of interaction between gas-liquid jet and fluidized bed particles. Portoghese et al. (5) investigated the effect of atomization gas flow rate, liquid mass flow rate, and size on the performance of gas-atomization nozzles. Leach et al. (6) compared performances of various nozzles using conductance measurement techniques. Portoghese et al. (5) and Leach et al. (6) found that the nozzle spraying performance can be improved by increasing the atomization gas flow rate and reducing the nozzle size.

The objectives of this study include the investigation of the impact of liquid properties, fluidization velocity and atomization gas flow rate on the liquid distribution throughout the bed utilizing a reliable and fast response capacitance meter. This non-invasive method can be used both at room temperature and at high temperature and, in addition, it can be adapted to monitor the gradual agglomerate breakup kinetics.

EXPERIMENTAL

Experimental Setup

The experiments were carried out in a fluidized bed 1.97 m high with a 1.54 m by 0.288 m rectangular cross section (Figure 1b). The fluidization velocity was set with two banks of calibrated sonic orifices and pressure regulators. Three rectangular wooden windows were mounted on each side of the bed walls, to allow for capacitance measurements (Figure 1b).

For most of the experiments, a scaled-down version of an industrial spray nozzle (7) with an internal diameter of 2.2 mm, as shown in Figure 1a, was used for liquid injection. Liquid was mixed with atomization nitrogen gas in a pre-mixer upstream of the spray nozzle. The flow rate of the atomization gas was set with a calibrated sonic orifice and a pressure regulator (Figure 1b).

A different spray nozzle was used for calibration experiments, which was operated at with a very large flow rate of atomization gas and very low liquid flow rate of 2 g/s to optimize the liquid distribution on the fluidized particles, preventing agglomerate formation. This ”ideal nozzle” was a straight cylindrical tube, 3.6 mm in diameter. The ratio of the mass flow rate of atomization gas to the mass flow rate of injected liquid was higher than 50 wt%.

For all the experiments, 430 kg of coke particles with a Sauter mean diameter of 140 µm and a particle density of 1470 kg/m^3 were used. The bed height was approximately 1.1 m when the fluidization velocity was 0.3 m/s. The bed pressure was measured with transducers located at different positions on the bed wall. The bed height and mass were calculated from pressure measurements.

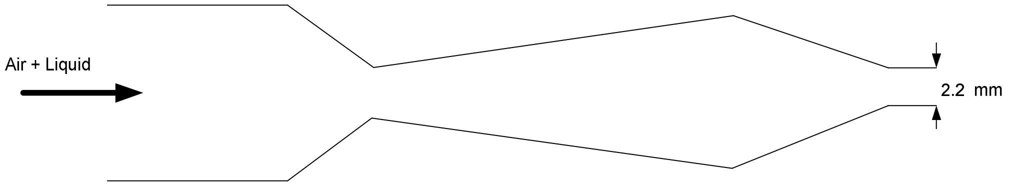

Figure 1a: Injection nozzle

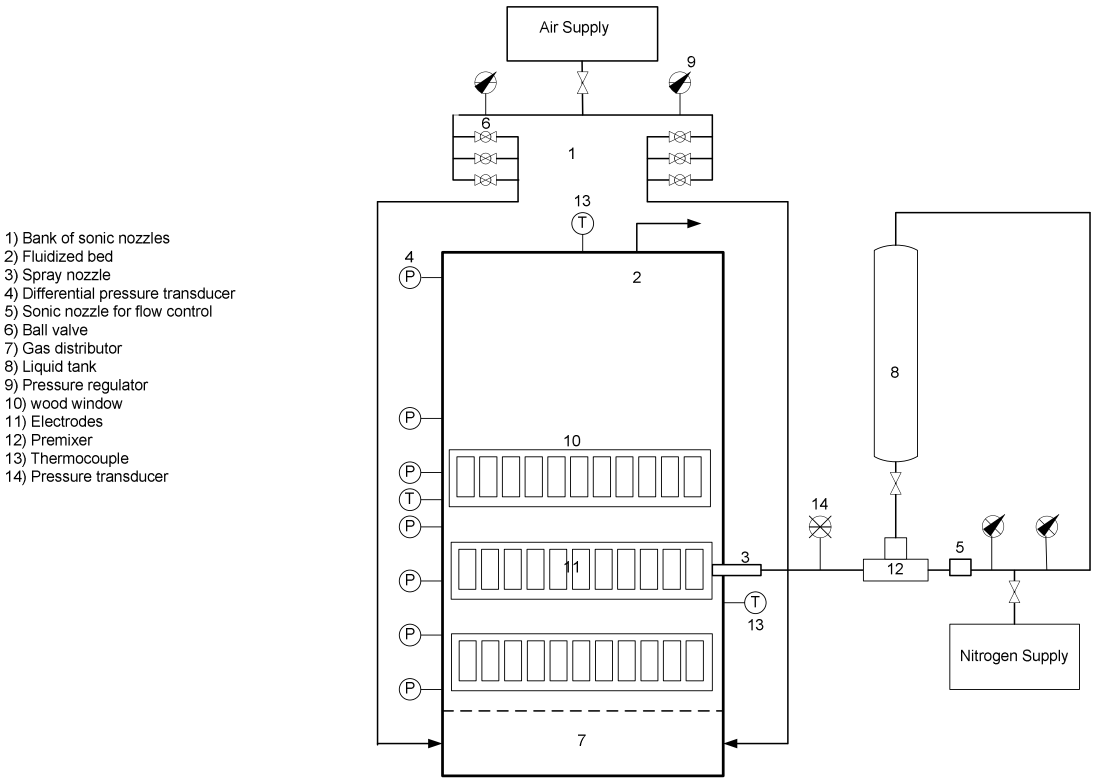

Figure1b: Schematic diagram of experimental setup

Measuring System

In this study, the distribution of liquid on coke particles was measured using capacitance sensors. The results of preliminary experiments carried out in a small box confirmed that the normalized capacitance of a wet bed is a linear function of the free liquid volume fraction. Varsol was used as liquid feed. An advantage of using Varsol as liquid is that its relative permittivity of 3 can be detected with high contrast inside coke particles, which have a relative permittivity of 7.

Thirty two electrodes were installed on the inside of the wooden windows to measure the local bed capacitance (Figure 1b). Each set consisted of 2 opposing electrodes placed at the same location on opposing walls. The measuring circuit was an AC based capacitance meter with a differential noise cancelling system and a sampling frequency of 25 Hz for each electrode.

Calibration Experiments

In calibration experiments, the free liquid level was varied by changing the amount of liquid injected with the “ideal nozzle” that did not form any agglomerates. The calibration experiments provided the capacitance for each electrode for each free liquid level from capacitance measurements. Figure 2 shows the calibration curves for the average of 32 electrodes. This figure shows the normalized capacitance versus the mass ratio of free liquid to total mass of coke (X).

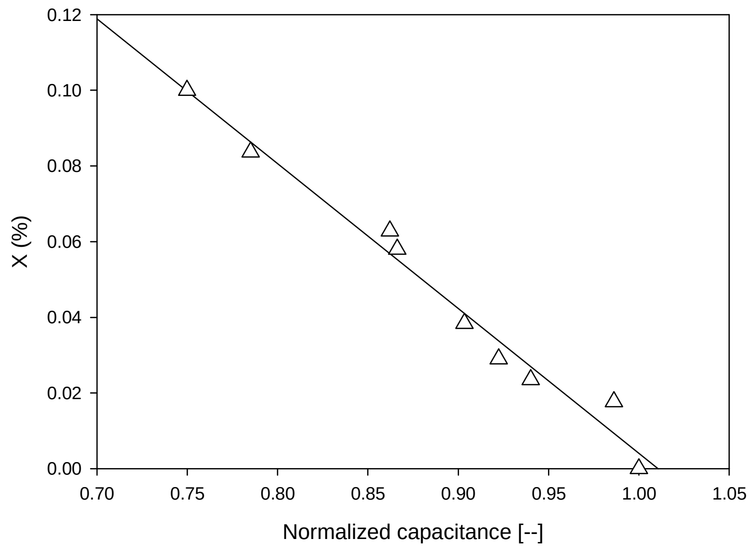

Figure 2: Calibration curve for average of 32 electrodes (with Varsol)

RESULTS AND DISCUSSION

Liquid Properties

The effect of wettability was studied by comparing a non-wettable system (water and coke) with a perfectly wettable system (Varsol and coke). With a ratio of injected liquid to bed solids of 0.13 wt%, no free liquid was detected for the non-wettable system under a variety of operating conditions, while a significant amount of free liquid was always detected with the wettable system.

To investigate the effect of viscosity, binary mixtures of alcohol (e.g. tertbutanol, iso-butanol) and water were used as liquid and coke was used as solid particles. Two mixtures with viscosities of 5 and 4 cp and wettabilities of 44^{O} and 54^{O} were injected. Results indicated that a liquid with a higher viscosity forms more agglomerates. The free liquid after injection at a liquid to solid ratio of 0.63 wt% and a fluidization velocity of 0.1 m/s was 22.5 % for the mixture with a viscosity of 5 cp and 30 % for the mixture with a viscosity of 4 cp.

Bed Hydrodynamics

The impact of atomization gas to liquid ratio and fluidization velocity was studied for the perfectly wettable system of Varsol and coke. Figure 3 shows that the free liquid mass increases with increasing atomization gas-to-liquid-ratio (GLR) for fluidization velocity 0.3 m/s, although there is little increase between 1 and 2 % GLR. To investigate the impact of fluidization velocity some experiments with different fluidization velocities during injection were performed at different GLRs. To analyze the results of these experiments, the fraction of total bed moisture which is distributed as free moisture was plotted versus time after injection using the calibration curves. Figure 4 shows that the amount of free liquid increases substantially with increasing fluidization velocity during injection.

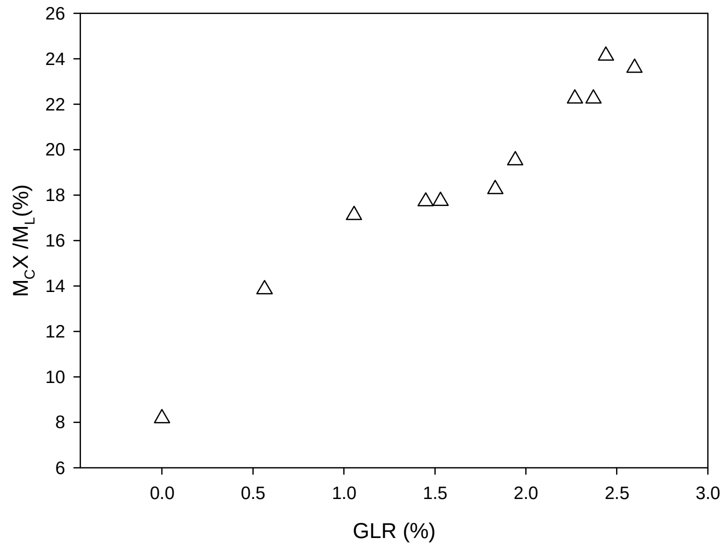

Figure 3: Percentage of total injected liquid which is free liquid after injection versus GLR for a fluidization velocity of 0.3 m/s

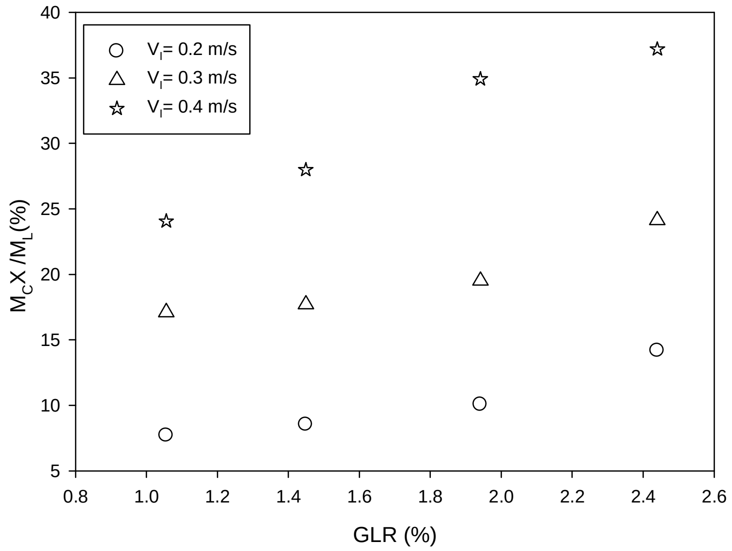

Figure 4: Percentage of total injected liquid which is free liquid after injection versus GLR for 3 different fluidization velocities during injection

To determine the effect of fluidization velocity on the breakage of agglomerates, the total amount of freed liquid was calculated by accounting for vaporization.

The breakage rate is defined as the rate at which liquid is freed from agglomerates, as they break up.

$$(breakage\ rate) = \left[\frac{d(M_C X)}{dt}\right]_{br} = M_C \left(\frac{dX}{dt}\right)_{br} \qquad (1)$$

For regular experiments, free liquid continuously disappears through evaporation and is continuously generated from agglomerate breakage:

$$\frac{d(M_C X)}{dt} = \left[\frac{d(M_C X)}{dt}\right]_{br} + \left[\frac{d(M_C X)}{dt}\right]_{e} \qquad (2)$$

Since there were no agglomerates formed during the calibration experiments, Equation 2 simplifies to:

$$\left[\frac{d(M_C X)}{dt}\right]_{calibration} = \left[\frac{d(M_C X)}{dt}\right]_{e} \qquad (3)$$

The evaporation rate is a function of gas velocity (V_g) and total mass of free liquid ($M_C X$). In this study, the evaporation rate depends only on free moisture, because V_g and M_C were kept constant in all the experiments. The evaporation rate can be obtained from the calibration experiments, using Equation 3.

$$f_e(X) = M_C \left[\frac{dX}{dt}\right]_e = M_C \left[\frac{dX}{dt}\right]_{calibration} \qquad (4)$$

Substituting Equation 4 into Equation 2, we obtain:

$$M_C \left[\frac{dX}{dt}\right]_{br} = M_C \left[\frac{dX}{dt}\right] - f_e(X) \qquad (5)$$

The total free liquid is the sum of the liquid freed during the injection and the cumulative liquid that has been freed from the agglomerates after injection ($t = 0$):

$$f(t) = M_C X|_{t=0} + \int_0^t \left[M_C \left(\frac{dX}{dt}\right) - f_e(X)\right] dt \qquad (6)$$

The total free liquid can also be expressed as a ratio to the total mass M_L of injected liquid:

$$g(t) = \frac{f(t)}{M_L} = \frac{M_C}{M_L}\left[X|_{t=0} + \int_0^t \left[\left(\frac{dX}{dt}\right) - \frac{f_e(X)}{M_C}\right] dt\right] \qquad (7)$$

$g(t)$ was plotted versus time after injection for several fluidization velocities, and for different GLRs. For instance, Figure 5 shows $g(t)$ versus time for GLR=1% and different fluidization velocities. The time constant of agglomerate breakage,τ was calculated based on exponential curve fitted to these graphs:

$$g(t) = 1 + (g(0) - 1)e^{t/\tau} \qquad (8)$$

where $g(0)$ represents the value of $g(t)$ at the end of injection.

Figure 6 shows time constants of agglomerate breakage at different GLRs and fluidization velocities during injection. Increasing the fluidization velocity during injection greatly reduces the time constant. The effect of the GLR on agglomerate breakage is much weaker than the effect of the fluidization velocity.

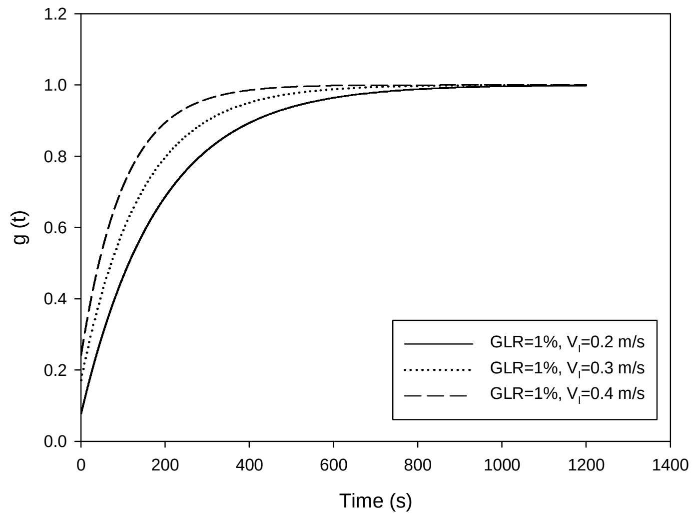

Figure 5: The ratio of total liquid freed from agglomerates to total mass of injected liquid after injection for several fluidization velocities during injection

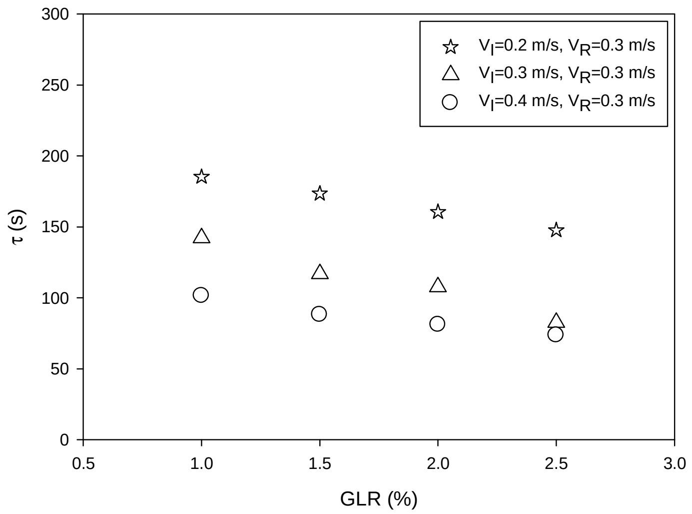

Figure 6: Time constant of agglomerate breakage versus GLR for three different fluidization velocities during injection

CONCLUSION

In this study, the capacitance of a gas-solid fluidized bed was measured at different locations. Using appropriate calibration experiments, non intrusive capacitance measurements provided accurate information on distribution of liquid on individual particles. The break-up rate of the liquid-solid agglomerates that were formed during the injection was calculated using information obtained from the evolution of the free liquid with time after injection.

Results show that increasing the atomization Gas-to-Liquid Ratio of the spray nozzle or the fluidization velocity during liquid injection can enhance the contact between atomized liquid and fluidized particles. Experimental observation also indicated that higher fluidization velocity during injection leads to the formation of weaker agglomerates that break up more quickly.

NOTATION

GLR	gas-to-liquid ratio	C	dry coke
M	total mass, kg	e	evaporation
V	fluidization velocity, m/s	I	during Injection
X	dry-basis free liquid, %	L	injected liquid
br	breakage	R	after injection

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