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Determination of onset of bubbling and slugging in a fluidized bed using a dual-plane electrical capacitance tomography system

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HIGHLIGHTS

- Fluidization index decreases with an increasing Archimedes number.
- The bed height for stable slug flow depends on the particle size distributions.
- Both the particle size and the bed height influence the transition from bubbling to slugging.
- The dependency of slug index on the bed height decreases with an increasing Archimedes number.

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ABSTRACT

For a successful application of fluidized beds in chemical reactions and solids circulation, the boundary of regime of operation such as bubbling and slugging regimes, needs to be clearly defined. This study provides a method for determining the onset of fluidized bed regimes using a two-plane electrical capacitance tomography (ECT) sensor. The method involves computation and analysis of standard deviations of the solids fraction recorded at each plane of the ECT sensor for different superficial gas velocities. The experimental study is based on two different samples of 100–550 μm glass particles and one sample of 150–450 μm limestone particles. The results show that the onset of bubbling is determined when a bubble is first observed in the upper plane. The onset of slugging is obtained at the peak of the difference in the solids fraction fluctuation between the two planes, which is determined at the point where the rates of increase in the fluctuations are the same in both planes. The method developed in this study provides a means of obtaining accurate superficial gas velocities at the onset of slugging in fluidized beds.

1. Introduction

1.1. Background

Application of fluidized beds in processes involving chemical reactions and solids circulation, for example catalyst regeneration or heat transfer, requires a well-defined and stable contact regime [1]. Maintaining the appropriate regime is a major challenge in optimizing the design of fluidized bed reactors due to limited understanding of the dynamics characteristics of fluidized beds [2]. The properties describing the dynamic behaviour of a fluidized bed include the variation of bubble shape, bubble size and solids fraction distribution at different regimes [3].

When a bed is fluidized, it may transit from one flow regime to another depending on the gas velocity. The fluidized bed regimes include bubbling, slugging, turbulent fluidization, fast fluidization and pneumatic conveying regimes [4]. The transition from one regime to another is characterized with a certain superficial gas velocity and a certain bed void fraction. Being able to determine when transition occurs is important for the design of fluidized bed reactors. The most common method to determine the minimum fluidization velocity is by taking measurement of pressure drop in the bed at different superficial gas velocities. The onset of fluidization corresponds to the point where the pressure drop across the bed reaches a maximum value. The minimum fluidization velocity may vary with temperature, pressure or both depending on the properties of the bed [4].

The understanding of transition from the fluidized state to the bubble regime is not as good as that of minimum fluidization [5]. In a bed of larger particles, for example 100–1000 μm, many researchers have observed that bubbles appear as soon as the

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bed is fluidized. For fine particles such as fluid catalyst cracking particles, the bed expands significantly after the minimum fluidization before bubbles appear. This means that the superficial gas velocity at which bubbling occurs is higher than the minimum fluidization velocity. The difference between the minimum bubbling velocity and the minimum fluidization velocity is attributed to the significant magnitude of inter-particle forces between the fine particles [5].

With further increase in the gas velocity, the bubbles grow in size, and when the bubble size is in the order of the bed diameter, the bed slugs [6–8]. The superficial gas velocity at which a slug appears in the bed is the onset of slugging. The occurrence of slugs depends on the bed aspect ratio defined as the ratio of bed height to bed diameter, and on the particle size. In a large diameter bed, slugs rarely occur because the bubbles will not be able to grow in size up to the bed diameter. When a bed contains fine particles, it will be difficult for it to slug. This is because the stable bubble size in the bed is lower than the bed diameter due to competitive bubble coalescence and bubble splitting [4,5]. Slugs can be in the form of round-nosed structure in beds of materials that can be fluidized easily, or in form of square-nosed structure in difficult-to-fluidize bed materials [9].

The transition between regimes in fluidized beds is accompanied by the solids fraction fluctuation, pressure fluctuation and bed expansion [5]. Different techniques used in fluidized bed studies measure these properties directly or indirectly. Such measurement techniques include pressure transducers, capacitance probes, optical fibre probes, etc. Since different techniques may provide different information about the bed [10], a systematic analysis is required to evaluate the information from the different measurement methods [11]. Among other statistical tools, standard deviation is widely used in analysing the measurement data. The standard deviation can be used to measure the fluctuation of dynamic behaviour of a fluidized bed. In this paper, the fluctuation of the solids fraction is used to determine the behaviour of the fluidized beds. The solids fraction is measured using electrical capacitance tomography (ECT). ECT is a non-intrusive sensor used to measure the relative permittivity between two non-conducting phases. It is non-intrusive as it does not interrupt the flow or bed it measures. In addition to being relatively cheap, fast and flexible to use, ECT can be used in real-time applications, and this makes it more versatile compared to other tomographic methods such as X-ray, γ-ray and ultrasonic tomography [2]. Despite its numerous advantages, the temperature and size of the bed limit its application. In a bed with diameter larger than 30 cm, ECT is not reliable due to the nature of the soft field on which the measurement principle depends [12].

1.2. Previous works

Several studies have been published on different fluidized bed regimes and their transitions. Different techniques employed in identifying a fluidized bed regime are visual detection and analyses of bed property signals such as pressure fluctuation, voidage fluctuation and bed expansion. In a bubbling fluidized bed, the fluctuations arise due to propagation of pressure waves generated during bubble formation, bubble movement, bubble coalescence/splitting and bubble eruption at the surface of the bed [5]. These fluctuations are often analysed in terms of standard deviation, power spectra distribution and probability density function obtained over the measurement period.

The onset of transition from fixed bed to particulate regime (non-bubbling fluidized state) has been widely obtained from the measurement of pressure drops or their fluctuations at different gas velocities [4]. This method has been found to give consistent results independent on the particle size, bed diameter and bed static height. The minimum fluidization velocities have also been obtained from analyses of absolute pressure fluctuation [13–15], and void or solids fraction fluctuation for larger particles [16,17] on the assumption that the minimum fluidization condition coincides with that of bubbling regime.

The transition into bubbling regime is usually visualized as the gas velocity where the first bubble is seen erupting from the bed surface [18]. On the assumption that the fluctuations in fluidized beds are due to bubble formation and passages, different researchers have obtained the onset of bubbling regime at the gas velocity where the pressure [19] or solids fraction [17] fluctuations begins to rise from zero. Leu and Tsai [19] also observed that the minimum bubbling velocity is independent on the bed static height but on the location of the sensors for measurement of the absolute pressure fluctuations.

Slugging fluidized beds have been widely studied due to inconsistencies in the results presented by several authors. Different factors may be responsible for this variation, and these include sensor position during the measurement, variation in the bed diameter, bed height, particle size and particle shape [20]. Broadhurst and Becker [21] used visual detection to identify slugs, where the onset of slugging regime was obtained as the minimum gas velocity at which a bubble is seen to have a continuous floor around the bed circumference before arriving the surface of the bed. This method was shown to produce successful results where the bed height is above twice the bed diameter. Ho et al. [22] measured the minimum slugging velocity at a point where the absolute bubble rise velocity is locally minimum near the transition zone. The bubble rise velocity was obtained from the cross correlation of two different pressure fluctuation signals measured in the bed. In different beds of glass and sand particles, 358 – 1112 μm, Ho et al. found that the minimum slugging velocity is independent on the bed diameter and bed height.

Dimattia et al. [20] used the same technique as Baeyens and Geldart [7] to predict the onset of slugging regime. Baeyens and Geldart [7] identified the flow of slugs in a fluidized bed as either a single slug or a complete slugging. A single slug is observed when the pressure fluctuation spike passes through the datum established at the minimum fluidization condition while complete slugging is obtained when the slug frequency is constant for any change in the gas velocity. For larger particles (diameter above 500 μm), Dimattia et al. [20] observed that the minimum slugging velocity is independent on the bed height due to low resistance to gas flow offered by these particles. In a similar technique, Kong et al. [18] identified a slug flow when a negative amplitude followed by a positive amplitude of the pressure fluctuation crosses a datum line. In their results, Kong et al. concluded that the minimum slugging velocity for fine particles (diameter below 100 μm), is independent on the initial bed height.

Noordergraaf et al. [23] distinguished slugging from bubbling regime by the occurrence of single predominant frequency and a more regular pressure fluctuation pattern. The predominant frequencies are due to passage of single chain of bubbles when the bubble diameter is more than half of the bed diameter. In large particle systems, Noordergraaf et al. obtained the minimum slugging velocity at the point where the curve of predominant frequency versus gas velocity is minimum. For glass particles, 450–540 μm, no predominant frequency was found. The authors concluded that even for fine particles the method will not give results since the pressure fluctuations associated with their fluidization are too small to be sensed by the pressure transducers.

Du et al. [2] used ECT sensors to measure the solids fraction fluctuation at different gas velocities above the minimum bubbling velocity in different beds with diameters: 0.05, 0.1 and 0.3 m and initial bed height 0.5 m. The authors obtained the minimum slugging velocity at the peak of the solids fraction fluctuation. For the