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Original Research Paper

Experimental investigation of bubble and particle motion behaviors in a gas-solid fluidized bed with side wall liquid spray

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ABSTRACT

Bubble and particle motion behaviors are investigated experimentally in a gas solid fluidized bed with liquid spray on the side wall. The particles used in the experiment are classified as Geldart B particles. The results reveal that when the fluid drag force is less than the liquid bridge force between particles, liquid distribute all over the bed. Bubble size increases as the increase of inter-particle force, then decreases owing to the increase of particle weight with increasing liquid flow rate. When the fluid drag force is greater than the liquid bridge force, liquid mainly distribute in the upper part of the bed. And it is difficult for the wet particles to form agglomerates. Bubble size decreases with increasing liquid flow rate due to the increasing of minimum fluidization velocity. Besides, the acoustic emission (AE) measurements illustrate that the liquid adhesion and evaporation on particles could enhance the particles motion intensity. Consequently, the bubble and particle behaviors change due to the variation in fluidized gas velocity and liquid flow rate should be seriously considered when attempting to successfully design and operate the side wall liquid spray gas solid fluidized bed.

1. Introduction

Gas solid fluidized beds are commonly used in many industrial processes due to the excellent mixing of solids and high heat and mass transfer rate, such as agglomeration and coating of particles, heterogeneous gas-phase catalysis. A variety of operations have been used to improve the efficiency of these processes carried out in the fluidized bed where liquid spray is one of the most effective methods to enhance the heat and mass transfer in several industrial applications, such as fluid catalytic cracking (FCC), aniline synthesis and polyethylene process [1–3]. On the one hand, the sprayed liquid improves the contact efficiency between solids and liquid and removes more reaction heat from the bed through evaporation. On the other hand, the liquid also severely affects the fluidization behavior of the bed. Therefore, a comprehensive understanding of the fluidization characteristics of a fluidized bed with liquid spray is of prime importance to establish design criteria for this kind of fluidized bed.

Van der Waals force, electrostatic force and liquid bridge force are the main inter-particle forces in the liquid spray gas solid fluidized bed. Van der Waals force is significant between Geldart A particles [4]. Electrostatic force is induced by frequently collision between particles, but it is weak in the liquid spray fluidized beds. Liquid bridge force resulting from liquid bridge between wet particles is much larger in magnitude than the van der Waals and electrostatic forces [5]. If the liquid bridge force is large enough, the formation of particle agglomerates will be promoted. Bruhns et al. [6] investigated the mechanism of liquid spray into fluidized bed experimentally. They found that particles were wetted by the sprayed liquid and formed agglomerates in the vicinity of the nozzle exit according to the measurements of bed temperature and vapor concentration. The agglomerates were rapidly transported into the interior of the fluidized bed by the gross solids mixing and decayed under the action of the fluid drag force. Additionally, when liquid is sprayed into a high temperature fluidized bed, the volume of the gas phase will be affected due to the evaporation of liquid, further affecting the bubble size and its velocity. In conclusion, the hydrodynamics in the liquid spray fluidized bed is more complicated compared to conventional fluidized beds.

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Nomenclature

Notations

C_a C_δ	correction function
C_D	drag coefficient
D_c	collision energy ratio
D_f	fraction energy ratio
d_p	diameter of the particle, m
E	acoustic energy, V^2
F_H	inter-particle force, N
F_l	liquid bridge force, N
F_d	fluid drag force, N
F_l	liquid bridge force, N
f	frequency of acoustic emission signal, Hz
P	pressure, Pa
Q_l	liquid flow rate, ml/min
Re_p	Reynolds stress
S	liquid saturation ratio
T	temperature, °C
t	time, min
U_g	superficial gas velocity, m/s
U_{mf0}	superficial gas velocity at minimum fluidization for dried particle, m/s

Greek letters

γ	surface tension of the liquid, mN/m
μ	viscosity of the liquid, mPa·s
w	characteristic frequency of the bed, Hz
Φ	half filling angle, °
ε	voidage of the bed
ρ_p	density of fluidized particles, kg/m^3
ρ_f	density of fluidizing gas, kg/m^3

Current experiment researches on gas-solid fluidized beds with liquid spray mainly focus on the following aspects. Some researches focused on the effect of liquid spray on the fluidization state of the bed. Berruti et al. [7] decomposed the pressure fluctuation signals acquired from a liquid spray fluidized bed into large and small fluctuation parts. The ratio between the amplitude of small and large components was used to characterize the fluidization condition in the bed. This criterion was utilized successfully in determining the critical liquid amount for defluidization [8]. Tsujimoto et al. [9] obtained acoustic emission signals from a liquid spray granulation fluidized bed experimental setup. They found that liquid affected the movement of particles in the bed. When excessive liquid was sprayed into the bed, the particles were in a packed state and the bed was defluidized. Briens et al. [10] analyzed the standard deviation (STD) of the acoustic emission signals in a granulation fluidized bed with liquid spray. It was found that the STD fluctuated more wildly when the bed was in a stable fluidization state compared to an unstable state. It illustrated that the sprayed liquid influenced the particles motion intensity obviously. According to the above experiment results, it can be concluded that the sprayed liquid has a prominent effect on the hydrodynamics in the bed. And the amount of the sprayed liquid should be less than the critical value to ensure stable fluidization of the bed. When liquid is sprayed into a high temperature fluidized bed, the distribution of the bed temperature will be affected obviously. Bruhns et al. [6] and Zhou et al. [11] observed that there was a large temperature gradient between the liquid spray region and other regions owing to liquid spray in the bed. The sprayed liquid with high velocity can also affect the circulation pattern of particles in the bed. Wnukowski et al. [12] and Turchiuli et al. [13,14] obtained different particle flow patterns by measuring the temperature profile in a top spray fluidized bed. Börner et al. [15] used particle image velocimetry (PIV) to measure the particle flow pattern in a top spray fluidized bed. They found that there was an extra circulation of particles induced by liquid spray compared to a gas–solid fluidized bed. Zhou et al. [16] investigated the particle circulation patterns in a gas solid fluidized bed with liquid spray and found that large number of particles moved downwards as agglomerates with increasing liquid flow rate. The earlier studies have provided a preliminary understanding of the hydrodynamics in the fluidized bed with liquid spray. It can be found that the competing effect of the fluid drag force and liquid bridge force is the main factor that affects the fluidization state of the bed in a liquid spray fluidized bed. However, there are few works concerned with the effect of liquid on the bubble and particle behaviors in the presence of different magnitude of liquid bridge forces when integrated with the variation of fluid drag forces. The variation of bubble and particle behaviors greatly affects the heat and mass transfer efficiency between gas and solid phase and even the quantity and quality of the product. Therefore, it is of vital importance to investigate the effects of liquid on bubble and particle motion behavior in the gas solid fluidized bed.

This work investigates the effect of liquid spray on bubble and particle motion behaviors in a cold model fluidized bed with high temperature inlet gas and liquid spray on the side wall. Thermal resistance is used to measure the temperature in the bed. Bubble and particle behaviors are characterized by pressure transducer and acoustic emission respectively.

2. Experimental apparatus

Fig. 1 shows the schematic diagram of the experimental apparatus, which consists of the fluidization system and signal acquisition system. The fluidized bed column is made of stainless steel with 100 mm i.d., 800 mm in height and a perforated distributor. A thermal insulation jacket is mounted on the outside wall of the bed with circulating hot water of 85 °C in it. In order to observe the fluidization state during the experiment and install the acoustic sensor, a 30 mm wide glass window slot is inserted in the wall of the fluidized bed.

In each test, the bed was filled with linear low density polyethylene (LLDPE) to a static bed height of 270 mm (Sauter mean diameter of 650 μm and particle density of 920 kg/m^3), classified as Geldart B particles. The particle size distribution was measured by a laser diffraction system (Malvern Mastersizer 2000), as shown in Fig. 2. The minimum fluidization velocity U_{mf0} of the dry particles is 0.11 m/s when the air temperature is 85 °C. The bed was fluidized with air at four different superficial gas velocities at ambient pressure, i.e., 3.3, 3.7, 4.1 and 4.6 times of U_{mf0}. Pure alcohol (density of 820 kg/m^3 and boiling point of 78 °C) was used as test liquid, which was sprayed continuously into the dense bed by a nozzle illustrated in Fig. 3. The nozzle was located at a bed height of 170 mm and its exit was 10 mm away from the inner side wall of the fluidized bed. The flow rate of alcohol was controlled by a metering pump, i.e., 10.2, 14.25, 18.5, 22.5, 28 and 34.2 ml/min. The maximum flow rate is chose to ensure steady fluidization of the bed. In each test, liquid was sprayed into the bed when the outlet temperature of the bed was steady until the data acquisition

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