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A new quantitative measurement method for mixing and segregation of binary-mixture fluidized bed by capacitance probe

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HIGHLIGHTS

- A new method for mixing or segregation of binary mixtures was developed.
- Mixing process of initially segregated binary mixtures was acquired.
- Distributions of mixing in binary mixtures fluidized bed were acquired.
- Effect of operating condition on mixing of binary mixtures was studied.

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ABSTRACT

Dissimilar solids fluidization is a widely encountered phenomenon in many industrial processes in which the inevitable mixing or segregation phenomenon is very important for reactor design and operation. In this paper, a new quantitative measurement method for mixing and segregation of binary mixtures in bubbling fluidized bed was developed based on capacitance probe. Verification experimental results showed that capacitance probe is a reasonable method for mixing and segregation of binary mixtures. A linear relationship between probe signal and fraction distribution of solids in binary mixtures was found. Transient and steady fluidization experiments of binary mixtures with almost equal size but different densities were conducted. In transient fluidization experiments, the real-time mixing process of initially totally segregated binary solids and finally reached steady mixing state were acquired. The mechanisms of mixing processes in binary mixtures fluidized bed with different density ratios were analyzed. In steady fluidization experiments, the distribution of mixing information in bubbling fluidized bed was acquired and the results showed reasonably good agreement with theories in the literature. In summary, capacitance probe proved to be a useful method in mixing or segregation of binary mixtures fluidization.

1. Introduction

Fluidized bed reactor has been extensively used in many industrial processes such as power plant, food, mining, pharmacy industries and so on. So far, developed theories of fluidized bed were obtained mainly based on single component solids fluidizations. But in a large number of industrial processes, dissimilar particles are usually used for various purposes, e.g. solids-solids mixer or classifier, assist fluidization in biomass gasification reactors and so on. Usually, the addition of secondary solids into fluidized bed makes the fluidization much more complex and the fluidization properties of binary mixtures have received great attention in recent years [1–6]. Inevitable mixing and segregation phenomenon of binary mixtures have a great influence on fluidization properties and have been the emphasis of many research works [7–14].

In binary mixtures fluidized bed, the bigger/heavier particles tend to reside at the bottom of the bed and referred to as jetsam while the smaller/lighter particles show the opposite tendency and referred to as flotsam [15]. The mixing of binary mixtures has been reported as a function of particle density and size, operating fluidization velocity, bed aspect ratio and the height of particle layer [11]. But a widely accepted theory of mixing and segregation of binary mixtures in fluidized bed has not been developed so far due to its complexity, as the particle shape, particle surface properties and other operating conditions may also affect the mixing and segregation property.

Previous researchers have conducted numerous investigations to achieve a comprehensive understanding of mixing and segregation phenomenon in binary mixtures fluidization. Nienow et al.

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Nomenclature

C_1	volume fraction of solids#1 in the total mixtures	ε	effective permittivity of mixtures
C_2	volume fraction of solids#2 in the total mixtures	ε_1	effective permittivity of the packing of solids#1
C_a	volume fraction of air in the total mixtures	ε_2	effective permittivity of the packing of solids#2
v	probe voltage signal	X^*	% of jetsam particles in any layer
v_1	voltage signal corresponding to pure solids#1	X_{bed}	% of jetsam particles in the bed
v_2	voltage signal corresponding to pure solids#2	S_b	solids mixing entropy
v_a	voltage signal corresponding to pure air	n	number of kinds of solids in mixtures
f_1	fraction of solids#1 in binary solids mixtures	h	bed height
f_2	fraction of solids#2 in binary solids mixtures	α_j	volume fraction of jth solids in mixtures
V_1	voltage signal of solids#1 packing	k	sensitivity of the measured probe signal
V_2	voltage signal of solids#2 packing		

carried out an experimental study in which two kinds of particles with equal size but different densities were fluidized [16]. Wu and Baeyens investigated a binary mixture system that particles of different sizes but equal density were fluidized in a 30-cm diameter bed [17]. In their work, the relationship between mixing/segregation properties to the bubble properties was discussed. In the experimental work conducted by Marzocchella et al., fluidization of binary mixtures of particles belonging to group B of the Geldart classification of powders was studied [18]. Different proportions of particles with almost equal density and dissimilar size were fluidized in a segmented fluidization column. Gilbertson and Eames experimentally investigated the formation of segregation patterns in initially homogeneous, fluidized, binary mixtures of particles [19]. Olivieri et al. conducted an experimental study in which fluidization behavior of binary mixtures of solids was addressed [20]. Axial solids concentration profiles along the bed and solids segregation rates were assessed as a function of the operating conditions. Palappan et al. studied the effect of particle density on segregation of binary mixtures of solids in a continuous fast fluidized bed [9]. What's more, in recent years, thanks to the rapid development of computer technology, numerical simulation has become a very useful tool in studying mixing and segregation phenomenon in fluidized bed [3,10,21–23].

In the experimental investigation of mixing and segregation of binary mixtures fluidization, the measurement method is a very important issue. By reviewing the previous experimental investigations, we found that rapid shut off method is a quite commonly used method. In this method, binary mixtures were usually extracted out of the fluidized bed after the fluidization was fully developed and the air supply was shut off instantaneously. This method provides a direct way to acquire the mixing information at the sampling ports, but there may be also some weaknesses such as:

1. The openings on the wall or segmenting the fluidized bed destroy the integrity of the reactor, which limits this method in many applications, such as high pressure, higher temperature and other extreme conditions.
2. Suddenly cutting off the gas supply interrupts the continuous production process and may be unrealistic in actual industrial processes.
3. The real-time mixing or segregation process in reactor with initial totally segregated or fully mixed binary mixtures cannot be acquired.

Based on these considerations above, the application of rapid shut off method to further experimental investigation and actual industrial process is limited. Fluidized bed as an important reactor has been widely investigated and many measurement technologies have been developed. But only a few of them have been adopted in binary mixtures fluidization, such as pressure drop [20], digital image analysis [24], X-ray radiography [23], neutron radiography [12], magnetic resonance (MR) [25], electrical capacitance tomography (ECT) [26] and so on. Pressure drop method has been used in binary mixtures fluidized bed to acquire the dynamics characteristics of fluidization such as minimum fluidization velocity [20], jet penetration depth in jetting fluidized bed [27] and so on. But the mixing or segregation of binary mixtures cannot be acquired directly through pressure drop method. Zhang et al. studied the fluid dynamic parameters in a jetting fluidized bed of a binary mixture using coloured particles with the same physical properties as those of the bed particle as tracers [3]. The solids circulation pattern in the bed was investigated by recording the movement of these tracers by digital image analysis. Wei et al. conducted a numerical study of mixing and segregation in a biomass fluidized bed and the results were compared to measurements obtained using X-ray computed tomography [23]. In the measuring process, an initially well-mixed bed was fluidized for 20 s and then abruptly collapsed by immediately stopping the fluidization gas. Wirsum et al. studied particle mixing in bubbling fluidized bed of binary particle systems with a new developed single particle trajectories method [7]. A new mixing index was proposed which was calculated based on the distribution time of tracer. Umekawa et al. conducted an experimental study in which quantitative measurement of segregation phenomena in a binary-mixture fluidized bed was achieved by neutron radiography [12]. The real-time segregation processes of initially mixed binary mixtures were acquired. Sommie et al. studied the mixing process of binary mixtures of free flowing sugar beads in a rotation mixer using MR method [25]. The results were quantified on the bases of image analysis to characterize the degree of mixing. The relationship between size ratio and number of rotations needed to acquire a steady state was discussed. The writer found that the lower the rotation speed, the more segregated the final state was. Rautenbach et al. investigated the segregation of spherical glass particles of different size in a bench scale cold fluidized bed using Electrical Capacitance Tomography (ECT) [26]. In their work, ECT method was used to identify the polydispersity due to segregation of different particle sizes with the same material density. The segregation was not directly measured but visually observed through the plexiglass column wall.

Here, the applicability and weakness about these methods are discussed. The pressure drop method has a good applicability in many experimental conditions, but the mixing or segregation of binary mixtures are reflected in the pressure drop file and cannot be measured directly. ECT method was used to identify the polydispersity of mixtures fluidization, but the mixing or segregation of binary mixtures also cannot be measured directly. In digital image analysis method, the mixing information can be visually observed, however in some cases the bed materials have the