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Bubbling behavior of cohesive particles in a two-dimensional fluidized bed with immersed tubes

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ABSTRACT

Fluidization hydrodynamics are greatly influenced by inter-particle cohesive forces. This paper studies the fluidization of large cohesive particles in a two-dimensional fluidized bed with immersed tubes using “polymer coating” to introduce cohesive force, to gain better understanding of bubbling behavior when particles become cohesive and its effect on chemical processes. The results show that the cohesive force promotes bubble splitting in the tube bank region, thereby causing an increase in the number and a decline in the aspect ratio of the bubbles. As the cohesive force increases within a low level, the bubble number increases and the bubble diameter decreases, while the aspect ratio exhibits different trends at different fluidization gas velocities. The difference in the evolution of bubble size under various cohesive forces mainly takes place in the region without tubes. When the cohesive force is large enough to generate stable agglomerates on the side walls of the bed, the bubble number and the bed expansion sharply decrease. The tubes serve as a framework that promotes the agglomeration, thus accelerating defluidization. Finally, the bubble profile around tubes was studied and found to greatly depend both on the cohesive forces and the location of tubes.

Introduction

Fluidized beds are widely used in industrial processes for their excellent heat and mass transfer and flexibility in handling particles continuously. Heat exchanging tubes are usually placed inside the fluidized bed to remove heat and control the operating temperature. Additionally, the presence of tubes may also modify the structure of the flow, thus benefiting fluidization and the corresponding chemical reactions (Rüdisüli, Schildhauer, Biollaz, & van Ommen, 2012). For example, particle elutriation is minimized and local particle circulation is enhanced by the presence of tubes (Ramamoorthy & Subramanian, 1981). Moreover, such tubes reduce bubble size by enhancing bubble splitting and inhibiting bubble coalescence, which leads to better mass transfer and higher chemical conversion (Lorences, Laviolette, Patience, Alonso, & Diez, 2006).

In many applications of fluidized reactors (e.g., liquid waste and sludge incineration, and biomass combustion), the particles processed are rich in alkali species that produce a cohesive low-melting medium between bed materials under high temperature. The presence of inter-particle cohesive forces causes different fluidizing dynamics compared with the non-cohesive case. It has become widely accepted that the fluidizing dynamic field is closely related to the local heat transfer around immersed tubes (Di Natale, Bareschino, & Nigro, 2010; Di Natale & Nigro, 2012; Kim & Kim, 2013; Schmidt & Renz, 2005). Therefore, a detailed understanding of the fluidization of cohesive particles in beds with immersed tubes will be helpful for optimizing the operation of such systems.

As an important phenomenon for heat transfer, the behavior of bubbles in beds with immersed tubes have been extensively studied, mainly focusing on the effects of tube bank geometry and operating parameters on the diameter, frequency, rising velocity, and distribution of bubbles. Yates and Ruiz-Martinez (1987) observed the critical role of the geometric arrangement of tubes in bubble breakage and proposed an equation to predict the size of “daughter bubbles” created by the splitting of large bubbles after encountering a row of tubes (Yates, Ruiz-Martinez, & Cheesman, 1990). Rong, Mikami, and Horio (1999) observed that particle impacts and bubble behaviors are different for staggered and in-line tube banks. Olowson (1994) demonstrated the additional effects of tube configuration on bubble properties outside the tube bank and also found that the influence of immersed tubes on bubble behavior is more pronounced at high gas velocities than that at low velocities. Olsson, Wiman, and Almstedt (1995) pointed out that the presence

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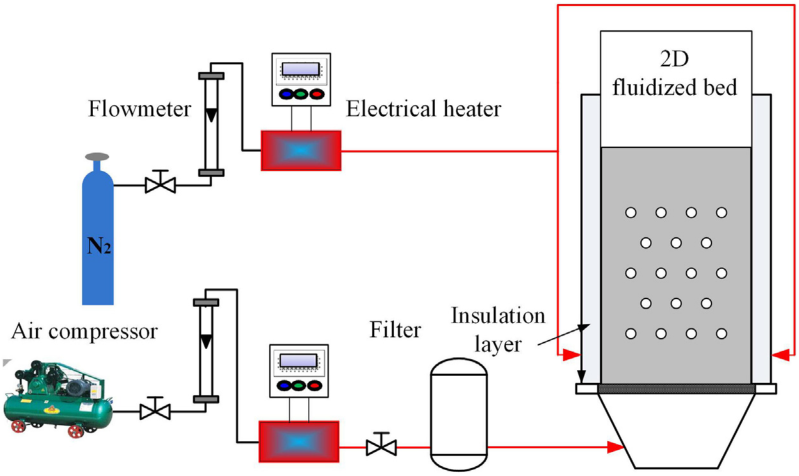

Fig. 1. Schematic of 2D fluidized bed system.

of tubes in a bed causes a significant increase in the local bubble fraction as well as the mean bubble frequency, which were then proved to be crucial parameters for the heat transfer coefficient around tubes by Wiman and Almstedt (1997). Hull, Chen, Fritz, and Agarwal (1999) used experimentally obtained data to develop semi-empirical correlations for bubble size and rising velocity, and applied these correlations to the interpretation of experimental data on the mixing of solids (Hull, Chen, & Agarwal, 2000). Das Sharma and Mohan (2003) used computational fluid dynamics (CFD) approach to predict the bubble characteristics within and outside the tube bank, and validated the results with the experimental data of Hull et al. (1999). Asegehegn, Schreiber, and Krautz (2011a) performed numerical simulations of a bubbling fluidized bed with immersed tubes and achieved consistency between predicted and experimental results obtained for a 2D bed (Asegehegn, Schreiber, & Krautz, 2011b). Medrano, Voncken, Roghair, Gallucci, and van Sint Annaland (2015) demonstrated the critical role of the bubbles attached to tubes (referred as “gas pockets”) in the interpretation of experimental results by applying a new algorithm to distinguish them from normal bubbles.

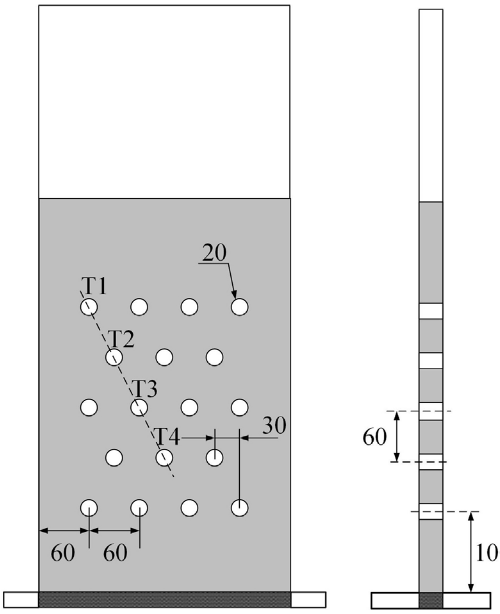

Fig. 2. Geometry of fluidized bed with immersed tubes.

Generally, the above studies have two common features. First, these works were performed in 2D fluidized beds. Note that, the translation of results obtained for a 2D bed to 3D systems or industrial applications has to be done with caution, because the fluid dynamics in 2D and 3D beds are different. However, the use of 2D beds is still valuable, for example, for calibration of some types of measurement equipment and validation of numerical simulations (van Ommen & Mudde, 2008). Second, all the studies were limited to fluidization with normal particles viz. non-cohesive particles. Few studies have reported on cohesive systems, although the cohesive force has been found to greatly affect bubble behavior and the smooth running of the bed (Ma, Liu, & Chen, 2016).

In the present paper, we study the fluidization dynamics of cohesive particles in a 2D fluidized bed with immersed tubes, using digital image analysis (DIA) to obtain the bubble properties and “polymer coating” to introduce an inter-particle cohesive force. The variation of bubble properties, including the spatial distribution, equivalent diameter, aspect ratio, and number density of bubbles throughout the bed as well as the distribution of bubbles around the tubes were studied and compared with those observed in beds without tubes.

Experimental

Experimental set-up

Fig. 1 shows a schematic of the experimental set-up. Fig. 2 shows the geometry and arrangement of tubes in the bed. The experiment was undertaken in a pseudo two-dimensional Perspex fluidized bed of 300 mm in width, 1000 mm in height, and 20 mm in thickness. Perspex tubes with a diameter of 20 mm were placed in a staggered arrangement in the bed. The ratios of vertical and horizontal pitches to the tube diameter both equaled 3. Full details of the experimental system have been described in our previous work (Ma et al., 2016). Bubbling behavior was recorded by a digital camera with a frame rate equal to 24 frames per second for a full size image (1080 × 1920 pixels). The static bed height, H_s, was set to 0.4 m in all cases. The fluidizing gas velocity, U_g, was adjusted from $2U_{mf}$ to $3U_{mf}$ (U_{mf} is the minimum fluidization velocity of the bed materials). The bed temperature was varied between 30 and 52 °C.

Materials

The particles used in this study were coated glass beads with a density of 2500 kg/m^3 and an average diameter of 600 μm, corre-

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