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Applying image processing methods to study hydrodynamic characteristics in a rectangular spouted bed

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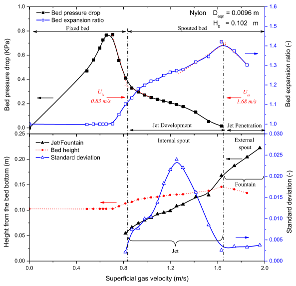
HIGHLIGHTS

- The bed expansion ratio (H/H_0) is obtained by image analysis and defined algorithm.
- The jet (H_j) and fountain (H_f) heights are determined by image contour detection.
- The H/H_0 reaches a maximum value of 1.4 at the onset of the external spouting.
- The profiles of H_j and H_f vs. U_g verifies the feasibility of the image methods.
- The flow regime determination proves that the image methods is effective and useful.

GRAPHICAL ABSTRACT



Flow regime discrimination with dynamic behavior of hydrodynamic characteristics

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ABSTRACT

This paper presents systematic image processing methods for investigating hydrodynamic characteristics in a rectangular spouted bed (30.2 mm × 101.6 mm). The objective is to provide a non-intrusive technique to determine the bed expansion ratio, the jet height and the fountain height due to their significant influence on the hydrodynamics of the entire bed. A high-speed video camera is used in the experiment with Geldart D particles as the bed material. After the image acquisition, image denoising, thresholding, logical and mask operations are applied correspondingly for the boundary discrimination, based on which an algorithm has been developed to determine the bed height successfully. With the discriminated boundary, morphological operations viz. erosion and dilation have been used to accurately determine the jet height and the fountain height. The feasibility of the technique is proven through profiles of bed expansion ratio, jet height and fountain height under three initial bed heights (0.0762 m, 0.102 m, and 0.127 m) for two different nozzle sizes (0.0096 m and 0.0127 m). Depending on the determination of the hydrodynamic characteristics, different flow regimes can be distinguished comprehensively through profiles of the bed expansion ratio and bed pressure drop in combination with the standard deviation of jet/fountain height. The proposed flow regime discrimination verifies the feasibility and effectiveness of the image processing methods in assessing the solids behavior in the spouted beds. Results about the variation of the jet height and the fountain height under current operating conditions as determined by the new technique are also discussed.

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1. Introduction

A spouted bed system, which can be regarded as a composite of a dilute central core and a dense annulus from the solid flow point of view, ensures good contacting and mixing between the gas and the solid phases due to the systematic cyclical movement of solids. Because of the unique hydrodynamic characteristics, spouted beds have been widely used in drying (Wiriyaumpaiwong et al., 2003, 2004), coating (da Rosa and dos Santos Rocha, 2010; Donida and Rocha, 2002), pyrolysis (Alvarez et al., 2015), combustion (Konduri et al., 1999) and gasification (Lopez et al., 2015).

In spouted beds, the jet and the fountain are two distinctive formations, the existence of which have significant influence on the hydrodynamics and practical efficiency of the system. For example, the jet is intrinsically responsible for gas bypassing and erosion of bed internals (Hong et al., 1996, 2003), while the fountain plays an important role in spouted bed reactor design and particle segregation (Grace and Matheur, 1978; Olazar et al., 2004). One major focus in studying the jet behavior is the jet penetration height (H_j). Collectively, both experimental and simulation efforts in quest for more understanding of the jet phenomenon have progressed. However, investigations targeting the influence factors on H_j have produced contradictory trends. Markhevka et al. (1971) studied the vertical jets in a cylindrical bed through motion pictures. They observed that the bottom part of the jet is conical, while the upper part exhibits an ellipsoidal shape. The upper part elongates and takes the form of a bubble until separating from the jet, after which the jet collapses. The process of jet expansion before and during bubble growth and contraction after bubble separation demonstrates a rhythmic and pulsating cycle. They defined the jet penetration depth as the vertical distance between the orifice and the lower edge of the bubble at the moment of separation. Additionally, they found that the defined depth varies by ±20% about its mean value due to its pulsating nature. Merry (1975) sketched the geometric arrangement of vertical jet and bubble based on the observations of Markhevka et al. (1971), and derived an expression to predict the penetration depth of the vertical jet. Blake et al. (1990) developed a correlation to represent the jet penetration height. Both equations from Markhevka et al. (1971) and Blake et al. (1990) showed that the initial bed height has no effect on the penetration depth. Knowlton and Hirsan (1980) defined three types of jet penetration depth according to the jet structure: the dilute phase height of the jet with the shape of a "torch" or flame, L_{min}; the dilute phase height of the jet having an appearance of a series of coalescing bubbles with "periodic necks", L_{max}; the deepest penetration of the jet bubbles before losing their momentum, L_B, where it was determined visually by measuring the distance that the bubbles penetrated the bed before the bed momentum could divert the bubbles significantly from their vertical path. Hong et al. (1996, 2003) adopted the definition of Markhevka et al. (1971) and Merry (1975), and derived a two-phase model to calculate jet penetration height under various operating conditions. They found that the jet penetration height increases with the jet velocity, but the bed height has little effect on jet penetration height. Adopting the definitions of Knowlton and Hirsan (1980), Zhong and Zhang (2005) reported that the determined jet penetration height in their study was consistent with L_{max}. According to their results, the jet penetration height is significantly affected when the bed height is low and decreases with increasing initial bed height in a two-dimensional spout-fluid bed. What caused these contradictory results, i.e., the jet penetration height has little relationship (Hong et al., 1996, 2003) or decreases (Zhong and Zhang, 2005) with the bed height? Possible reasons contributing to the contradiction may in part lie in differences in definitions of the jet, operating conditions, measurement methods, or bed configurations. To understand the contradictory trends and shed some light on the true hydrodynamic behavior of H_j, more studies are required before comprehensive insights can be obtained. As mentioned earlier, the fountain region has aroused much research interest largely because of its direct effect on reactor design and gas-solid contact efficiency. Grace and Mathur (1978) proposed a theoretical model to calculate the fountain height, which depends on the spout voidage and particle velocity at the bed surface level. Day (1990) presented an empirical correlation to predict the fountain height, which is a function of the gas-particle properties, the bed geometry and the fluid flow rate. The correlation predicted that the fountain height increases with the ratio of inlet gas velocity to the minimum spouting velocity but decreases with the bed height. The study of He et al. (1997) implied that the fountain height is very sensitive to particle shape. Olazar et al. (2004) found that the fountain height decreased with increasing initial bed height, particle diameter and inlet diameter as well. Increasing the relative velocity (gas velocity above the minimum spouting velocity) leads to linearly-increasing fountain height. Studying the spout characteristics in a cylindrical spout-fluid bed, Zhong et al. (2008) reported that the fountain height increases with increasing spouting gas velocity while it decreases with initial bed height. By increasing the fluidizing gas velocity and particle diameter, the fountain height decreases. Moreover, the fountain height increases with increasing bed pressure. Because of its unique effect on gas-solid contacting and mixing efficiency, modifications have been stimulated to optimize the hydrodynamic performance of the fountain region in spouted beds in an attempt to improve the heat and mass transfer rates in the gasification (Lopez et al., 2017) and combustion (Okasha, 2016) applications. A fountain confiner has been applied by Lopez et al. (2017), which greatly enlarges the fountain region, especially the fountain height so that the contact between the reacting gas and the catalyst is improved. As a result, tar cracking and biomass conversion efficiency could be promoted. Adopting the jet-fountain configuration, a bubbling fluidized bed combustor has been modified into a jetting-fountain fluidized bed (JFFB) by Okasha (2016). By creating a higher fountain with more particles, the JFFB can control the freeboard temperature to a higher extent effectively along the reactor height and dampen the overheating. In particularly, it is an option to utilize the staged-air technique in combustion process of gaseous and biomass fuels. Considering its great potential support to industry, more knowledge and data are needed to provide complete understanding of the hydrodynamic characteristic of the fountain region.

Techniques that have been used to investigate hydrodynamic characteristics experimentally in the published works can broadly be divided into two categories: intrusive and non-intrusive methods. The former is expedient for providing and revealing localized information and particulate behavior (He et al., 1994; Hong et al., 1996; Olazar et al., 1998), but the unquantified flow disturbance is inevitable and has always been a debatable topic. The latter is superior notably for little disturbance to the hydrodynamics being characterized, while data interpretation is more complex and relies on complicated programming and analysis (Liu et al., 2008; Sutkar et al., 2015; Zhang et al., 2017a,b). Despite the fact that each technique has its pros and cons, it is hard to ignore that non-intrusive techniques have been attracting more attention in different fluidization systems as a result of the development of digital image acquisition system and the improvement of imaging processing methods. Combining high-speed video techniques with digital image analysis to study hydrodynamic characteristics has been reported in different gas-solid systems, such as circulating fluidized beds (Lackermeier et al., 2001; Yang and Zhu, 2014, 2015), fluidized beds (Busciglio et al., 2008; Laverman et al., 2008), packed

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