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SCIENCE DIRECT

Powder Technology 161 (2006) 175 – 184

POWDER TECHNOLOGY

www.elsevier.com/locate/powtec

Measurement techniques to characterize the contact between injected liquid and circulating solids in a downer mixing chamber

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Received 2 June 2005; received in revised form 26 July 2005; accepted 13 September 2005
Available online 19 December 2005

Abstract

Gas–solid fluidized-bed reactors operating in either conventional or circulating (riser or downer) modes are used in many applications such as fluid catalytic cracking and fluid coking. In such applications, uniform contact of the liquid feed droplets and entrained particles is essential for minimizing heat and mass transfer resistances and generating high yields of desirable products. This contact may be intensified in the mixing chamber of downer reactors. The objective of this study was to measure the quality of mixing between injected liquid feed and circulating solid particles in a downer mixing chamber.

An efficient method was developed to determine the local quality of solid–liquid mixing on a short time scale. The measurement technique used two types of measurements in order to obtain the cross-sectional distribution of liquid-to-solid ratios. First, temperature measurements were used to characterize the solid/liquid distribution and, second, tribo-electric probes were used to obtain the local solids fluxes. The measurement technique has proven to be a very reliable and reproducible method to determine the extent of liquid and solid mixing resulting from a variety of injection configurations. Very good and rapid contact between sprayed droplets and particles can be achieved by using appropriate mixing chamber geometries where four or more liquid spray jets impact each other.

Keywords: Downer; Mixing chamber; Liquid injection; Solid–liquid mixing; Tribo-electric probes

1. Introduction

Liquid injection into conventional and circulating gas–solid fluidized-bed reactors is encountered in many industrial applications such as fluid catalytic cracking and fluid coking. In such applications, the initial interaction of the liquid jet spray and the fluidized particles represents a crucial step in the process. In particular, the fluid coking and fluid catalytic cracking processes require uniform contact of the liquid droplets and particles in order to achieve efficient cracking and high yields. A poor initial distribution of the liquid feed on the particles can cause a thick liquid film to form on the solids surface, imposing a high resistance to mass and heat transfer, resulting in the formation of undesirable secondary products. To avoid slow cracking and prevent heat or mass transfer limitations, the feedstock must contact a large number of particles quickly and uniformly. Using a downer equipped with a mixing chamber located at its entrance may intensify this contact. This mixing chamber must ensure good initial contact between liquid and solids at the inlet to the downer.

Although spray nozzles are widely used to inject atomized feeds in industrial circulating fluidized bed reactors such as FCC risers, which could presumably be replaced by downers [1–5], they are not typically used in the published studies of downer reactors. Therefore, it is important to evaluate the liquid–solid mixing in the downer reactor equipped with a nozzle injection system.

A previous investigation involved the injection of gas jets into down-flowing solid particles in a mixing chamber, very similar to the experimental set-up used in this study [6]. Although their techniques provided direct, reliable results for the gas–solid system, the authors only measured the mixing between a gas jet and particles.

The majority of the work conducted to measure local solids flow and mixing patterns in circulating fluidized beds focuses on radiation absorption methods such as X-ray absorption tomography, and electrical capacitance methods [7–10]. However,

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doi:10.1016/j.powtec.2005.09.004

these techniques result in poor spatial resolution and long scan times, and cannot be easily adapted to a gas–liquid–solid system.

Temperature measurements have been widely used in circulating fluidized beds [11–14]. In particular, Wang and Zhu [14] developed a model for the hydrodynamic mixing between solids and evaporating spray jets in dilute gas–solids pipe flows and studied the effect of solids loading, inlet gas velocity, and spray mass. They acquired temperature measurements along the spray jet axis to obtain an averaged mixture temperature, from which information regarding each phase was obtained. However, temperature measurements have not been used to characterize the mixing between solids and non-evaporating liquids.

The use of tribo-electric probes to measure the flux of solids in a two-phase gas–solid flow has been employed in previous studies [15–17]. However, tribo-electric probes have not been used to measure the solids or liquid flux in gas–liquid–solid flows.

There have been several studies conducted that consider the interaction of evaporative liquid jets in gas–solid risers [1,18,19]. However, droplet evaporation is a key factor in the phase mixing and flow characteristics of evaporating spray jets, and the same methods cannot be adapted to applications with a non-vaporizing liquid.

To date, there have been no studies done which investigate the injection of non-evaporative liquids into downer reactors equipped with a mixing chamber. The objective of this study was to develop a technique to determine the local, instantaneous quality of solid–liquid mixing when non-evaporative, gas–liquid spray jets are injected into a downer mixing chamber. The effects of using two different entrance configurations for the solids (a circular solids jet or an annular solids jet), and the geometry of the mixing chamber were examined using a mixing chamber equipped with either 4 or 8 injection nozzles.

2. Experimental set-up

A unique technique involving temperature measurements coupled with tribo-electric measurements was developed to characterize the initial contact between injected liquid and particles in a mixing chamber.

Experiments were conducted in a mixing chamber that was located at the entrance of a downer, as depicted in Fig. 1. Coke particles with a Sauter mean diameter of 140 μm, which were stored in a silo, flowed down through an orifice plate into the mixing chamber before entering the 0.076 m diameter downer. An orifice plate was placed at the inlet of the mixing chamber in order to control and distribute the solids flow over the cross-section. Two types of orifice plates were used in this study, which produced either a circular or an annular solids jet. The circular orifice plate had a diameter of 20 mm and the annular orifice consisted of 4 mm slots that had an outside diameter of 35 mm, as shown in Fig. 2. In order to achieve the desired solids flow rate resulting in a liquid to solid ratio of approximately 5%, the silo was pressurized by delivering a constant flow rate of pressurization air. The solids flow rate when 4 injection nozzles were used was approximately 0.5 kg/s

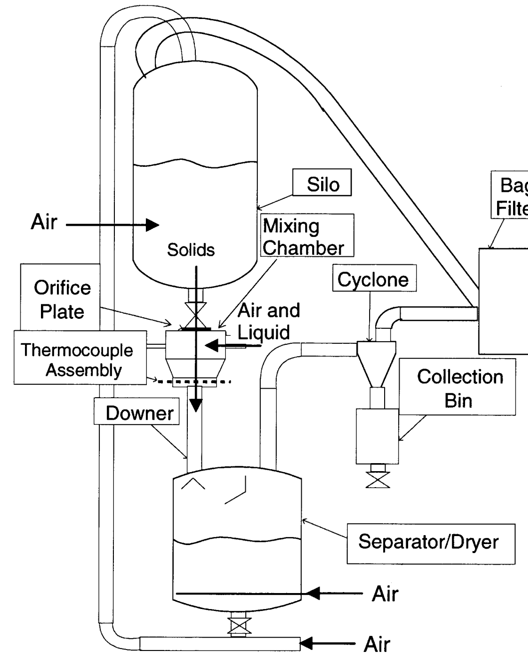

Fig. 1. Experimental apparatus.

(110 kg/m^2 s) and 1 kg/s (220 kg/m^2 s) when 8 injection nozzles were used, to keep the solids to liquid ratio constant.

Liquid from two-phase spray nozzles was contacted with the down-flowing particles in a mixing chamber, which is shown in Fig. 3. The mixing chamber consisted of a 0.145 m diameter cylindrical section followed by a conical section angled at 30° that led to the 0.076 m diameter downer. The mixing chamber used in this case was equipped with either 4 or 8 air–liquid injector nozzles. The injector nozzles could be oriented independently in both the horizontal and vertical planes. They could be angled in the horizontal plane to induce a swirl, and inclined to hit the solids jet near the top or bottom of the mixing chamber.

Fig. 4 depicts the geometry of spray nozzle that was used. The liquid was supplied to the nozzle through a centrally located hypodermic needle with an internal diameter of 1.5 mm, while the atomizing air flowed through an annular region. The liquid tube was offset by 2 mm towards the inside of the nozzle to allow for internal mixing of the two phases [20]. Ethanol–water mixtures were used as liquid. A constant air mass flow rate from a high-pressure cylinder was supplied to each injection nozzle through a sonic nozzle located in the upstream line. The liquid was supplied to the nozzles from a tank pressurized by nitrogen in order to ensure uniform liquid flow rate to each injector nozzle. The air and liquid flow rates for each nozzle were kept constant at 0.43 g/s and 6.83 g/s, respectively, resulting in an average air-to-liquid ratio (ALR) of 5.9%.

The solid–liquid mixture flowed through the downer and entered a separator vessel where it was subsequently dried. A pneumatic line returned the dry solids to the silo.

2.1. Temperature method

The first technique used temperature measurements to characterize the solid–liquid mixing. Cold ethanol at −10 °C