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Experimental analysis of volatile liquid injection into a fluidized bed

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ABSTRACT

Experiments were conducted on a lab-scale fluidized bed to study the distribution of liquid ethanol injected into fluidized catalyst particles. Electrical capacitance measurements were used to study the liquid distribution inside the bed, and a new method was developed to determine the liquid content inside fluidized beds of fluid catalytic cracking particles. The results shed light on the complex liquid injection region and reveal the strong effect of superficial gas velocity on liquid distribution inside the fluidized bed, which is also affected by the imbibition of liquid inside particle pores. Particle internal porosity was found to play a major role when the changing mass of liquid in the bed was monitored. The results also showed that the duration of liquid injection affected liquid–solid contact inside the bed and that liquid–solid mixing was not homogeneous during the limited liquid injection time.

Introduction

Fluid catalytic cracking (FCC) is used to upgrade low-value refinery gas–oil feedstock to more valuable products. It continues to play a key role as the primary conversion process used in integrated oil refineries. The injection of liquid jets is an important component of FCC reactors, as well as fluid cokers and other processes, and has a key role in determining their overall performance. Effective contacting of liquid droplets and solid particles is necessary to obtain high yields.

Research and development on FCC risers (Gao, Xu, Lin, Yang, & Guo, 1999) has focused on three aspects: the hydrodynamic behavior of two-phase flow in the risers; complex feed vaporization phenomena in the feed-injection zone; and catalytic cracking kinetic models.

The process of initial liquid–solid contact at the bottom of the riser reactor is a very important step in determining unit performance, and even dominates product distribution and quality (Mauleon & Courelle, 1985; Mirgain, Briens, Pozo, Loutaty, & Bergougnou, 2000). Feed vaporization and the feed-injection configuration have been evaluated in experimental studies of commercial catalytic cracking reactors and pilot units. There have also been many attempts to simulate entire FCC units, almost all of which have assumed instantaneous vaporization of the feed at the riser entry (e.g. Gupta & Rao, 2001, 2003). In recent years, several attempts have been made to study the mechanism of liquid feed vaporization at the inlet of riser reactors more thoroughly.

Rapid vaporization of liquid droplets in fluidized bed reactors leads to a substantial increase in volumetric gas flow. This significantly influences gas–solid contact, temperature distribution, and flow behavior, thereby affecting process efficiency and product quality (Fan et al., 2001). Mohagheghi, Hamidi, Berruti, Briens, and McMillan (2013) investigated the effect of hydrodynamics on liquid distribution in a fluid coker and reported that the superficial gas velocity had a considerable effect on particle–liquid contact. Liu (2003) conducted experiments to visualize the behavior of evaporating spray jets in dilute gas–solid flows. He measured the temperature distribution of a three-phase mixture near the spray region. The experimental results were then used to develop a parametric model which included phase interactions and phase changes. The predictions of this model were in good agreement with the experimental results.

Research has also been carried out on non-evaporative (Leach, Portoghese, Briens, & Berruti, 2008; Mohagheghi et al., 2013; Portoghese, 2007) and evaporative (Du, Warsito, & Fan, 2006; Gehrke & Wirth, 2007) water and liquid nitrogen injection into gas-fluidized beds. These studies have shown that the diameter of liquid droplets plays a key role in the injection process. One of the most

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widely used experimental methods for studying liquid dispersion is optical visualization, for example, by non-intrusive X-ray imaging or using a charge-coupled device (CCD) camera to provide information such as the jet penetration and expansion angle. In X-ray imaging, the pulse-rate frequency of an X-ray beam is synchronized with a video camera to freeze the internal motion and allow internal flow patterns to be recorded (Bruhns, 2002).

X-ray imaging has the advantage of not being intrusive, but it has poor spatial resolution and/or long scan times (Gehrke & Wirth, 2007). The relatively high capital investment required and radiation hazard have also discouraged widespread adoption. Other methods for studying liquid dispersion in fluidized beds include temperature measurements via fast response thermocouples, suction probes for measuring injected tracer gas concentrations, and capacitance probes for the detection of liquid within the dense gas–solid phase (Ariyapadi, 2004). Fast response thermocouples (Bruhns & Werther, 2005) have also provided useful information. X-ray or CCD camera recorder visualization techniques have also been combined with temperature distribution measurements (Bruhns, 2002; Gehrke & Wirth, 2007).

Electrical capacitance/conductance impedance methods have been employed as non-intrusive techniques to determine liquid distribution inside fluidized beds (Leach et al., 2008; Mohagheghi et al., 2013). Despite rapid vaporization of the injected liquid at the nozzle exit, studies (Gu, Tuzla, & Chen, 1966; Newton, Fiorentino, & Smith, 2001; Skouby, 1999) have disproved the assumption of instantaneous evaporation at the nozzle exit. Zhu, Wang, and Fan (2000) studied the effect of solids concentration on evaporative liquid jets and found that the jet penetration could be shortened by as much as 45% with a solids concentration of 1.6% compared with that of a solids-free flow. However, these conditions differ significantly from those at the injection level of FCC riser reactors, where solids volumetric concentrations are 20%–30%. More experimental work is required to determine the effect of particle concentration on liquid vaporization.

There have been numerous experimental studies on liquid injection and the wetting/drying characteristics of solid particles in fluidized beds (Bruhns & Werther, 2005; Davidson et al., 2001; Fan et al., 2001; Maronga & Wnukowski, 1997; Zhu, Wang, Liu, & Fan, 2001). Bruhns and Werther (2005) injected water and ethanol into fluidized beds of quartz and FCC catalyst particles. Based on their experimental results, they proposed a model for the mechanism of liquid injection and dispersion which assumed instantaneous wetting of the fluidized particles at the nozzle exit and considered the transport of wetted particles by gross solids mixing. McMillan et al. (2005) studied liquid sprays by injecting ethanol into a fluidized bed of coke particles, and developed a temperature-based method to determine the local quality of solid–liquid contact on a short time scale. Better mixing and rapid contact between liquid droplets and particles were obtained when a horizontal draft tube was inserted downstream of the liquid spray nozzle.

Leclere et al. (2001, 2004) developed a method to investigate the vaporization of injected liquid inside a fluidized bed based on quenching of the bed and creating agglomerates. They developed a heat-transfer-based model which predicted the formation of agglomerates when liquid droplets larger than the bed particles were injected into a high-temperature fluidized bed. Particle pore filling was reported to be greater than 80%.

Li, Grace, Bi, Reid, and Wormsbecker (2012) simulated the vaporization of liquid feed in a fluid coking reactor by investigating three limiting cases to simplify the process. (a) The liquid feed entirely vaporizes at the entrance of the column. (b) The liquid feed vaporizes immediately upon contact with coke particles. (c) The liquid uniformly coats the particles, generating vapor uniformly throughout the bed. The vaporization rate was shown to have a significant impact on the hydrodynamics, complementing their previous study on the influence of the volume change of the gas phase caused by phase change and chemical reactions in the fluidized beds (Li, Mahecha-Botero, & Grace, 2010). The temperature was assumed to be uniform in the entire bed, so the energy equation was not solved in their system.

Pougatch, Salcudean, Chan, and Knapper (2009) and Pougatch, Salcudean, and McMillan (2012) developed a model that resolved the flow through the nozzle, fluidization, and droplet-particle interactions. This model shows good agreement with experimental data, but requires high grid resolution in the nozzle and its vicinity, which is not practical for large-scale modeling applications. Agglomeration during liquid injection into fluidized beds was studied numerically by Darabi (2011), who considered the effects of both capillary and viscous forces. He proposed an approach for predicting agglomerate formation by considering the effect of capillary and viscous forces and calculating the maximum possible energy dissipation and total kinetic energy of colliding wet particles.

Particle internal porosity is an important parameter for liquid–solid mixing in fluidized beds, but has received little attention. While most models do not take particle porosity into account, Terrazas-Velarde, Peglow, and Tsotsas (2011) developed a model which accounted for the effect of porosity on liquid distribution. Computational fluid dynamics models are needed to improve understanding of the mechanism of liquid distribution inside fluidized beds.

The objective of this work was to obtain a better understanding of the mechanism of liquid jet dispersion inside fluidized bed reactors. Liquid injection tests were conducted and the liquid distribution in the bed was measured based on an electrical capacitance (EC) impedance technique developed previously (Leach et al., 2008; Leach, Chaplin, Briens, & Berruti, 2009). Ethanol was chosen as the injected liquid owing to its favorable EC characteristics and volatility. The experiments were carried out to compare liquid mixing in fluidized beds of porous and non-porous particles, to qualitatively and quantitatively measure liquid dispersion in fluidized beds containing FCC particles to obtain quantitative data for an evaporative liquid using the EC measuring technique, and to determine the extent of liquid diffusion inside particle pores. Liquid was also injected into a fluidized bed containing non-adsorbing silica sand particles and compared with the injection into the bed of FCC particles. However, because of the poor wettability of sand by ethanol, no quantitative analysis was performed on the sand bed.

Experimental

Apparatus

Experiments were performed in a rectangular Plexiglas fluidization column, 0.49 m × 0.1 m in cross-section and 0.92 m high. A dipleg of 25 mm in diameter was installed inside the column to a depth of 0.51 m to return entrained particles captured by the cyclone to the top section of the column as depicted in Fig. 1. A high air-to-liquid mass flow ratio (*ALR*) nozzle was used, through which up to 0.15 m^3/min of atomization gas was passed to provide excellent dispersion of the injected liquid onto the fluidized particles (*ALR* ≈ 45%). Twenty evenly spaced electrodes were attached at different heights on one side wall of the column. All electrodes were 0.05 m high × 0.1 m wide metal strips. A single common electrode (0.4 m high × 0.5 m wide) was located on the opposite side of the column, facing the 20 electrodes on the other side. All the electrodes were connected to an electrical board, the measuring circuit of which was an AC-based capacitance meter with a differential noise canceling system and a sampling frequency of 10 Hz for each electrode. The board used a sine-wave voltage as the excitation source to produce an AC input current and an amplifier to

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