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Study of the effect of local hydrodynamics on liquid distribution in a gas–solid fluidized bed using a capacitance method

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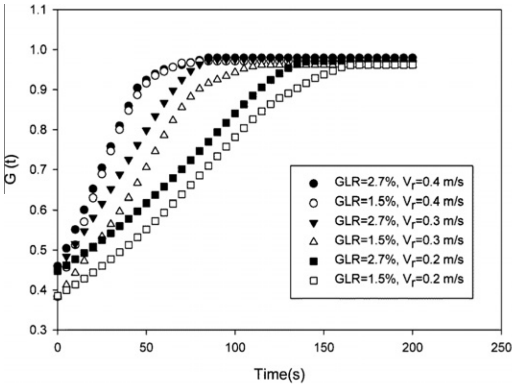
HIGHLIGHTS

- New capacitance method measures distribution of liquid injected in a fluidized bed.
- More atomization gas improves the contact between liquid and fluidized particles.
- Increasing the fluidization velocity improves liquid-particle contact.
- Increasing the fluidization velocity breaks up wet agglomerates.

GRAPHICAL ABSTRACT

Liquid was sprayed into a fluidized bed for 10 s and formed wet agglomerates that slowly broke up, releasing "free" moisture. $G(t)$ is the ratio of total liquid freed from the agglomerates, since the start of the injection, to the total mass of injected liquid. GLR is the mass ratio of the atomization gas to injected liquid. V_r is the fluidization velocity.



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ABSTRACT

Injection of liquid into fluidized beds is widely applied in the petrochemical, chemical, food and pharmaceutical industries. The local bed hydrodynamics have a strong impact on the contact between the injected liquid and the bed solids. By adjusting the local bed hydrodynamics or locating the injection nozzle in the appropriate region of the bed, the contact between the injected liquid and the bed solids may be optimized to minimize agglomerate formation, which is detrimental to many industrial operations such as Fluid Coking. The effect of bed hydrodynamics on liquid distribution was investigated with a new, reliable and sensitive capacitance method. Results show that the fluidized bed hydrodynamics have a considerable impact on the contact efficiency between injected liquid and fluidized solids.

1. Introduction

Many industrial processes, such as Fluid Coking, Fluid Catalytic Cracking (FCC) and gas-phase polymerization, utilize the process of liquid injection into a fluidized bed. The liquid distribution on the fluidized particles has been found to have a considerable impact on the performance of these processes. Bruhns and Werther [1] showed that particles enter the jet cavity formed by the injected liquid and immediately form agglomerates. Agglomeration is a problem in Fluid Coker units as it reduces the yield of valuable products by increasing mass and heat transfer resistances and

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Nomenclature

C	capacitance (F)
F	frequency (Hz)
GLR	mass ratio of the atomization gas to injected liquid
I	current (A)
M	total mass (kg)
R	resistance (Ω)
V	fluidization velocity (m/s)
x	dry-basis free moisture (%)
$\bar{x}$	average free moisture of six electrodes (%)

Subscripts

b	bed
br	breakage
e	evaporation
I	during Injection
i	electrode number
L	injected liquid
m	measured
r	during refluidization
S	dry sand
w	wood

influencing the thermal cracking reactions [2]. Therefore, identifying the operating conditions that enhance the liquid distribution over individual free flowing solid particles is essential to minimize the agglomerate formation.

Several publications address the characteristics of liquid jets in a fluidized bed. Ariyapadi et al. [3] employed an X-ray imaging system to study the jet expansion angle and its penetration distance into a fluidized bed. These authors also studied the formation of liquid–solid agglomerates using radio opaque tracers mixed with the feed liquid. Knapper et al. [4] used a tracer to measure the liquid–solid contact in a pilot plant Fluid Coker, and showed that the liquid distribution on the bed solids strongly depends on the nozzle geometry. Gehrke and Wirth [5] implemented temperature and capacitance measurement methods to identify the spray zone with injecting liquid feed in a high density circulating fluidized bed. House et al. [6] used a simple model to show that liquid distribution has a major impact on the yield of valuable products in Fluid Cokers. Darabi et al. [7] proposed a simplified mathematical method to determine the agglomeration tendency of bitumen-coated coke particles in Fluid Cokers, showing that liquid distribution has a significant impact on agglomerate formation, which is detrimental to Coker operation.

Several authors injected cold liquids into hot fluidized beds and inferred the liquid distribution from local temperature measurements. McMillan et al. [8] studied the injection of cold ethanol into a fluidized bed of coke particles in order to develop a quick method to determine the quality of solid–liquid mixing on a short time scale from temperature measurements. Bruhns and Werther [1] investigated the mechanism of liquid injection into a pilot plant bubbling fluidized bed using water and ethanol and a bed temperature between 120 and 180 °C. They found that the agglomerates formed at the exit tip of the nozzle.

Methods were developed to evaluate the liquid distribution at room temperature, which is easier and more convenient than performing experiments at high temperature. Portoghese et al. [9] used a triboelectric probe to evaluate spray nozzle performance, since wet solids give completely different triboelectric charging then dry solids. Because the triboelectric method is very sensitive to the local bed hydrodynamics, Portoghese et al. [10] and Leach et al. [11] developed another method that is much less sensitive to the local hydrodynamics. They measured the electric conductance of the bed solids after liquid injection and defluidization of the wetted particles. Fan et al. [12] developed electrical capacitance tomography as an imaging technique to study gas–solid flow system with evaporative liquid jets. Leach et al. [13] showed that the performance of various spray nozzles could be ranked with a Nozzle Performance Index (NPI), obtained from bed conductivity measurements. Leach et al. [13] and Portoghese et al. [10] found that increasing the mass ratio of atomization gas to injected liquid (GLR) improves the spray nozzle performance. However, in industrial units increasing the GLR is associated with significant costs and flow constraints. Therefore, it is necessary to accurately assess the effect of atomized gas to injected liquid on the performance of the nozzle.

The objective of this study was to investigate the effects of local hydrodynamics on liquid distribution in a gas–solid fluidized bed, using a capacitance method, by changing the fluidization velocity. Another objective was to develop experimental methods that make it possible to separate the effects of the local hydrodynamics on the initial liquid–solid agglomerate formation during liquid injection from the effects on the agglomerate breakup subsequent to the liquid injection.

2. Experimental

2.1. Experimental setup

The experiments were performed in a fluidized bed 1.97 m high with a 1.54 m by 0.288 m rectangular cross sectional area, as shown in Fig. 1a. Two banks of calibrated sonic orifices and pressure regulators were used to adjust the fluidization velocity. Three rectangular wooden windows were mounted on each side of the unit walls.

For most of the experiments, the liquid injection was carried out with a scaled-down version of a proprietary industrial convergent–divergent–convergent spray nozzle, with a 3 mm tip diameter as shown in Fig. 1b [14]. Nitrogen as atomization gas was mixed with water in a pre-mixer (Item 12 in Fig. 1a) ahead of the spray nozzle [15]. The flow rate of the atomization gas was set with a calibrated sonic orifice and a pressure regulator (Item 1 and Item 9 in Fig. 1a). For the regular experiments, the fluidization velocity was set at a specified value and the liquid was injected for 10 s. The liquid flowrate for these experiments was about 20 g/s.

The bed temperature was measured with 2 thermocouples (Item 13 in Fig. 1a). The thermocouple at the top of bed measured the freeboard temperature. The bed height and bed mass were calculated from pressure measurements performed with transducers located at different positions on the side of the unit wall.

2.2. Measuring system

In preliminary experiments, bed solids were sampled just after the liquid injection. The injected liquid was found in three forms: liquid forming a thin layer around individual free-flowing particles that is called “free moisture”; liquid trapped within “micro-agglomerates” that were small enough to remain fluidized; and liquid trapped within “macro-agglomerates”, which defluidized and