Simulation of Particle Mixing and Separation in Multi-Component Fluidized Bed Using Eulerian-Eulerian Method: A Review

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ABSTACT: In practical engineering applications, the mixing and separation behavior of multi-component particles is of great importance to the fluidized bed operation. The development of many practical processes is inseparable from the knowledge of particle mixing and separation, such as material processing of ash-soluble coal gasification, multi-phase flow in boilers, and petrochemical catalytic processes. In recent years, due to the obvious advantages of the Eulerian–Eulerian model, many researchers at home and abroad have used it to study the mixing and separation behavior of particles. This paper reviews the use of Eulerian–Eulerian model to study the mixing and separation of multi-component particles in fluidized beds. The Eulerian–Eulerian model describes

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the gas-phase and each of the individual particles as continuums. The mechanism of particle mixing and separation, the influence of different factors on the particle mixing and separation including differences in particle size and density, the differences in apparent air velocity, the differences in model factors are discussed. Finally, an outlook for the use of Eulerian–Eulerian model to study the mixing and separation behavior of three component particles and related research on the drag model between particles.

KEYWORDS: Multi-component Fluidized bed, Eulerian-Eulerian model, Particle mixing and separation.

1 INTRODUCTION

Fluidized bed technology is widely used in energy, chemical, metallurgical, pharmaceutical and other industrial fields. Because of high combustion efficiency, low pollutant emission, strong fuel adaptability are consistent with the characteristic advantages of energy development and it has received extensive attention and research. However, it has internal dense gas and solid two-phase flow, high randomness and variety. Therefore, it is difficult to study the numerical study with the complex factors of coupling and solid-phase properties.

In an attempt to predict the internal dense gas and solid two-phase flow trends in gas-fluidized beds, a wide variety of mathematical models have been used. There are two calculation models of numerical simulation. One is Eulerian-Lagrangian model and the other is Eulerian-Eulerian model. Figure 1 shows the difference between the Eulerian-

Lagrangian model and the Eulerian-Eulerian model. The Eulerian-Lagrangian model uses two ways to research the fluid phase and particle phase: the fluid as a continuous state and the particle as a discrete state. However, different phases are considered as interpenetrating continua in Eulerian-Eulerian model. Because the Eulerian-Lagrangian model is limited by the memory and speed of the computer, only a small number of particles can be studied and the calculation process is simplified. And for fluidized bed, flow-flow mixtures, etc., where the volume fraction of some second phases is not negligible, the model has limitations. Therefore, when studying the mixing and separation of a large number of particles in a fluidized bed, the Eulerian-Eulerian method shows a significant operational advantage. Thus, using the Eulerian-Eulerian model for the study of gas-solid two phase flow is the current development trend of research.

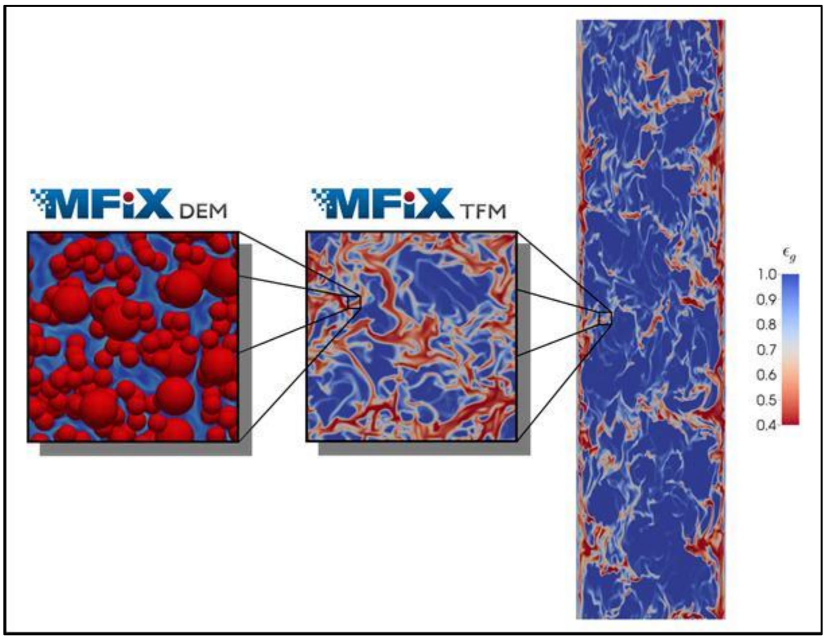


Figure 1: The simulation method of Eulerian-Lagrangian model and Eulerian-Eulerian model. (Tang, 2016).

The Eulerian-Eulerian model is a relatively mature model, and in recent years, with the addition of some theoretical models, the Eulerian-Eulerian model has been improved. In particular, the study of particle dynamics theory has greatly promoted the development of the Eulerian-Eulerian model. Bagnold (Bagnold, 1954) began to research on particle dynamics in 1954, and proposed the introduction of the original equation of particle collision frequency. In the 1980s, Savage and Jeffrey (Savage and Jeffrey, 2006) applied the theory of molecular motion to the theoretical study of the smooth hard sphere model, and they assumed that the collision between particles was purely elastic. Then, Jenkins and Savage (Jenkins and Savage, 2006) introduced the particle-particle restitution coefficient and proposed energy consumption concept. In order to better describe the movement of particles with different diameters and densities in actual systems, in 1987, Jenkins and Mancini (Jenkins and Mancini, 1989) proposed particle-based temperature definitions for multicomponent particle streams for two-component particle phase systems. Subsequently, Alam et al. (Alam et al., 2002) perfected the model and established particle models of different masses and sizes. Based on non-Maxwellian velocity distributions and energy non-average assumptions, Iddir and Arastoopour (Iddir and Arastoopour, 2005) applied particle dynamics theory to multi-component (including size and density) particle systems. In their results, each component particle is assumed to have an average velocity, turbulent kinetic energy and particle pseudo temperature. Gidaspow et al. (Ding and Gidaspow, 2010) applied particle kinetics theory to the particle continuous phase to save the computational resources and to find the macroscopic particle motion state. Recently, a multiphase model based on the kinetic theory of granular flow has been developed to study the mixing behaviour of biomass and sand particles in a bubbling fluidized bed by Hameed et al (Hameed et al., 2019). The accuracy of the model was verified by existing experimental data, and the effects of various parameters such as surface gas velocity, mixture composition and particle size were studied using the model.

The introduction of the drag model has further improved the Eulerian-Eulerian method. The drag calculation model in the multi-particle system is based on the single-particle drag model, and the particle volume fraction is introduced to correct the influence of the surrounding particles, and then correlated with the particle Reynolds number and volume fraction. There are two main methods: one is derived from the free sedimentation process of the particles, such as the Richardson & Zaki model (Zaki and Richardson, 1954); the other is derived from the fluidization process, such as Wen-Yu, Ergun and Gidaspow models (Wen, 1966, Ergun, 1952, Ding and Gidaspow, 2010, Gidaspow et al., 2004). Subsequently, some scholars made relevant corrections for the problems of the basic model. Lu et al. (Lu and Gidaspow, 2003) gave a method to modify the continuity of the Gidaspow model. Syamlal et al. (Syamlal and O'Brien, 1987) derived the drag force calculation formula ased on the minimum Richardson-Zaki velocity-porosity correlation. Vejahati et al. (Vejahati et al., 2009) proposed a new correction method based on the particle balance characteristics and gas-solid velocity characteristics at minimum fluidization velocity. The drag calculation model also includes Gibilaro, Koch-Hill and Mckeen models, etc (Gibilaro et al., 1985, Koch and Hill, 2001, Mckeen and Pugsley, 2003). Regarding the use of the drag model, the researchers conducted a large number of related simulation calculations. Peng et al. (Peng et al., 2009) studied the influence of classical Gidaspow model and improved the Syamlal-O'Brien model on the gas-solid flow in a fluidized bed by comparing theoretical calculation and experimental data. Esmaili et al. (Esmaili and Mahinpey, 2011a) used the Eulerian-Eulerian model for bubbling fluidized bed gas-solid two phase flow for studying the Wen&Yu, Gibilaro, Gidaspow, Syamlal-O'Brien, Arastoopour, the RUC, Di Felice, Hill Koch Ladd and a series of models for the movements of phase-to-phase. Lin et al. (Lin et al., 2010) embedded the Koch-Hill and Mc Keen models into Fluent through programming, and simulated the effects of the two and Gidaspow models on the gas-solid two-phase flow in a two-dimensional bubble bed. The results show that the Gidaspow model can realistically describe the shape of the bubble; the Koch-Hill model predicts that the bed expansion is more obvious; the Mc Keen model performs best in quantitative results. Li et al. (Li and Song, 2013) used Wen-Yu, Gibilaro and Gidaspow drag models to simulate the gas-solid flow characteristics in a bubbling fluidized bed. The results show that the Wen-Yu model produces large prediction errors, while the Gibilaro model achieves better prediction results.

It is an important research direction to study the mixing and separation behavior of multi-component particles. It has undergone the perfection of enlarging and theoretical research from a single particle to multi-component particles and has done a lot of theoretical research and experimental verification. The study on the mixing and separation of multi-component particles using the Eulerian-Eulerian model is obviously less than Eulerian-Lagrange model. However, the use of Eulerian-Eulerian model to study the mixing and separation behavior of multi-component particles is a trend in current research, and many scholars at home and abroad have studied the aspect. It is the purpose of this work to provide an overview of the development of Eulerian-Eulerian model was used to study the mixing and separation of multi-component particles in the fluidized bed.

2 MECHANISMS OF MIXING AND SEPARATION

2.1 Mechanisms of Bubble Dynamics

The movement of bubbles has an important influence on the mixing of particles (Sitnai, 1981). The upward movement of the bubbles in the vertical direction, the confluence of adjacent bubbles causes the lateral movement of the bubbles and the bursting of the bubbles at the surface of the bed, which together contribute to the intense mixing of the particles in the bed. The characteristic parameters such as the bubble size, speed and the density of the bubbles play decisive roles in the pressure drop, density, porosity and distribution of solid particles in the fluidized bed.

The bubble dynamics show that the movement of bubbles in the fluidized bed drives the movement of the particles. Some scholars have studied the mechanism of the effect of bubble motion on particle mixing and separation. Rowe and Nienow et al. (Nienow et al., 1973b) and Lin et al. (Lin, 2010) found that the mixing and separation of two-component particle systems in a gas-solid fluidized bed is caused by bubble motion. Figure 2 shows a large number of bubbles are generated in the vicinity of the fluidized bed distribution plate, and the deposition component entrained in the wake vortex moves upward with the bubble, and when the bubble rises through the fluidized bed, a local cavity is formed, and the hole will be filled by the upper particle. The whole phenomenon shows that the particles are mixed at high gas velocity and separated at lower gas velocity. The constant movement and exchange process causes the particles to exhibit different distances of separation, resulting in separation. Scott Cooper et al. (Cooper and Coronella, 2005a) researched the bubble behaviour, such as bubble growth, bubble coalescence and bubble eruption, having a significant influence on the mixing/segregation of binary particles. The simulation mainly studies the effect of mass exchange mechanism between particle phase and bubble on particle mixing and separation. Figure 3 shows the effect of bubble motion on particle separation. Figure 3 (a) indicates these velocity vectors changing over time, and Figure 3 (b) and (c) show that point inspace beside the rising gas bubble. Studies have shown that the separation effect between particles is due to the existence of smaller slip speeds. The apparent particle slip velocity, though slight, its influence accumulates over the passage of both time and additional bubbles.

Some studies have shown that the rotation of the particles themselves or the rotation of the bed structure itself will produce a large number of bubbles, which will have a certain impact on the mixing and separation of the particles. Numerical analyses of effect of particle rotation on gas and particles flow behavior were performed using two-fluid flow model by Wang et al. (Wang et al., 2007) and Zhu et al. (Zhu et al., 2009). Simulations show that bubbles are formed in the bed with particle rotation due to the more energy dissipated by rotation. Due to the generation of bubbles, the variation of particle concentration distribution in the bed is increased, which is more likely to enhance the non-uniform structure of the bed. Liu et al. (Liu et al., 2016) used the Eulerian-Eulerian model to simulate the flow characteristics of solid particles in an internal swirling fluidized bed. The simulation results show that the bubbles in the internal swirling fluidized bed are mainly generated on the high-speed wind side, and the bubble generation is beneficial to the lateral and vertical diffusion effects of the particles. The overall research results reveal that the structure of the bed is effective to emerge a large amount of bubbles, which is conducive to the strong mixing of materials in the bed.

The impact of bubble motion on particle mixing and separation in some specific cases is also reported in related literature. Norway's mark Taylor university college B.M. Halvorsen and B. Arvoh (Halvorsen and Arvoh, 2009) studied the fluidized bed with different particle size minimum fluidizing gas velocity, bubble motion behavior and pressure drop. By comparing the numerical simulation of bubble behavior with the experimental results, it is found that the phenomena of bubble formation, pressure drop and particle separation are basically the same. The document provides an effective way to study the motion behavior of bubbles in a fluidized bed in combination with numerical simulation techniques. He (2012) used numerical simulation to study the dynamic process of bubbles in aggravated fluidized bed. Exploring the effects of bubble dynamics on the separation behavior in fluidized bed and the separation effect of Geldart B particles. Computational Fluid Dynamics (CFD) simulations have been carried out to examine the hydrodynamics of a mixture of biomass and biochar particles in a bubbling fluidized bed by Sharma et al. (Sharma et al., 2014b). Figure 4 qualitatively shows the fluidization behavior of pinewood particles in the biochar bed following by the bubbles motion at different superficial gas velocities（u=0.45m/s，0.68 m/s，1.14 m/s，1.59 m/s）. The results show that the bubbles starts forming only at the minimum fluidization velocity, and this vigorous movement of particles with bubbles favours the mixing of the solid phases of different densities and sizes along the bed height. Because the segregation of binary particle mixtures is promoted by solids movement around rising bubbles, the segregation mechanism can be identified by tracking the velocity vectors of both solid phases near a passing bubble. And Cardoso et al. (Cardoso et al., 2018) studied the effect of bubble dynamics on the mixing effect of biomass particles. The research shows that biomass and sand particles movement within the fluidized bed is promoted by gas bubbles flow along the bed height. And the difference in frequency of bubbles formation and bubbles size leading to variation in axial and lateral movements of solid phases in the bed. Wang et al. (Wang et al., 2015) used a three-dimensional numerical study of the mixing and segregation of binary particle mixtures in a two-jet spout fluidized bed based on an Eulerian-Eulerian model. It is found that the segregation mechanism of binary particle mixtures can be identified by tracking the velocity vectors of both solid phases near a passing bubble. Lim et al. (Lim and Lim, 2019) found that the formation of bubbles generated more vigorous motions within the fluidized bed and higher particle velocities, especially at the bed surface where bubbles burst. Bubble formation generally promoted mixing and reduced segregation between flotsam and jetsam in such pulsating fluidized bed systems. Lim et al. (Lim and Lim, 2019) investigated the mixing and segregation behaviors of a binary mixture in a pulsating fluidized bed using Eulerian-Eulerian model. The research found that an increase in mean velocity increases the formation of bubbles and promoted mixing of the flotsam and jetsam in the fluidized bed. The formation of bubbles generated more vigorous motions within the fluidized bed and higher particle velocities especially at the bed surface where bubbles burst. Bubble formation generally promoted mixing and reduced segregation between flotsam and jetsam in such pulsating fluidized bed systems

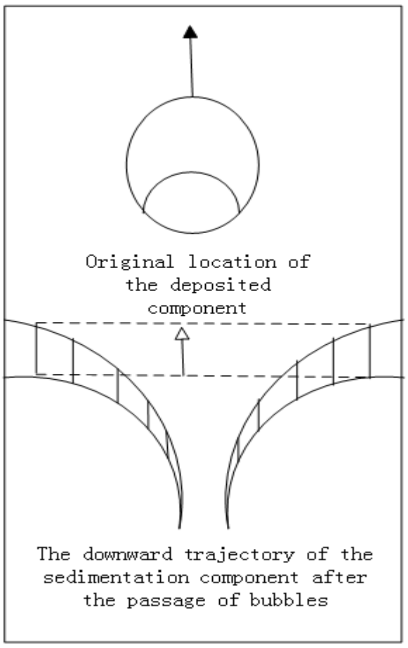


Figure 2: Schematic diagram of particle mixing and separation mechanism. (Nienow et al., 1973a).

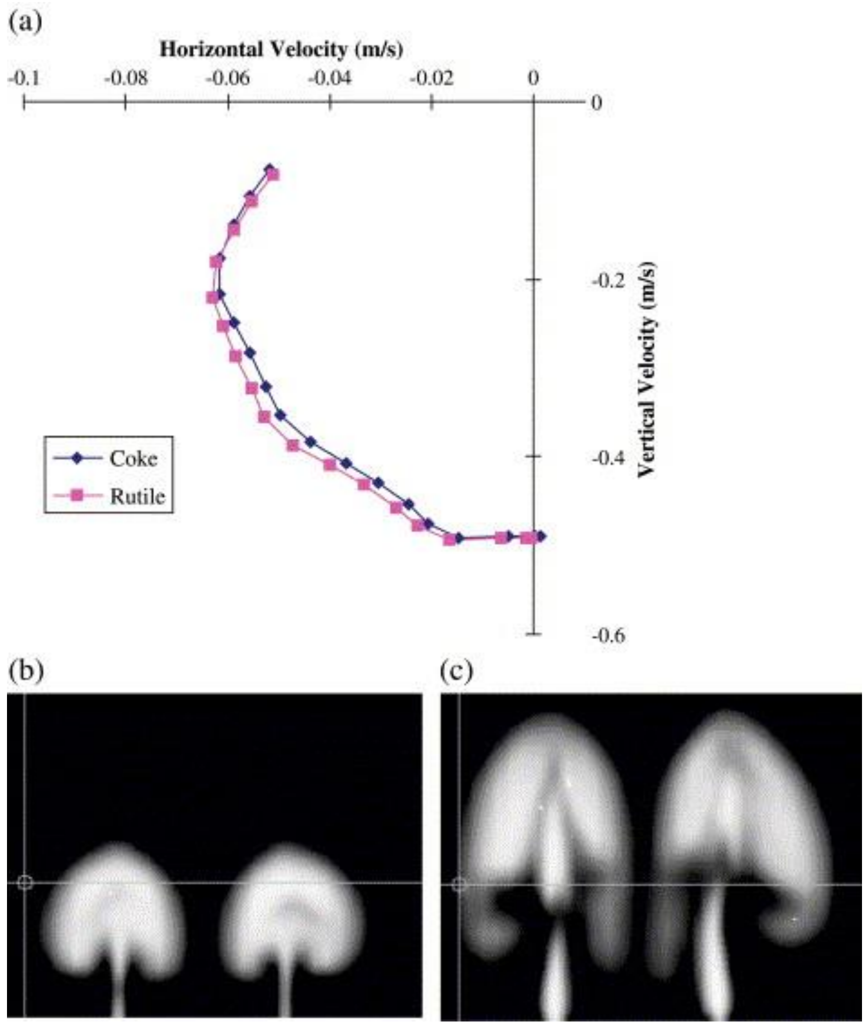


Figure 3: Illustration of segregation mechanism due to bubbling through a comparison of the velocity vectors for rutile and coke at fixed point (x, y)=(0.006 m,0.050 m). (a) Each point is the endpoint of a velocity vector beginning at the origin. (b) Location of bubble relative to the fixed point at t=0.20 s. (c) Location ofbubble relative to the fixed point at t=0.36 s. (Cooper and Coronella, 2005a).

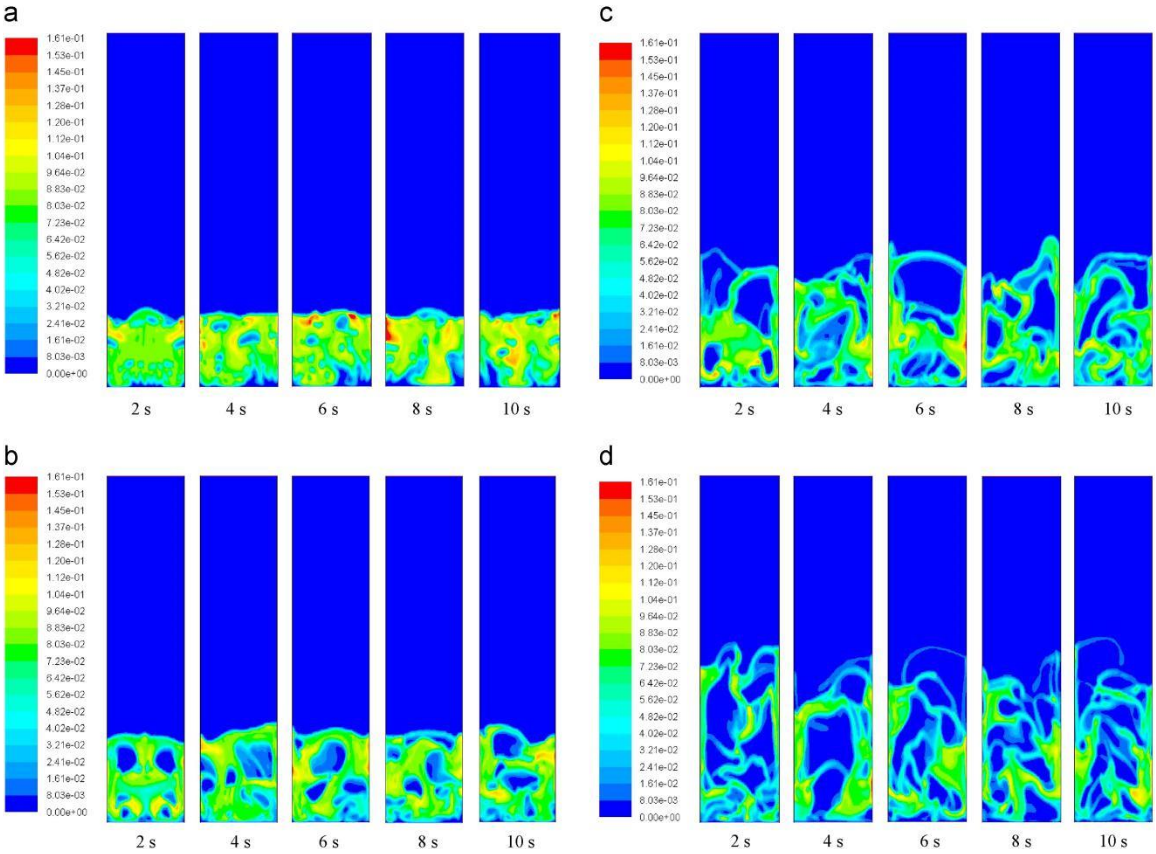


Figure 4: Volume fraction profile of pinewood as a function of time at different superficial gas velocities. (a) u=0.45m/s (u/umf=1); (b) u=0.68 m/s (u/umf=1.5); (c) u=1.14 m/s (u/umf =2.5); and (d) u=1.59 m/s (u/umf=3.5). (Sharma et al., 2014b).

2.2 The Drag Force Model Between Gas-Solid and Particle-Particle

In a gas-solid-solid system as illustrated in Figure5, moving particles are subject to various forces including accelerating forces, gravity, solid-solid stresses, and inner stress in a solid phase. The accelerating force, include drag force, lift force and virtual mass force etc. And the drag force between gas-solid and particle-particle plays an important role in the mixing and separation of particles.

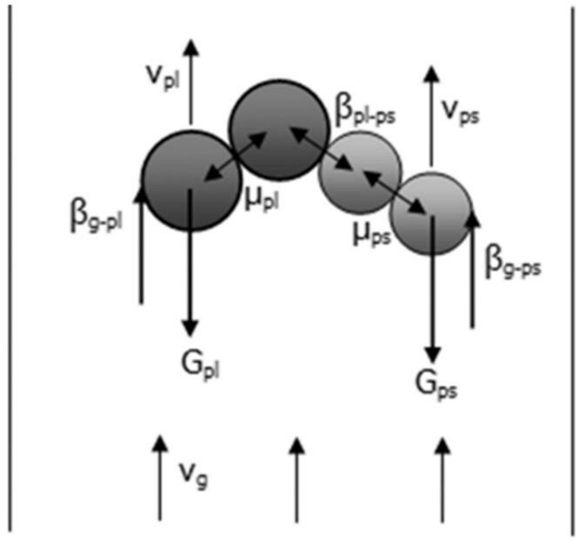


Figure 5: Forces and stresses in a binary particle system. (Du et al., 2016).

2.2.1 The Drag Force Model between Gas-Solid

There are three traditional drag models describing the interaction between the gas and solid: one is the empirical or semi-empirical model based on the experimental data, such as the Syamlal-O'Brien model (Gera et al., 1998) and the Gidaspow model (Yuan and Gidaspow, 1990) . And the common feature of the model is the basis of the single particle drag model, introducing the particle volume fraction function to describe the effect of surrounding particles. The second is a model derived from a purely mathematical method based on the theory of gas-solid interaction, such as the model of Zhang et al. (Zhang and Reese, 2003) and the Koch-Hill model (And and Hill, 2001) . The third is the modified empirical or semi-empirical model. The modified models, such as the modified Syamlal-O'Brien model (Zimmermann and Taghipour, 2005), the MeKeen model (MCKEEN et al., 2003).

Some scholars have studied the effect of traditional gas-solid drag model on the movement of particles in a fluidized bed. Azizi et al. (Azizi et al., 2010) simulated the size, density and combined size/density segregations in a bubbling fluidized bed with different gas–solid drag models and found that the Wen-Yu drag model was suitable for the simulation of these segregations. Based on the two-fluid model, Lin et al. (Lin, 2010) adopted a three gas-solid drag models based on different mechanisms: the Gidaspow model, the KochHill model and the McKeen model, and studied the gas-solid two-phase flow by observing the bubble behavior. The study found that the McKeen model is more accurate in calculating the bubble diameter quantitatively and in predicting the rate of bubble rise, suggesting that the model can better predict particle mixing and separation phenomena. Modeling the dynamic behavior of gas-solid flow in a pilot scale coal beneficiation fluidized bed (CBFB) model was performed by Wang et al. (Wang et al., 2013), a transient two-dimensional simulation was done based on two gas-solid drag models together with the kinetic theory of granular flows. It can be drawn conclusions that the Syamlal drag model gives better results than the Gidaspow model, as more realistic bubble number and size, particle velocity distributions and bed density distributions can be obtained. Sharma et al. (Sharma et al., 2014a) found that the choice of gas-solid drag models had a considerable impact on the hydrodynamics of the biomass-biochar mixture. Gidaspow, Syamlal-O'Brien and Huilin-Gidsapow model have been considered. The simulation results show that the Syamlal-O'Brien and Gidaspow models have similar trends in the prediction of results. However, compared with the Syamlal-O'Brien and Gidaspow models, the Huilin-Gidsapow model predicts less separation between pine and biochar particles. Bakshi et al. (Bakshi et al., 2015) modeled the hydrodynamics of dense-solid gas flows strongly affected by the Gidaspow and Syamlal-O'Brien model. The results suggest that the Gidaspow model is more applicable to homogeneous bubbling fluidization ($U/U_{mf} < 4$) while the Syamlal-O'Brien model is only suitable for high velocities ($U/U_{mf} < 4$) associated with larger bubbles and slugs.

However, for the traditional drag model, the gas-solid phase is generally based on the research, so it is difficult to accurately predict the mixing and separation between particles. The traditional gas-solid drag model is based on a gas-solid uniform structure, which overestimates the drag between gas and solid and can not reflect well the non-uniform flow structure in the fluidized bed. Therefore, in recent years, some scholars have improved the model based on the traditional drag model. Using the concept of minimum energy, Xiao et al. (Xiao et al., 2003) combined the traditional CFD method with the macroscopic systematic analysis method to establish a new theoretical model of gas-solid drag force for studying the particle agglomeration effect, which is consistent with the experimental data, and find it universal. Compared with the existing models, the new model not only has the same functional change relationship, but also can reasonably describe the physical process of gas-solid two-phase interaction, and predict the mixing and separation of particles accurately. Wang et al. (Yingce et al., 2014) proposed a structure-based drag model. The new model takes into account the influence of bubbles and mesoscale structures on the resistance, and more accurately predicts the mixed motion state of the particles in the bed. Zheng et al. (Zheng et al., 2015) obtained an improved drag model through a smooth function and coupled the Eulerian-Eulerian model to numerically simulate a two-dimensional bubbling fluidized bed. The study found that the improved drag model can better predict the agglomeration between particles and more accurately show the internal circulation process of particles. Wang et al. (Wang et al., 2018) extended the bubble-based drag model to binary hybrid systems. The simulated results reveal that the bubble-based drag model captures a relatively low bed expansion compared to the Gidaspow drag model and predicting the mixing and separation of particles near the surface of the bed is more consistent with measured data.

In recent years, the Yang Ning drag model based on the minimum energy multi-scale (EMMS) (Yang et al., 2003) has been vigorously developed. Researchers have combined the EMMS drag force with the complete two-fluid model to study the mixing and separation effects of particles in a fluidized bed, and achieved good simulation results. Hong, Kun et al. (Hong et al., 2013) proposed a new version of the bubble-based EMMS model and verified it by comparison with experimental data. Figure 6 shows that uses the bubble-based EMMS drag model to study the gas-solid flow conditions in the fluidized bed under three different conditions（bubbling fluidized bed，turbulent fluidized bed，circulating fluidized bed）. In all, the bubble-based EMMS drag predicts various heterogeneous structures in gas-solid fluidized beds, which agrees qualitatively with experimental findings. Qi et al. (Haiying et al., 2014) studied the

EMMS model based on "theory of energy minimum multi-scale" (EMMS). The core of EMMS theory is to decompose the entire non-uniform flow into “particle dilute phase”, “interaction phase "and “three uniform subsystems” (Li and Kwauk, 2003b). The study proposed different particle mass parameter models than all the existing drag models, which not only improved the model accuracy but also met the physical judgment. Chen et al. (Chen and Qi, 2014) used the particle cluster model to improve the EMMS drag model and numerically simulated the different working conditions. The flow characteristics of the fluidized bed of class A and B successfully predict the non-uniform distribution characteristics, local slip velocity, local non-uniformity and clogging state of the particles. The improved drag model more accurately predicts the mixing state of the particles in the bed and successfully captures the radial non-uniform distribution characteristics of the particles.

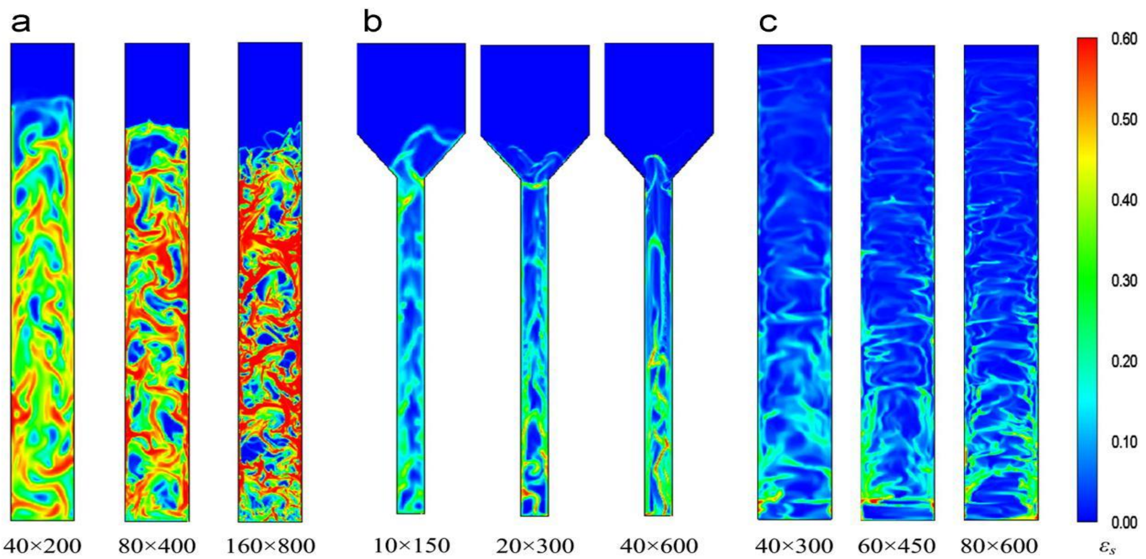


Figure 6: Snapshot of predicted solids concentration for (a): bubbling fluidized bed (Zhu et al., 2008), (b): turbulent fluidized bed (Venderbosch, 1998) and (c): circulating fluidized bed (Li and Kwauk, 2003a). (Hong et al., 2013).

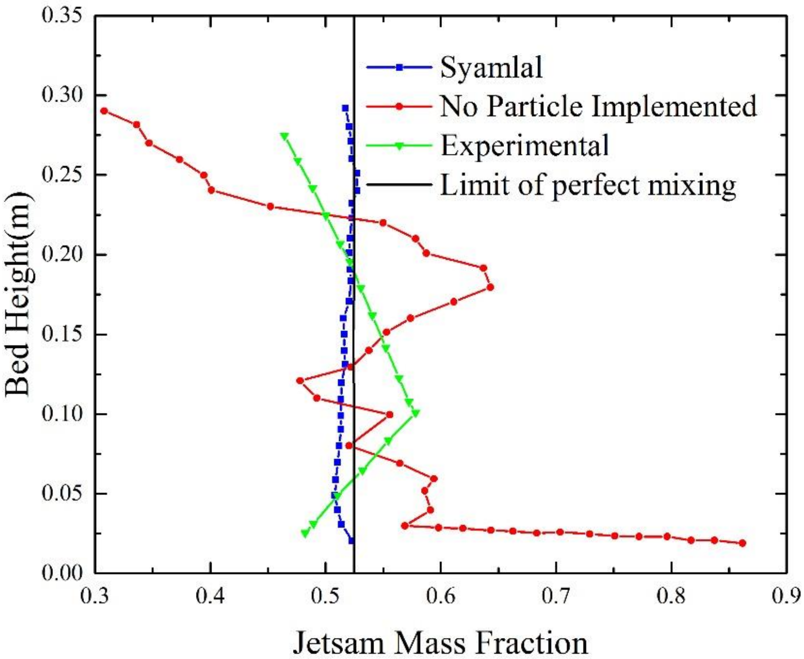
2.2.2 The Drag Force Model between Particle-Particle

The difference between particle sizes and densities cause the difference in the interaction between particles. The interaction between particles due to the generation of the small slip velocity and the accumulation of small slip velocity between the particles causes separation effect. The more common particle drag models are Arastoopour, Gidaspow, Nakamura Syamlal, Bell, Syamlal and Dinesh Gera drag models. Different drag forces between particles have their own using conditions and scope; they can obtain relatively accurate results in their scope of applications.

Some studies have shown that considering the drag model between particles, it is possible to better predict the separation effect between particles. Owoyemi et al. (Owoyemi et al., 2010) studied the effect of interparticle turbulence on mixing and separation by using the average of the particle phase instead of the usual solid phase average. Four simulations have been carried out in Figure 7; three wherein different constitutive equations for the particle-particle drag force are used, and a final one where the force is entirely neglected. The three drag models Syamlal, Bell and Gidaspow yielded similar results in terms of jetsam particle distribution within the bed, with an almost perfect mixing and a good agreement with the experimental data. In the no particle drag implemented case study, conversely, an overprediction of the jetsam mobility is found with a resulting tendency of such phase to segregate toward the bottom of the bed, which is in clear contrast with the experimental evidence. Li et al.

(Jun et al., 2013) based on the Eulerian-Eulerian model; a bubbling fluidized bed with two different particle sizes in a bed was studied using numerical simulations. In addition, the separation of large particles and small particles was investigated to the particle-particle phase drag model. The results show that the gas can fully interact with the solid particles considering the particle-particle phase drag model, indicating that the particle-particle phase drag model in the numerical simulation can predict the gas-solid two-phase flow in the bed more reasonably.

In order to better predict the interaction between particles, some scholars have improved the drag model between particle-particle based on traditional models. Wang et al. (Wang et al., 2012) based on the Eulerian-Eulerian model, a particle-particle drag model considering particle slope coefficient of segregation was presented for simulation of the bubbling fluidized bed with two different sizes particles and a uniform gas inlet. By comparing the simulation results with Owoyemi's experimental results and numerical simulation results, it is found that the model predicts and analyzes the characteristics of particle mixing and separation in the bed more reasonably. Gan et al. (Gan et al., 2012) showed that particle-particle drag played an important role in the separation and mixing of multi-component particles. In the work, several drag law models (Non-particle-particle drag force model (NPP-model), Syamlal model (SPP-model) and Bell model (BPP-model))are used to study their effects on particle segregation in a gas-solid fluidized bed. Compared to Syamlal and Bell model, the non-particle-particle drag model yields a significant particle separation in the axial direction, which is in good agreement with the experimental values. However, the simulation results indicate the limited ability of both SPP-model and BPP-model to capture the particle segregation in the fluidized system. Zheng (Zheng et al., 2015) proposed an improved resistance model for the problem of particle resistance drop at low particle concentration conditions and used the Eulerian-Eulerian model to simulate the flow characteristics in a bubbling fluidized bed. The results show that the improved drag model predicts the radial particle concentration distribution better and predicts the local pressure drop of the bed better.



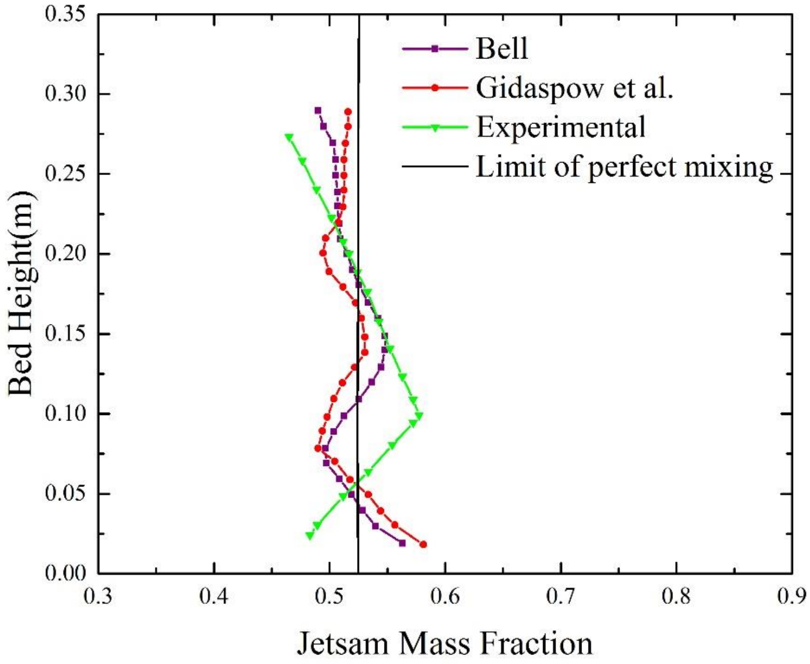


Figure 7: Comparison of computational and experimental segregation patterns (Syamlal, 1987, Bell, 2000, Gidaspow et al., 1986). (Owoyemi et al., 2010).

3 DIAMETER AND DENSITY AFFECTION MIXTURE AND SEGREGATION

The difference in particle size and density have a significant effect on the separation and mixing of particles. Solids mixing and segregation phenomena occur when a binary mixture is submitted to a fluidization process. Solids movement promoted by the air flux will induce a buoyancy effect, forcing the solid particles to arrange and find the equilibrium according to their size and density. Particles will then either segregate, if the size or density ratio is larger; or mix if the particles size or density ratio is lower. Depending on the composition of the particles, some researchers have defined the degree of mixing and the degree of separation (Murray, 1965, Bai et al., 1999, Rowe, 1972, Shao and Lai, 1991, Peng et al., 2013). Following the Owoyemi et al. (Owoyemi et al., 2010), the top 25% of the bed is chosen to calculate the top region. The variation of the mixing index with the jetsam particle size at different velocities is shown in Figure 8. It can be found that as the jetsam particle size decreases, the mixing index is reduced. When the operating velocity is reduced, the descending degree of the mixing index is enhanced. And it is mostly marked at low gas velocities especially when there is appreciable particle density difference. However, even a strongly segregating system, it can be fairly well mixed if the gas velocity is increased sufficiently(Rowe and Nienow, 1976). Hence, a reasonable match of particle propertiesand operating velocity is a key to achieve the segregation of a binary mixture. (Cardoso et al., 2019)

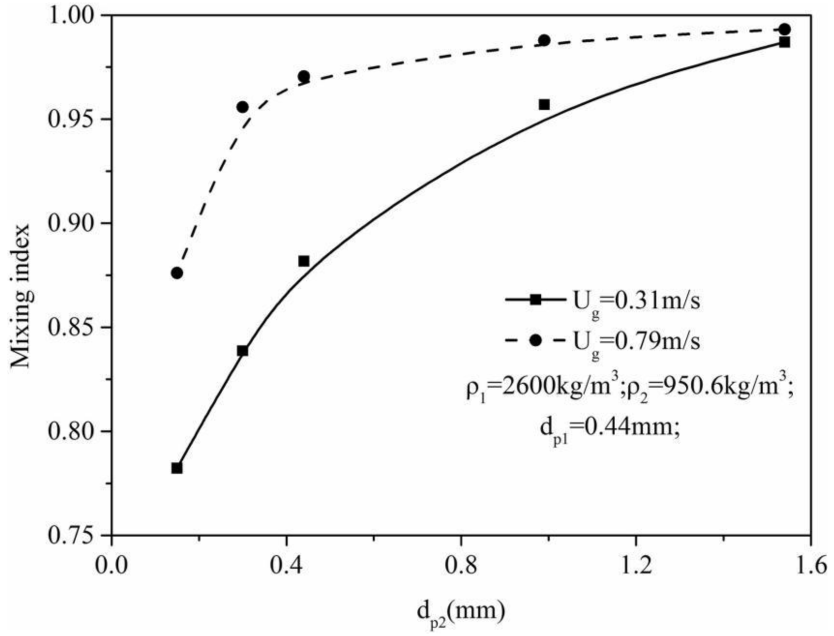


Figure 8: Variation of mixing index with jetsam particle size at different velocities. (Owoyemi et al., 2010).

3.1 System of Two-Component Particles

When two-component particles by different size or density of the composition, which one has a lower minimum fluidization velocity of the particle (flotsam) are first fluidized, and another has a large minimum fluidization velocity of the particle (jetsam) is still filling state. Therefore, the basic fluidization characteristics of two components the system is more complex than the single is not necessary to promote mixing component system. The fundamental reason for the separation or mixing of particles in the fluidized bed is due to the rising movement of the bubbles (Sinclair, 1994, Hoffmann et al., 1993) that we have explained before in the study of the mechanism. In recent years, many scholars have done some researches on the influence of mixing and separation on two-component particles density and size. The following will briefly summarize the research results of domestic and foreign scholars.

Some studies have shown that particle size differences in two-component systems have a significant impact on particle mixing and separation systems. The fluidization behavior of binary mixture differing in size in the gas bubbling fluidized bed is experimentally and theoretically studied by Lu et al. (Lu et al., 2003b). The research reveals that the fluidization behavior of a binary mixture differing in particle sizes with the same density is strongly influenced by the variations of average particle diameter in the bed. Reddy et al. (Reddy and Joshi, 2009) used the Eulerian-Eulerian model to simulate the mixing and separation of two-component particles. The report found that when there are certain particle size difference between particles, some segregation occurs; when the difference in particle size is small, the two particles are completely mixed in the flowing state. Mostafazadeh et al. (Mostafazadeh et al., 2013) and Zhong et al. (Zhong et al., 2016) studied the distribution of particles in a two-component system with different particle sizes at different superficial gas velocities. The research demonstrates that in the initial state, a mixture of large and small particles uniformly mixed at a certain height is accumulated in the bed. At the lower gas velocity, the two kinds of particles are classified according to the difference in particle size. During the large particle classification process, they are deposited on the bottom of the bed, while the small particles are concentrated on the top of the bed.

In the multi-component fluidized bed system, the effect of the difference in particle density on the motion behavior of the particles is also studied. Chao et al. (Zhongxi et al., 2012) used a two-fluid model to study the segregation behavior of two types of particles with approximately same particle diameters and different particle densities in a dense binary gas fluidized bed. The simulation result shows that the jetsam and flotsam are segregated apparently axially; generally, there are lighter flotsam in the top of the bed and more heavy jetsam near the bottom. Zhang et al. (Zhang et al., 2004) selected a representative non-equal density/diameter two-component system (resin and sand) as the research object, and used the Eulerian-Eulerian model to simulate the motion behavior of two-dimensional cold-mode jet bed particles. The study found that the local circulations exist randomly in the global circulating flow in a two-component particle system. Solid circulation pattern is divided into three regions : jetting region , bubble street and annular region, which results in strong mixing of particles. The effect of biomass density and particle size on the mixing/segregation behavior of biomass-biochar mixture was analyzed using the Eulerian-Eulerian model by Sharma et al. (Sharma et al., 2014a). It is found that by changing the density of the biomass particles while keeping the gas velocity constant, the mixing state of the two-component particles can be greatly changed. Since the biomass component content is relatively small in the whole, the change in the degree of biological plasmid does not change the overall mixing and separation state of the system. The aggregation process and flow behavior of ultrafine powders in a spouted bed were simulated and analyzed under varying operating conditions with a two-fluid model coupled by Sun et al. (Sun et al., 2017). Figure 9 shows the mixing behavior of ultrafine and coarse particles and illustrates the agglomerate diameter as a function of fluidization time for two different conditions. From the Figure 9, we can see that under theeffects of inter-particle force, ultrafine particles form agglomerates when collisions occur, and the agglomerate diameters increase with fluidization time, and for the case with coarse particles, the agglomerate diameter at a steady state is smaller than that without coarse particles because of the cutting and isolation effects. The mixing behavior demonstrates that the coarse particles may perform better when effectively mixed with bed materials. The results demonstrate that the movement of the coarse particles weakens the strong inter-particle force between ultrafine powders and breaks agglomerates into smaller ones, and effective mixing will lead to improved coarse particle performance. Hassen et al. (Hassen et al., 2018) used the Eulerian-Eulerian fluid model to simulate the cold flow of a gas-solid mixture in a G-Volution circulating dual gasification reactor. The mixing and segregation dynamics of a binary solid mixture of biomass(ρ =426kg/m^3, d=0.856mm) and sand(ρ =2650kg/m^3, d=0.385mm) with different size and density were considered. The result shows that a visible segregation of the biomass that rises above the sand particles is observed. This is due to the density which has the dominating effect and the denser component act as jetsam.

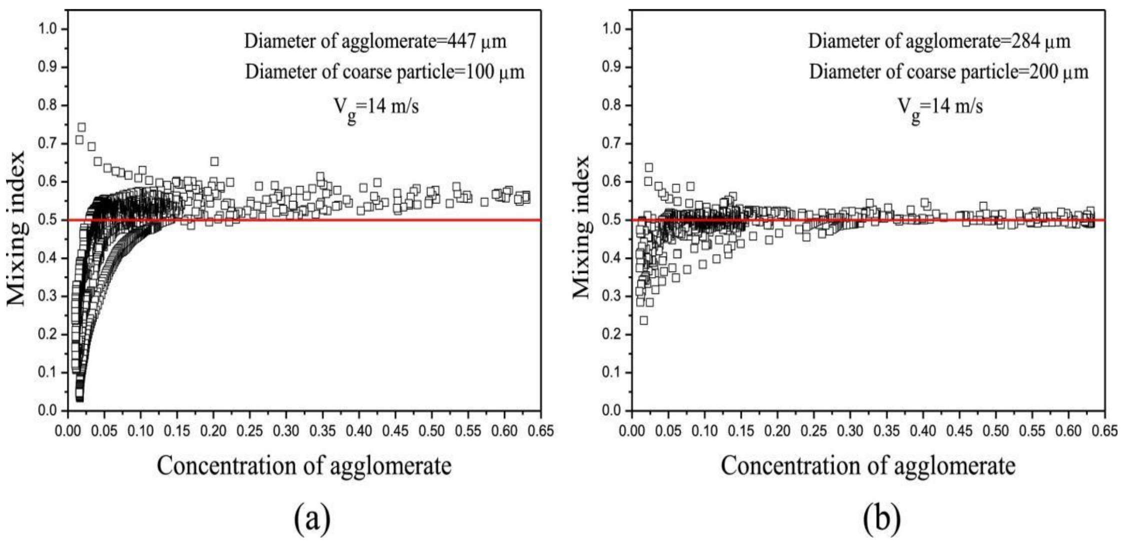


Figure 9: Agglomerate mixing index profile in the spout bed as a function of concentration: (a) 100μm and (b) 200μm. (Sun et al., 2017).

3.2 System of Three-Component Particles

In actual industrial production, many materials are made up of two or more obviously different materials. The particle size and apparent density of different particles in a gas-solid fluidized bed have different effects on fluidization characteristics. There is a strong interaction between the gas in the fluidized bed and the particles and the mixing and separation mechanism of the three-component or even multi-component particle system particles is more complicated than the two-component particle system. In practical engineering, most of the research objects are composed of three-component or even multi-component particle systems. Therefore, it is more practical to study the three-component or even multi-component particle system.

Some literature indicates that in a three-component particle system, the difference in particle size leads to the separation effect between particles. Mathiesen studied (Mathiesen et al., 2000) the flow behavior in a circulating fluidized bed by approximating a realistic PSD as three discrete particle sizes. A realistic description of the particle size distributions in gas/solids flow systems, the three solid phases have diameters of 84, 120 and 156 mm , respectively. Through the simulation, the research finds that the vertical segregation is observed for a wide PSD, and segregation for a narrow PSD. Wang et al. (Wang et al., 2018) investigated the mixing and segregation performance of binary mixture. Here, different biomass particle diameters (0.15mm, 0.3mm, 0.44mm, 0.99mm and 1.54mm) are chosen. The segregation behavior of the second solid phase for different sizes can be observed at the operating velocity. As the particle size decreases, the segregation phenomenon becomes significant owing to its descending minimum fluidization velocity. Liu et al. (Liu et al., 2003) based on the kinetic theory of dense gas molecules and particle dynamics, the interaction between particle-particle in multi-component particles, the interaction between gas-particles are considered. The study proposed a multi-component particle, non-isothermal particle, gas-solid two-phase flow model and multi-component radial distribution function calculation method, which predict the mixing and separation behavior of particles in the fluidzed bed accurately. Tang et al. (Tang, 2016) studied the numerical simulation of the fluidization characteristics of the multi-component particles in circulating fluidized bed. From the research, It can draw conclusions that the concentration distribution pattern does not appear different due to different particles. Although the distribution of fine particles in the hearth is also consistent with the trend of thinning and thickening, it is more uniform than the other two kinds of particles. The medium particles are mainly distributed in the middle and lower sections, and a high concentration of particles accumulates at the bottom slope. However, the shape of the particle distribution region is the same as that of other particles, and the coarse particles show a significant difference in concentration, and they are gathered at the bottom of the furnace to the secondary air. Cardoso et al. (Cardoso et al., 2018) studied the effects of particle size and density of three different biomasses and sand on particles mixing and separation. Fig. 10 and Fig. 11 show the distribution patterns relating the density and size effect in mixing and segregation, along the bed height, for the binary mixture of quartz sand and the three biomass species, respectively. The results of the simulation study indicated that mixing and segregation differences among the two granular species depend on the density and size ratio effect of the biomass-sand mixture, where the physical differences regarding the two species contribute to the solids distribution in the bed. Cardoso et al. (Cardoso et al., 2018) studied 2D and 3D numerical simulations to predict the behavior of the entire gasification process in a bubbling fluidized bed reactor. The effect of density difference of quartz sand and the three-biomass species on particle mixing and separation was studied in Fig. 12. The yellow shaded area points the level of biomass segregation at the bed top. Both 2D and 3D time-averaged density profiles show that the lighter biomass, balsa wood (137 kg/m^3), revealed higher segregation at the bed top. When the density of biomass particles increases, both models show a weakening of the separation effect between particles, and the mixing behavior tends to increase to some extent.

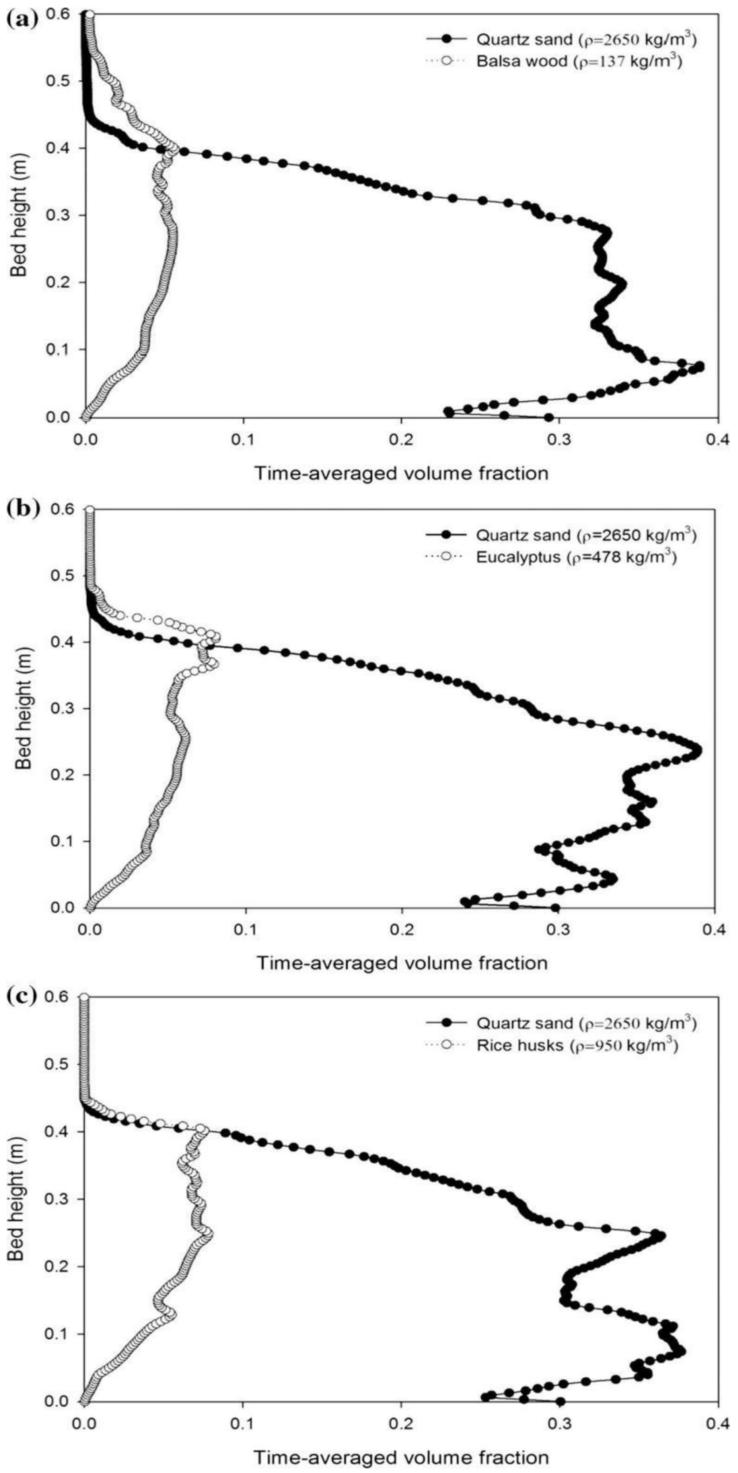


Figure 10: Density comparison between quartz sand and the three tested biomasssubstrates volume fractions along the bed height, measured by means of a vertical centerline. (a) balsa wood (ρ = 137 kg/m3); (b) eucalyptus (ρ = 478 kg/m3); (c) rice husks (ρ = 950 kg/m3); (t = 3 s) (Cardoso et al., 2018).

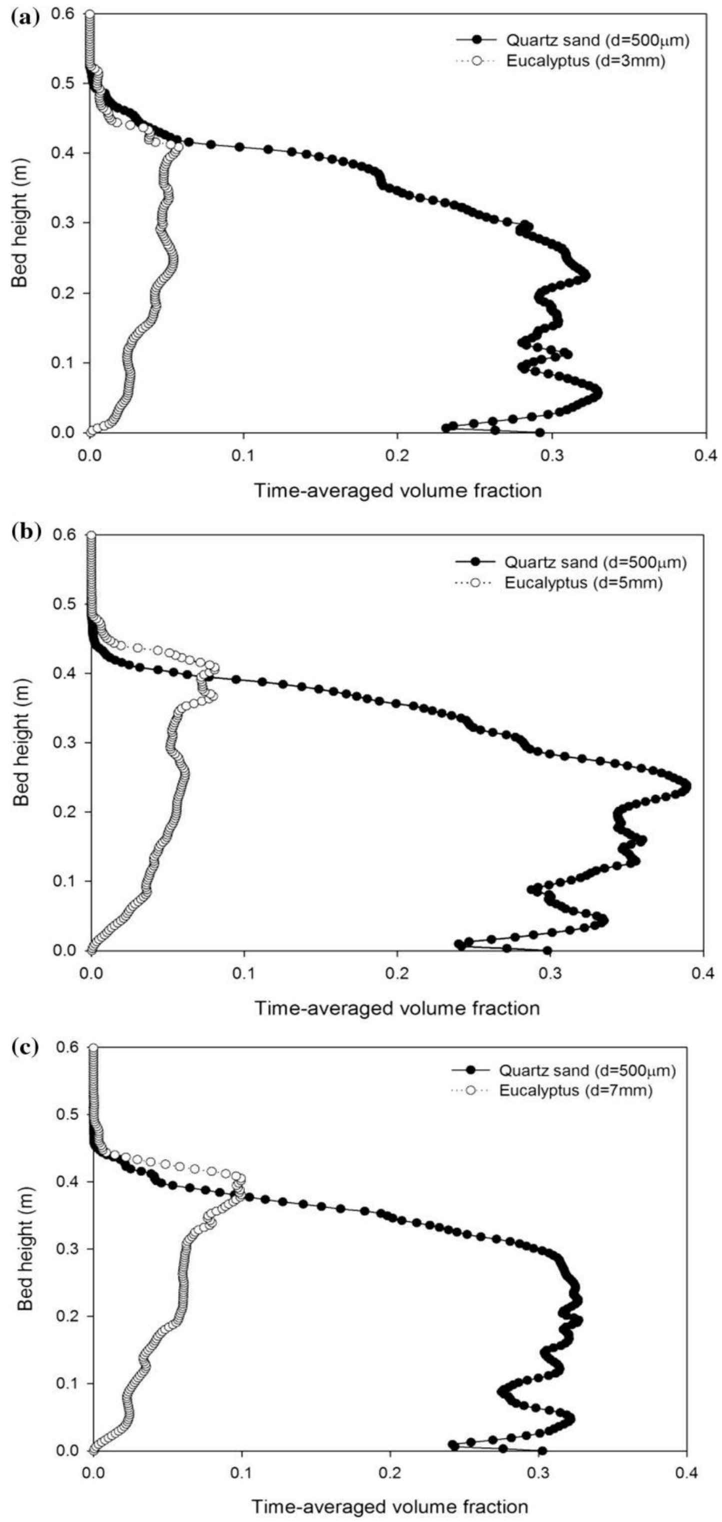


Figure 11: Size comparison between quartz sand and three different eucalyptus particle size volume fractions along the bed height, measured by means of a vertical centerline. (a) deuca=3mm; (b) deuca=5mm; (c) deuca=7mm; (t=3s). (Cardoso et al., 2018).

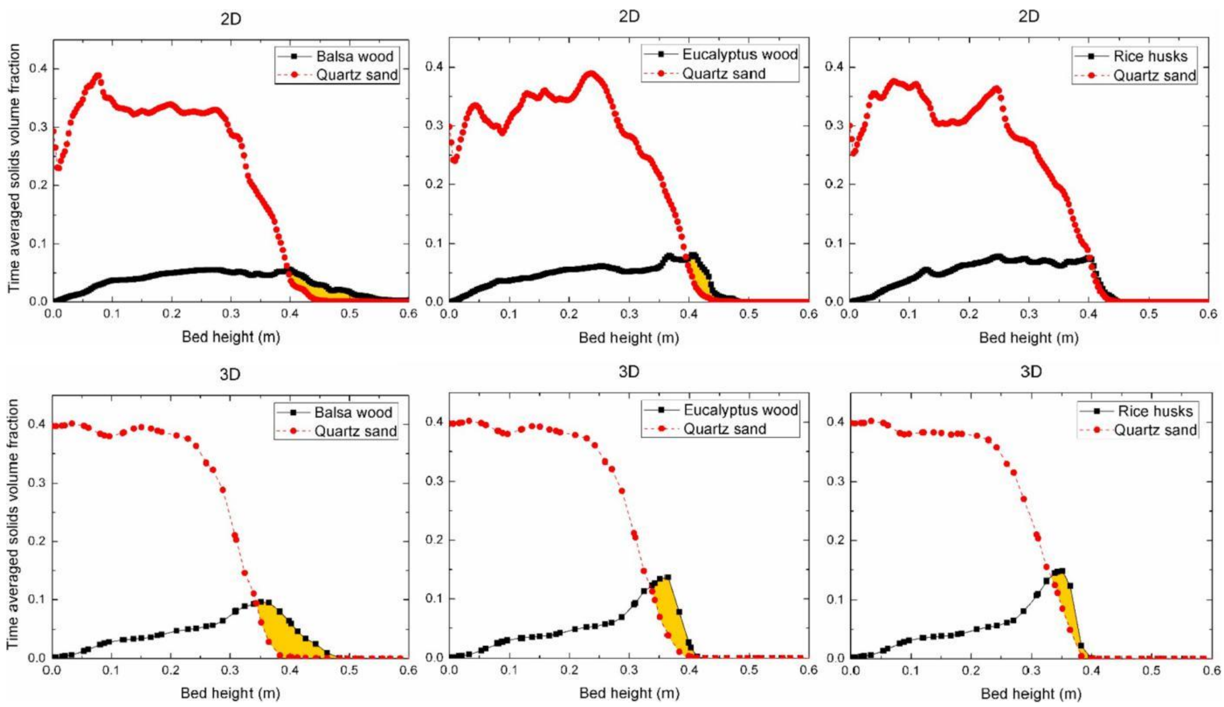


Figure 12: Density effect on mixing: 2D and 3D time-averaged solids volume fraction comparison between quartz sand and the three biomasses tested (balsa wood, eucalyptus and rice husks) gathered at the reactor's centreline. (Cardoso et al., 2019).

4 EFFECT OF THE GAS VELOCITY

The difference in gas flow rate will have an important effect on the mixing and separation of particles when the fluidized bed is composed of various particles with different diameters or densities, and there will be three typical particle mixing and separation states due to the gas velocity in Figure 13. In the three states, the first state is that when the air velocity is low, the particles are completely separated. The second state is when the gas velocity is moderate; the particles are partially separated and partially mixed. Finally, the particles are presented at high gas velocity, and they eventually reach the complete mixing stage. The minimum fluidization speed has a great influence on the movement of the particles. At present, for the minimum fluidization velocity of multi-component particles, the experimental value is generally fitted to determine the minimum flow of the mixture. The speed curve, and finally draw an empirical formula to predict the value. Mohammad Asif summarized and classified detailed calculation methods for minimum fluidization velocity under various conditions based on previous experience. For mixed-grained fluidized-bed with different properties and multi-component particles, a hybrid particle system was proposed. The minimum fluidization speed formula as follows:

$$\frac{1}{\sqrt{U_{mf}}} = \sum_{1}^{n} \frac{X_i}{\sqrt{U_{mfi}}}$$

(3)

Many researchers at home and abroad have studied the effect of gas velocity on the mixing and separation of particles.

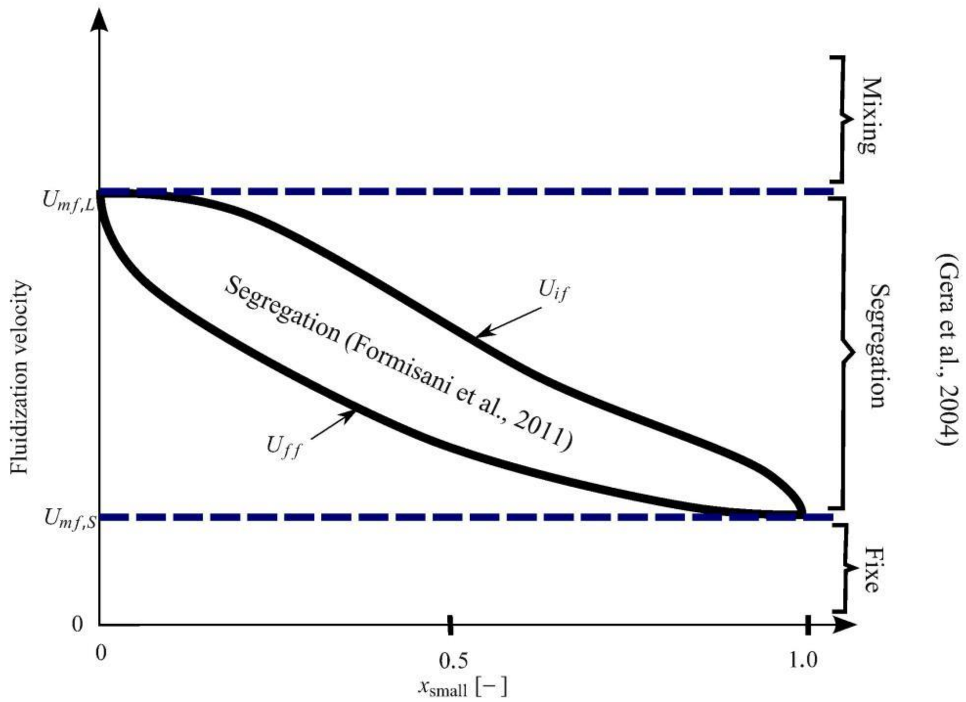


Figure 13: Diagram of the fluidization patterns of binary mixture system. Formisani et al. (Formisani et al., 2011) shows a density-based binary mixture:U_{if} is the initial fluidization and U_{ff} refers to the velocity at which fluidization state is achieved. $U_{mf,S}$ and $U_{mf,L}$ denote the minimum fluidization velocities of the small and large particles, respectively. (Konan and Huckaby, 2017) (Gera et al., 2004).

More studies (Sharma et al., 2014a) (Cardoso et al., 2019) (Lu et al., 2003b) have shown that in multi-component fluidized bed systems, at low gas velocities, particles of different compositions exhibit a separation state, and at higher gas velocities, uniform mixing phenomena are exhibited. Cardoso et al. (Cardoso et al., 2019) studied 2D and 3D numerical simulations to predict the behavior of the entire gasification process in a bubbling fluidized bed reactor. In order to evaluate the effect of superficial gas velocity on mixing in 2D and 3D configurations, four different inlet velocities were practised (0.15, 0.25, 0.4 and 0.6 m/s) and presented in Figure 14. Results show that higher superficial gas velocities (0.6 m/s) presented improved mixing ability (higher mixing index), while for the lower velocities (0.15 m/s) the trend changed providing a diminished mixture (lower mixing index). Concerning the superficial gas velocity effect on the mixture, the 2D and 3D profiles show a reasonable agreement. In addition, some literature indicates that gas velocity has a more sensitive effect on the mixing and separation of particles. Jinsen Gao et al. (Gao et al., 2009) showed that binary mixture of Geldart A and D particles with the gas velocity range of 0.2-0.7 m/s was researched in their simulations. The results show that at low gas velocity, most of the binary mixtures tend to segregate. At moderate gas velocity, particles mix well in the dense phase. Further increasing the gas velocity, small particles begin to accumulate in the upper regime of the bed, and a segregation trend appears again. At high gas velocities, segregation efficiency in the continuous classification process increases with increasing the gas velocity and mean residence time of the binary mixture, however, it will occur to decrease with increasing the small particle content. Chao et al. (Zhongxi et al., 2012)studied the separation behavior of two types of particles with roughly the same particle size and different particle densities in a dense binary gas fluidized bed using a two-fluid model. Research shows that at a comparatively low superficial gas velocity, the particles mainly segregate axially, and at a comparatively high superficial gas velocity, the particles segregate both axially and radially.

However, a few studies have shown that multi-component particles do not exhibit segregation at low gas velocities. Gera et al. (Gera et al., 2004) extended a two fluid model (gas and one granular phase) to a multi-fluid model (gas and several granular phases) by adding constitutive equations for the particle-particle drag and the maximum particle packing. The research reveals no segregation at low fluidization velocities, segregation at intermediate velocities, and vigorous mixing at large fluidizing velocities. The predicted segregation rate for a three-phase fluidized bed matches very well with the measured values. Moreover, Wang et al. (Wang et al., 2009) based on the particle trajectory model, and simulation of separation behavior of three-component particles in fluidized bed. The behavior differences of particles at different apparent gas velocities were studied. The apparent gas velocity has an important effect on the separation of three-components, when the gas velocity is small, the expression of heavy constituent and intermediate component particles show for jetsam and light component particles show for floatsam; when the gas velocity is moderate, three compounds were separated completely; when the gas velocity is large, heavy particles appear as jetsams, however, light particles and intermediate particles show floatsams; when the gas velocity is too large or too small, the three-components showed a completely mixed state. Lee et al. (Jian and Lim, 2017) studied the Eulerian-Eulerian model and CFD-DEM applied to perform simulations of solids mixing behaviors in gas fluidized beds with various inlet gas velocities. Figure 16 shows the solids volume fraction profiles of solids originally in the bottom section of bed at different times using Eulerian-Eulerian and CFD-DEM model. The figure indicates that solids mixing behaviors simulated use Eulerian-Eulerian and CFD-DEM approaches showing that significant differences could arise at low inlet gas velocities. At gas velocities close to that of incipient fluidization, CFD-DEM predicts higher rates of mixing than the Eulerian-Eulerian model.

Related studies have shown that increasing the apparent gas velocity directly affects the motion state of the bubbles in the bed, which in turn affects the mixing and separation behavior of the particles. Fox et al. (Rong and Fox, 2008) used a multi-fluid model to research the polydisperse fluidized beds, and segregation and mixing phenomena were studied for a binary system and systems with a continuous PSD. The research illustrates that when the superficial gas velocity was equal to or greater than the minimum fluidization velocity, more bubbles were observed in the bed, and better mixing was achieved. In such case, the segregation in the bed was greatly reduced and the segregation rate was very low, around 0.1. Wang et al. (Wang et al., 2015) studied a three-dimensional numerical study of the mixing and segregation of binary particle mixtures in a two-jet spout fluidized bed based on Eulerian-Eulerian model. The research shows that at lower jet velocities, the slip velocity between the two components of binary mixtures plays a dominant role to cause the obvious segregation phenomenon. However, with the jet velocity increasing, the jet penetration depth and bubble amount are increased, which promotes the circulating movement of particles and furthers the mixing of binary particle mixtures. Cardoso et al. (Cardoso et al., 2018) studied the effect of superficial gas velocity on the mixing and separation of quartz sand particles. As the velocity increases, bubbles size enlarges and grow in number and the average bed height increases at different velocity（V=0.15m/s, 0.25m/s, 0.4m/s）in Figure 15a . Such bed expansion can be reaffirmed by Figure 15b, as velocity increases, more bubbles make their way to the bed surface. A higher superficial air velocity causes the drag force acting on the sand particles to increase, resulting in increased particle movement promoted by the augmented turbulence of the carrier air flow. The increase of the superficial air velocity facilitates the mixing between the solid species with different sizes and densities. Lim et al. (Lim and Lim, 2019) studied the mixing and segregation behaviors of a binary mixture in a pulsating fluidized bed using the Eulerian-Eulerian model. It was showed that an increase in mean inlet superficial velocity of the pulsating flow increased the formation of bubbles as well as the magnitudes of particle velocity within the bed. Correspondingly, there were higher tendencies for particles to move upwards through the bed in the presence of more bubbles and this increased mixing effects and reduced segregation between the flotsam and jetsam.

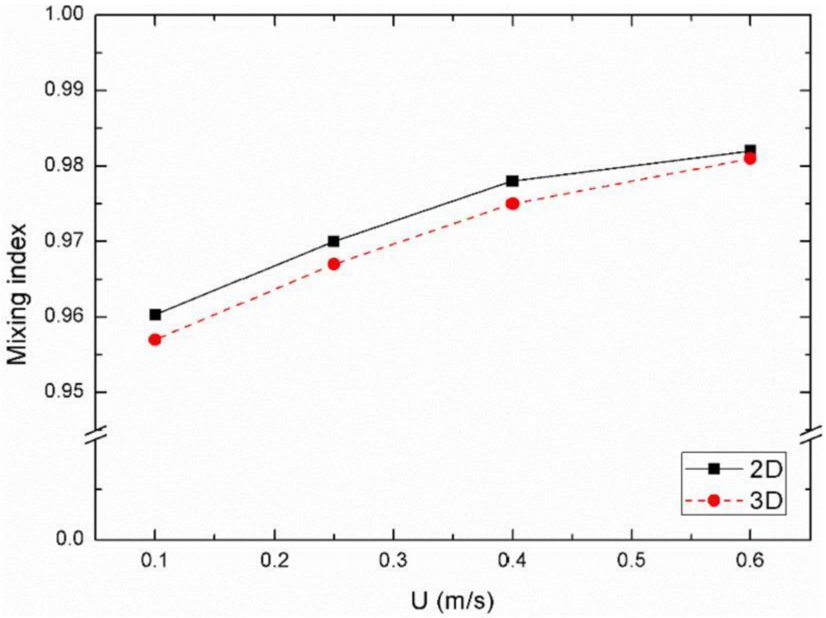


Figure 14: 2D and 3D superficial gas velocity effect on mixing. (Cardoso et al., 2019).

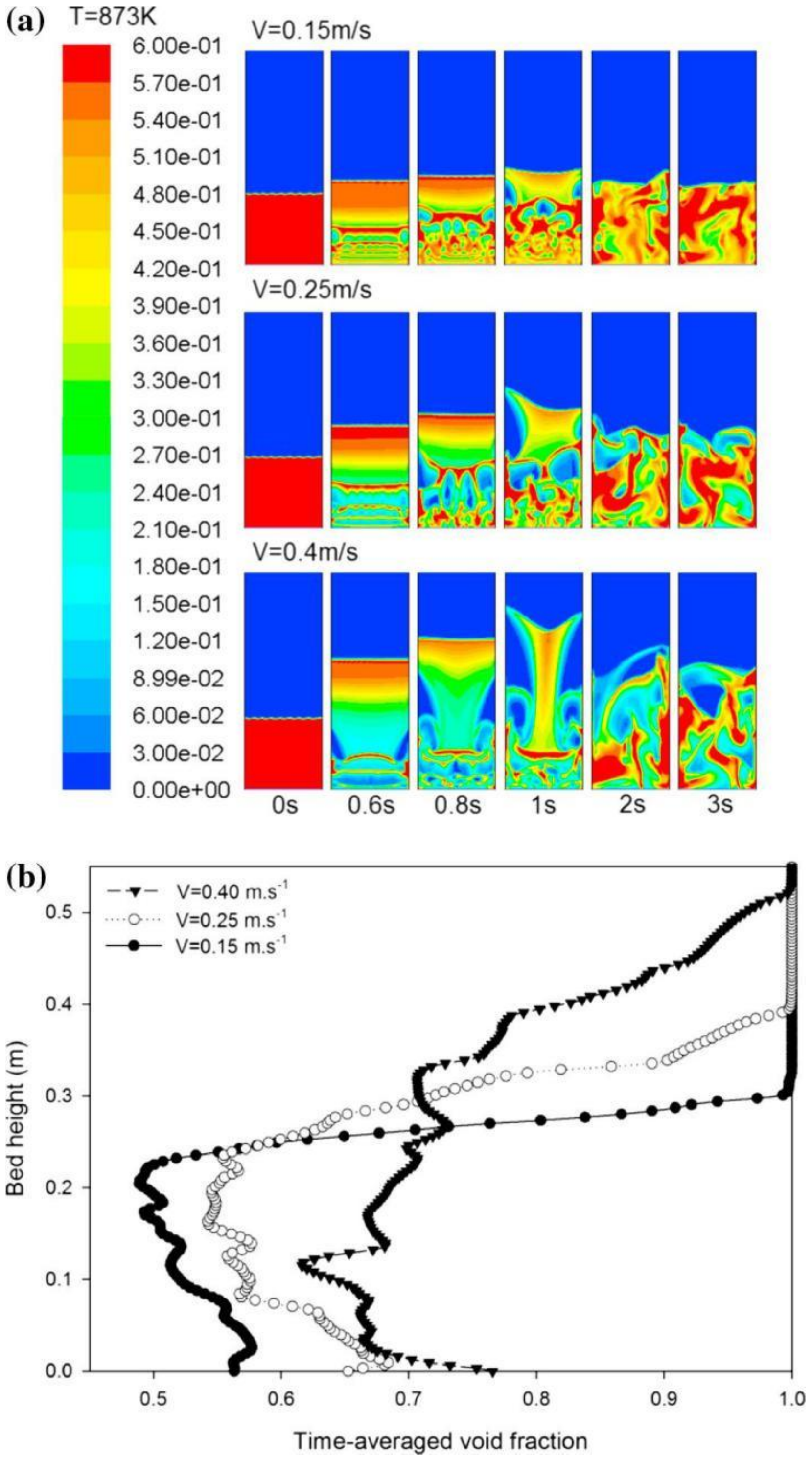


Figure 15: Superficial velocity study: (a) instantaneous contours for one granular phase (quartz sand) volume fraction at different superficial velocities (0.15m/s, 0.25m/s and 0.40m/s); (b) time-averaged void fraction along bed height at different superficial velocities (0.15m/s, 0.25m/s and 0.40m/s). (Cardoso et al., 2018).

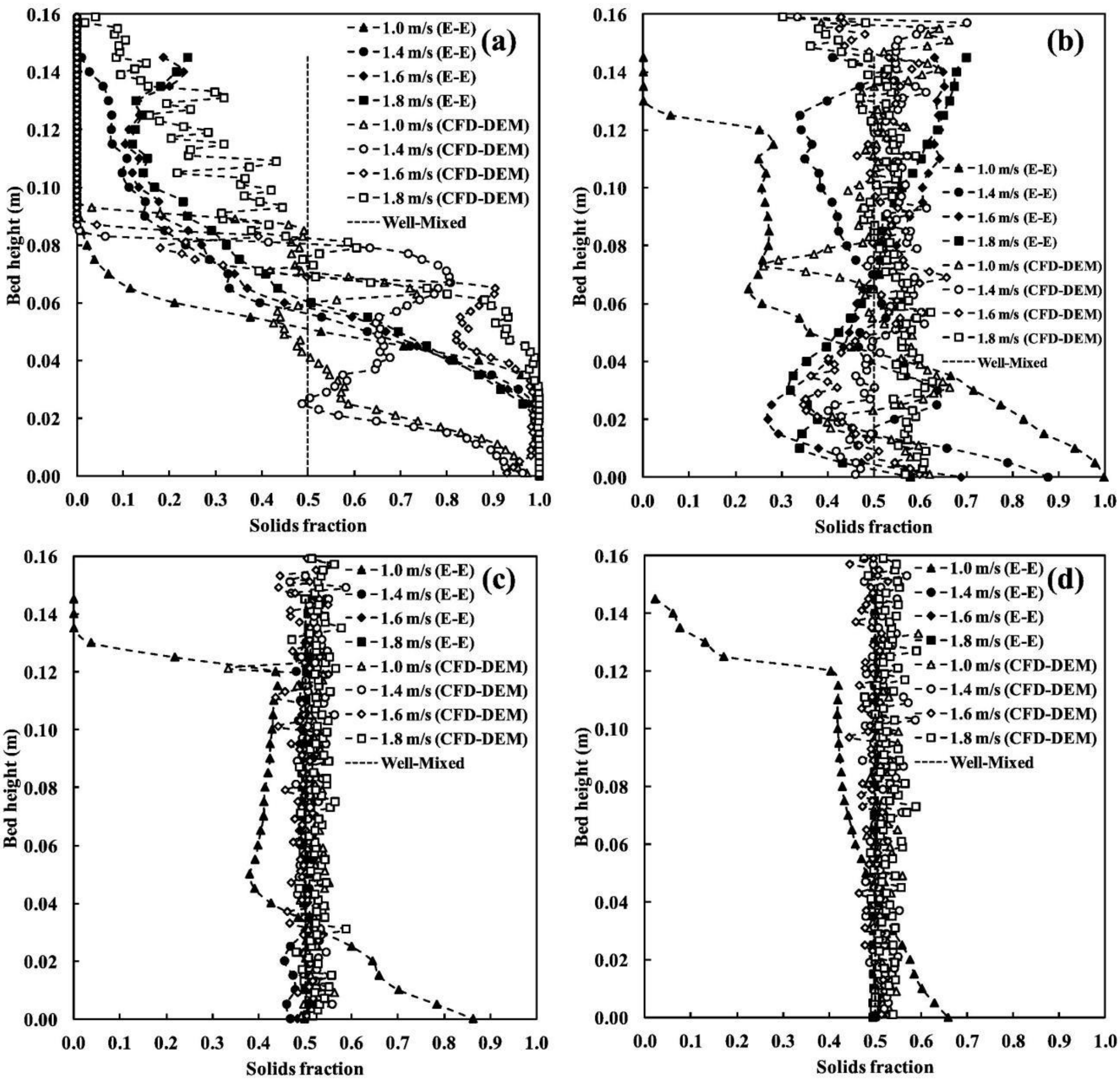


Figure 16: Solids volume fraction profiles of solids originally in the bottom section of bed at (a) 0.5s, (b) 2 s, (c) 5 s and (d) 10 s of fluidization with various gas velocities and twice the amount of solids compared to the original setup. The profiles obtained using Eulerian-Eulerian (E-E) simulations are compared with those obtained using CFD-DEM. (Jian and Lim, 2017).

5 EFFECT OF THE PARTICLES FRACTION

It is found that not only the particle size, density and superficial gas velocity will affect the movement of particles mixing and separation, but also the proportion of different particle fractions will have some influence on them. Granular flows in particle mixer display rich behavior and may perform solid-like behavior or fluid-like behavior depending on the state of packing and the external stresses acting on the mixture as schematically classified in Figure 17. The dense granular flow with very high solids packing shows a quasi-static flow regime. The frictional stress predominates between particles and the granular behavior therein is quite well modeled by soil mechanics (Luo et al., 2013). When the solids packing is very low, the dilute granular flow may show a rapid flow regime.

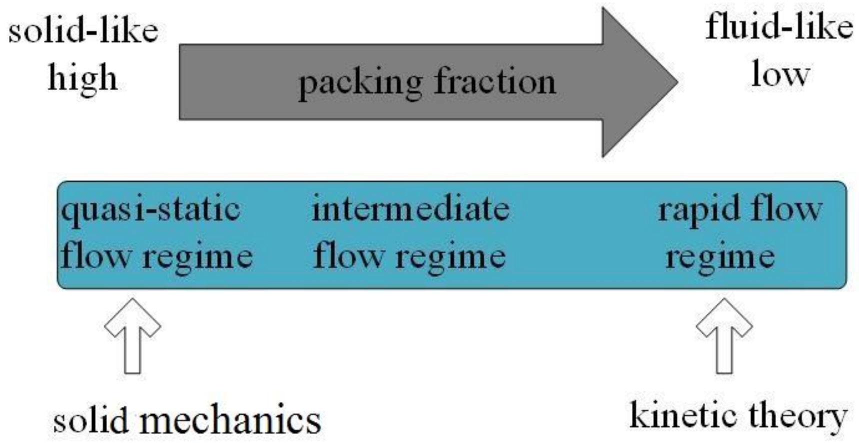
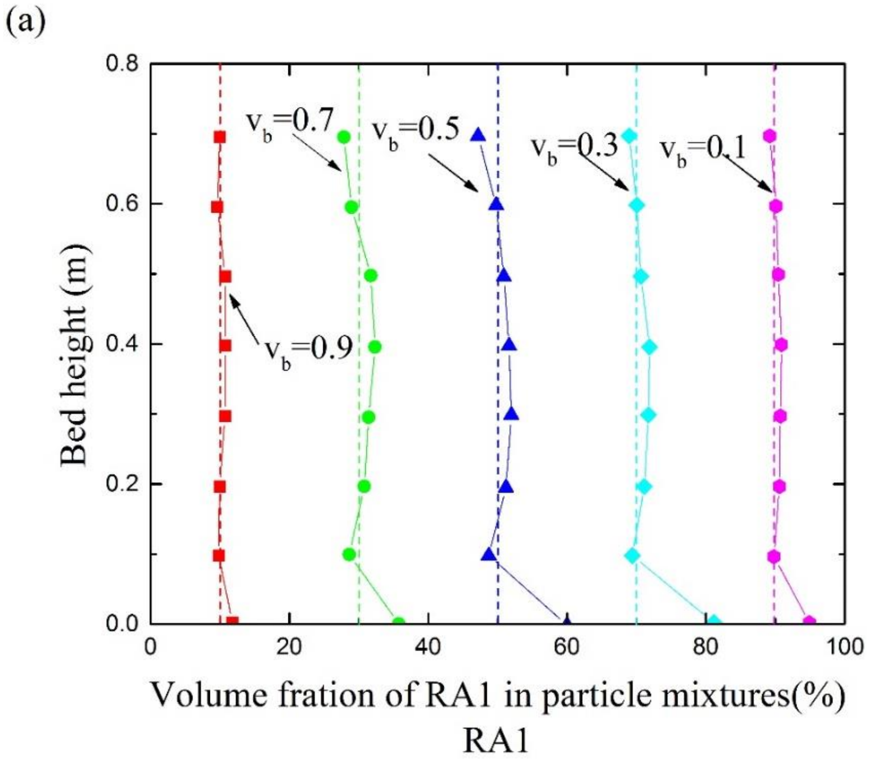


Figure 17: Schematic representation of different flow regimes of granular flow under different packing conditions. Soil mechanics and kinetic theory are frequently used models for the study of quasi-static granular flow and rapid granular flow, respectively. (Huang and Kuo, 2014).

Some scholars have studied the effects of different particle components on the mixing and separation of particles. Most studies have shown that the composition of solid particles has a certain effect on the mixing and separation of particles. Lu et al. (Lu et al., 2003b) studied the separation effect of particles with different sizes in a bubbling fluidized bed by experiments and numerical simulations. The results show that the mixed flow behaviors of two kinds of particles with the same density and different particle size are mainly caused by the difference of the average particle size and the mass fraction of the particles. In addition, the study found that the proportion of small particles is the key factor of particle separation. The reason for this phenomenon is that the initial fluidization state of the binary mixture is characterized by a total pressure drop equal to the minimum fluidization velocity of the particle weight per unit area of the bed, which depends on the average mass fraction of small particles. Gao et al. (Gao et al., 2009) studied the mixing and separation of Geldart A and B particles by experiment and numerical simulation. The study found that the mixing trend of binary mixtures increased with the increase of small particle content at a high gas velocity. The phenomenon occurs because the addition of small particles affect the flow of gas through the dense phase of the fluidized bed, producing smaller bubbles and resulting in smoother fluidization. In addition, the study also found that as the mass fraction of small particles increases, a large number of smaller bubbles are produced, causing more particles in the dilute phase. Therefore, the mixing of small particles and large particles is improved. Wang et al. (Wang et al., 2015) based on the Eulerian-Eulerian model, and the mixing and separation process of two-component particles in a double nozzle spouted bed was studied under three-dimensional conditions. Figure 18 shows the volume fraction variations of binary particle mixtures along with the bed height under different initial mixture compositions with a constant jet velocity (u_{jet} = 35_{uff}). It is found that when two kinds of particles are according to the equivalence ratio, they can achieve the best separation effect; as the ratio become larger, the two kinds of particles mixture well because the system is close to single particle state at this time. Mostafazadeh et al. (Mostafazadeh et al., 2013) used the Eulerian-Eulerian model coupled with the kinetic theory of granular flow to study the two-dimensional gas-solid fluidized bed reactor. Figure 1 shows that as the mass fraction of small particles increases, more particles are entrained into the dilute phase, resulting in a decrease in the average diameter of the mixture and an increase in bed height. In addition, when the mass fraction of larger particles increases, the average diameter of the mixture in the bed increases while bed height decreases. Du et al. (Wei et al., 2016) studied on the effect of mixing ratio on segregation with binary mixtures of A1 (Geldart-B) particle as the primary particles and S1 (Geldart-D) particles as the coarse particles. The mixing ratios of A1: S1 were set at 1:1, 1:2 and 2:1, respectively. The simulation results showed that by increasing the proportion of coarse particles, mixing between particles can be suppressed, and the stability of the bed can be improved. Sant'Anna et al. (Sant'Anna et al., 2016) studied the numerical simulation using CFD of a gasifier bubbling fluidized bed for the system composed of gas-biomass-sand. The simulations show that segregation of the particulate medium occurred for assays where the ratio between the mass of each biomass particle and the mass of each sand particle was $>$1.0 coupled to a ratio between biomass and sand volume fractions in the bed$\leqslant$0.5.

Wei et al. (Wei et al., 2019)extended a particle-particle (p-p) drag model to cohesive particle flow by introducing solid surface energy to characterize cohesive collision energy loss.The effects of the proportion of cohesive particles on the mixing of binary particles were numerically investigated with the use of a Eulerian multiphase flow model incorporating the p-p drag model. The study shows that cohesive particle proportions greatly affect the mixing index of binary particles and optimal mixing was observed with an increase of the cohesive particle proportion at a certain superficial velocity.

However, some studies have shown that the composition ratio of the particles has little effect on the mixing and separation of the particles. Cooper et al. (Cooper and Coronella, 2005b) investigated the parameters of maximum packing fraction for the relative effects on bubbling and hence on particle mixing and segregation. The results indicates that maximum packing fraction, and the composition ratio of the solid mixture does not affect the extent of mixing. Fotovat et al. (Fotovat et al., 2015) used different experimental techniques and an Eulerian n-fluid approach in the work to shed light on the fluidization and mixing characteristics of large biomass particles fluidized with sand under the bubbling conditions. Figure 20 presents the time-average axial profile of the normalized mass of biomass for mixtures composed of 8 wt% and 16 wt% biomass. A satisfactory level of consistency is observed between the numerical results and experimental measurements. Studies have shown that the difference in mass fraction of biomass particles has no significant effect on particle mixing and separation, and in both cases, the overall movement tendency of the particles in the bed is consistent.



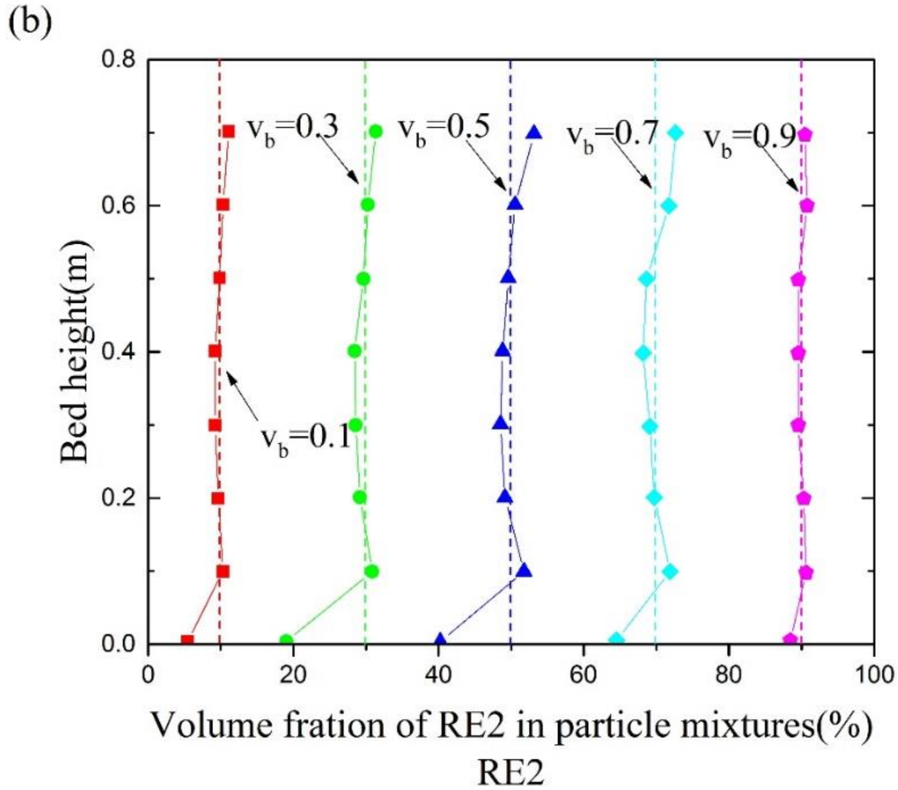


Figure 18: Volume fraction variations of binary particle mixtures with the bed height under different initial mixture compositions. (Wang et al., 2015).

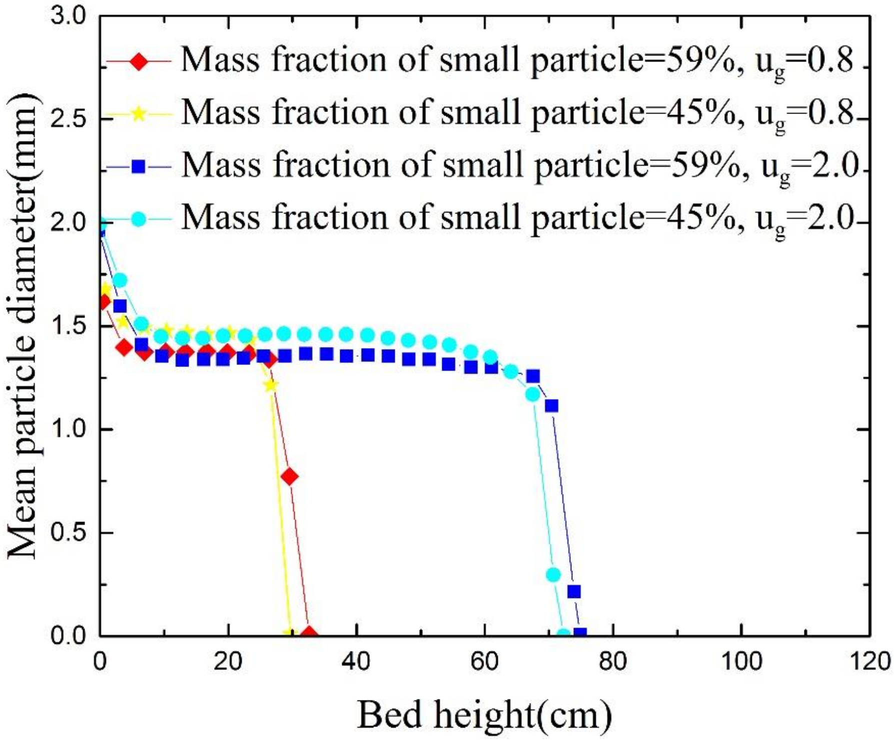


Figure 19: Bed average diameter for various compositions of the mixture. (Mostafazadeh et al., 2013).

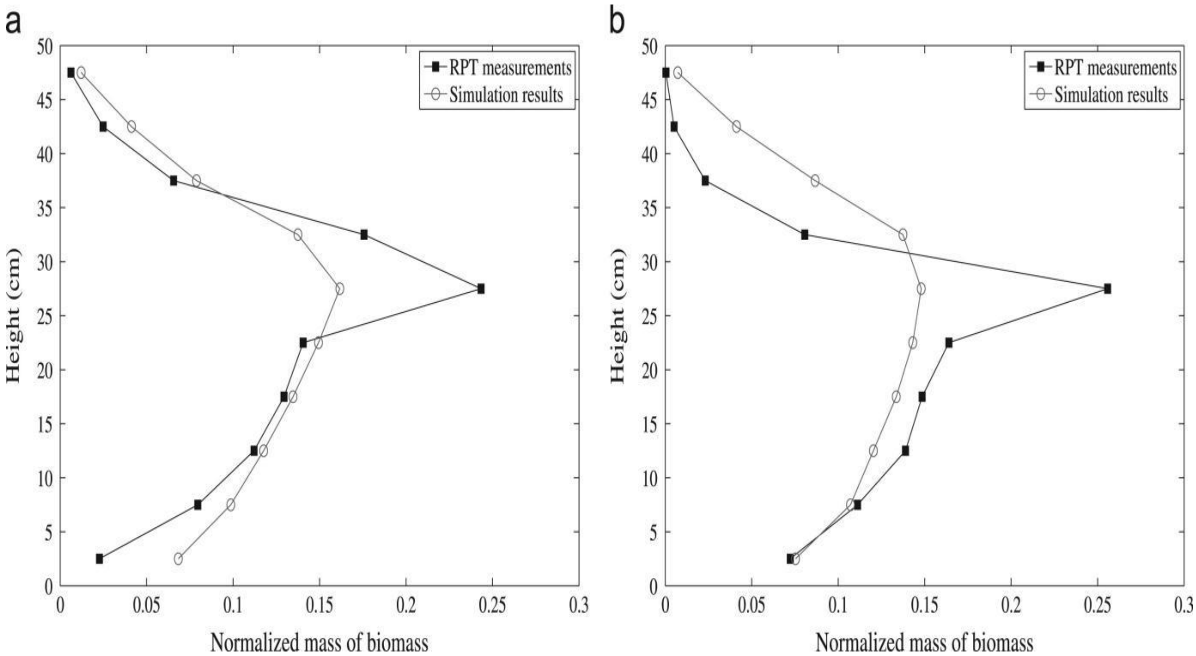


Figure 20: Comparison between (a) the RPT experimental measurements and (b) 3-D numerical simulation of the axial profile of the normalized mass of biomass. (U/Umf,s=4). (Fotovat et al., 2015).

6 EFFECT OF MODEL PARAMETRES

It is found that the selection of some important parameters in the model have an important effect on the multi-particles mixing and separation. Some scholars have studied the influence of some modeling parameters (including the expression of solid viscosity, recovery factor and particle temperature equation) on predicted mixing/segregation behavior or the combined effect of these parameters.

6.1 Effect of Particle-Particle Restitution Coefficient and Particle-Particle Friction Coefficient

The inelastic collision is considered by the recovery coefficient and friction coefficient. The lower e_{pp} means more energy loss due to particle-particle collisions. In general, an accurate measurement of the recovery coefficient is often difficult because its value depends not only on the properties of the material but also on the speed of the relative collision. Adjustment parameters generally used as the result of the matching experiment. Some researchers have done numerous research on related aspects.

In the early days, some scholars mainly conducted qualitative research on the particle-particle restitution coefficient. Liu et al. (Liu et al., 2003) based on particle dynamics and gas-solid two-phase fluid dynamics, and a hard-ball simulation method was used to study the interparticle collision. It has been found that the coefficient of elastic recovery of granule affects the flow structure of two-component particles of equal diameter and non-density, especially the separation effect between particles.

Specifically, under non-elastic collision conditions, the heavy particles will be carried to the surface of the bed under the action of upward moving bubbles. On the other hand, due to their own gravity, the particles will drop and settle on the bottom of the bed. The case is easier to separate between the particles. Under the elastic collision condition, bubbles are hardly formed because the energy loss between the particles is not considered, and the effect of particle deposition is not obvious, which is not conducive to the separation between the particles. Zheng et al. (Zheng and Liu, 2010) based on two-fluid flow model combining with the kinetic theory of granular flow, considering the effect of restitution coefficient of particle elasticity to the interaction and dissipations of fine particles. The simulation results show that the influence of restitution coefficient of fine particles on the fluidization characteristics in the bed can not be neglected. As the restitution coefficient between the particles increases, the collision between the particles becomes more intense, the size of the agglomerates of the particles becomes uniform, and the mixing of the particles in the fluidized bed is more uniform.

In recent years, more scholars have quantitatively studied the effect of particle-particle restitution coefficient on particle mixing and separation, and obtained the choice of values in specific cases. 3D Computational Fluid Dynamics simulation of a gas-solid bubbling fluidized bed was performed to investigate the effect of restitution coefficient on particle motion behavior by Esmaili et al. (Esmaili and Mahinpey, 2011b). The literature uses adjusted Di Felice drag model for seven different restitution coefficients

(e_{pp}=1，0.99，0.97，0.95，0.9，0.8，0.7) proposed for simulation of fluidized beds. As collisions become less ideal (and more energy is dissipated due to inelastic collisions) particles become closely packed in the densest regions of the bed, resulting in sharper porosity contours and larger bubbles. Sharma et al. (Sharma et al., 2014a) reported the restitution coefficient of biomass and bio-char particles affects the mixing/segregation behavior of the solid phases in the bubbling fluidized bed. It is shown that with the increase of restitution coefficient, there is a decrease in pinewood mass fraction (%) in the lower region of the bed, while there is an increase in mass fraction (%) in the upper region of the bed. However, the more precise impact still needs further in-depth research. Ebrahim et al. (Azimi et al., 2015) studied how to improve the accuracy of numerical simulation in predicting particle mixing and separation by simulating two-component particles in two-dimensional and three-dimensional systems under different conditions. The study found that the accuracy of the simulation under the three-dimensional system is higher than that of a two-dimensional system. When the recovery coefficient between particles is taken as 0.9, the accuracy of numerical simulation to predict particle mixing and separation can be effectively improved. Geng et al. (Geng et al., 2016) studied the hydrodynamics of binary coal-sand mixture in a pseudo-2D rectangular bubbling fluidized bed simulated and use the multi-fluid model incorporating the kinetic theory of granular flow. In the study three different values of e_{pp} (0.7, 0.8, and 0.9) were examined, the results of the study are shown in Figure 1. The study found that when the bed depth was equal to 20 mm, the influence of e_{pp} on particle axial mixing behavior was unimportant. However, for the bed with a depth of 5 mm, the axial segregation is strengthened with the increase of e_{PP}. Moreover, the best agreement with the experimental data was achieved when e_{pp} is equal to 0.9. However, A small number of scholars have shown that the coefficient of restitution between particles does not affect the mixing and separation of particles. Tagliaferri et al. (Tagliaferri et al., 2013) studied the values investigated for the restitution coefficient were 0.60, 0.70, 0.80, 0.90 and 0.99. The research shows that the value selected for the restitution coefficient does not affect the numerical results significantly, except for e=0.99.

Because the study found that the coefficient of friction between the particles has little effect on the system, only a small amount of literature is organized here. Zhong et al. (Zhong et al., 2014a) studied the effect of particle-particle friction coefficient on the mixing and separation behavior of particles in a bubbling fluidized bed based on the Eulerian-Eulerian model. The two solid particles studied in the literature have different densities and sizes. The results show that when modeling the segregation process at low gas velocity, both axial and radial jetsam velocities decrease with the increase of the particle-particle friction coefficient. The simulation with a small particle-particle friction coefficient overestimates the degree of segregation, and the good quantitative results are obtained when the particle-particle friction coefficient is 0.3. And the study found that the mixing effect of particles is not affected by the friction coefficient. Although the value of 0.15 was used in some literature (Gera et al., 2004, Rong and Fox, 2008, Mazzei et al., 2010), the particle-particle friction coefficient was generally set to 0 , which meant that the particle frictional sliding effect during collisions.

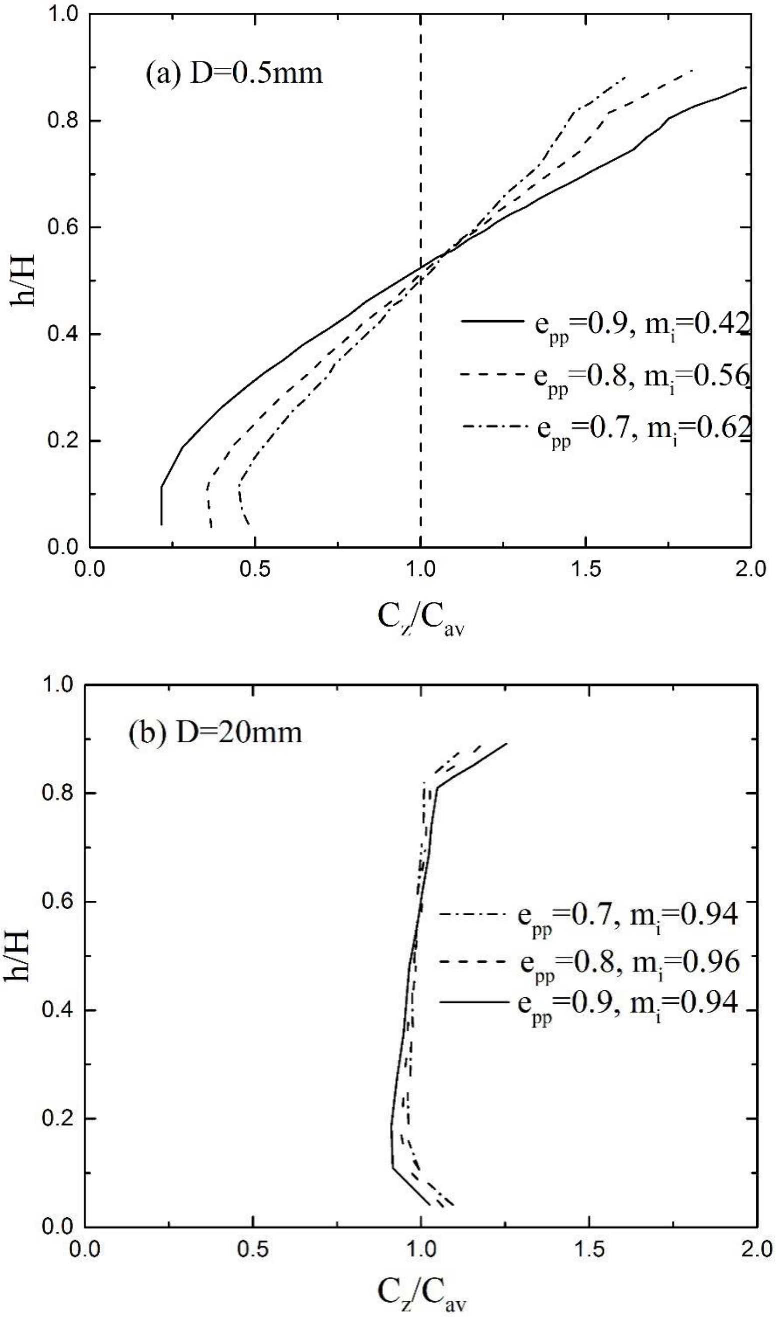


Figure 21: Coal concentration profiles for different solid-solid restitution coefficients of (a) D=5mm, and (b) D=20 mm beds. (Geng et al., 2016).

6.2 Effect of Wall Boundary Condition

The interactions between wall and particles are also critical for the accurate prediction of the complex hydrodynamics in fluidized beds. (Li et al., 2010) Generally, the

Johnson and Jackson (Johnson and Jackson, 1987) wall boundary condition is applied in the CFD simulations of gas-solids flow. This wall boundary condition includes two important parameters, the specularity coefficient, φ, which characterizes the tangential momentum transfer from the particles to the wall and the particle-wall restitution coefficient, e_{pw}. The specularity coefficient is an important parameter in the phase condition of Johnson-Jackson particle phase wall. For Φ =0, a free-slip boundary condition without frictional effect of particles on the wall is applied, while for φ =1, a no-slip boundary condition with frictional effect of particles on the wall is employed. And no-slip (Gao et al., 2009, Coroneo et al., 2011) or partial-slip (Lu et al., 2003b, Lu et al., 2007b, Benyahia, 2008, Mathiesen et al., 2010) wall boundary condition has been applied in the numerical investigation of bed hydrodynamics of binary particle mixtures.

Some scholars have done research in this area. Some literatures have qualitatively studied the effect of the specularity coefficient on the mixing and separation of multi-component particles. Lungu et al. (Lungu et al., 2015) investigated the effect of specularity coefficient on the flow characteristics of two-component particle mixture using a simplified two-dimensional simulation system. The specularity coefficient, φ is observed to have considerable effect on the axial mixing in the fluidized bed. The mixing index reduces sharply with increasing values of the specularity coefficient for the two drag models (Gidaspow and EMMS models) eventually becoming constant at φ = 0.05. Zhong et al. (Zhong et al., 2016) in order to reveal the fluidization characteristics of binary particles，the 3D computational fluid dynamics（CFD） simulation on the instantaneous segregation process of binary particles in gas-solid fluidized bed was performed using the multi-fluid model based on Eulerian-Eulerian method. The study investigated the effect of specularity coefficient on the three-dimensional CFD simulation results of transient grading process. As the specularity coefficient decreases, the degree of temporal grading predicted at the same time is significantly reduced. When the specularity coefficient is 0, the full-slip wall condition, even after the classification is completed, the classification degree of the large and small particles in the system is still very small, which is close to the state of complete mixing. A reduction in the specularity coefficient will hinder the classification behavior of the two-component particle mixture and enhance the mixing behavior of the system. Geng et al. (Geng et al., 2016) studied the boundary wall condition to investigate the influence on the predicted particles mixing/segregation behavior. To research the influence of specularity coefficient, the sand and coal particles and five different specularity coefficient values ($\varphi = 0, 0.005, 0.05, 0.5, 1.0$) were performed. It can be found that the predicted mixing degree decreased with the increase of specularity coefficient. The best agreement between simulation results and experimental data was achieved when specularity coefficient was equal to 1.0.

Quantitative effects of specularity coefficient on particle mixing and separation have been reported in related literatures. Zhong et al. (Zhong et al., 2012) investigate the influence of wall boundary condition on the predicted segregation and mixing behavior. They found that the predicted segregation is significantly affected by the specularity coefficient for the segregation process. However, it effects lightly on the mixture and no segregation can be predicted for small specularity coefficients. The axial segregation profiles for different specularity coefficients are shown in Figure 22. As we can see from the figure, the degree of segregation increases obviously when the specularity coefficient decreases from 0.5 to 0.05. However, when the specular reflection coefficient is smaller than 0.05, the particles will have a better mixing. This is because when the mirror coefficient is too small, it means that the friction between the particles and the wall surface can be neglected, so the separation effect between the particles is not obvious. Recently, Sharma et al. (Sharma et al., 2014a) reported that the variation of mixing degree versus specularity coefficient was not monotonous. It was found in high velocity when the specularity coefficient is 0.5 the pinewood and bio char particles segregation was clearly observed. However, when the specularity coefficient is 0 or 1, the solid particles mixture well. Bakshi et al. (Bakshi et al., 2015) modeled the hydrodynamics of dense-solid gas flows strongly affected by the wall boundary condition and in particular, the specularity coefficient φ. Comparison of simulation predictions with experimental data for different fluidization regimes and particle properties suggests that values of φ in the range [0.01,0.3] are suitable for simulating most dense solid-gas flows of practical interest.

In the numerical simulation of multi-component particle mixing and separation systems, the setting of the particle-wall restitution coefficient is less important than the specularity coefficient. Zhong et al. (Zhong et al., 2012) studied the e_{pw}=0.9 and 0.99, and found that the particle-wall restitution coefficient only plays little role in predicting the segregation and mixing of binary particle mixtures in bubbling fluidized beds, which is consistent with the previous work shows that the particle-wall restitution coefficient plays only a minor role in numerical modeling of bubbling fluidized beds (Li et al., 2010), CFB risers (Almuttahar and Taghipour, 2008), and spouted beds (Lan et al., 2012). And Enyahia et al. (Benyahia et al., 2005, Almuttahar and Taghipour, 2008, Wang et al., 2010) proposed to calculate the hydrodynamic behavior in a fast fluidized bed using the small wall reflection coefficient.

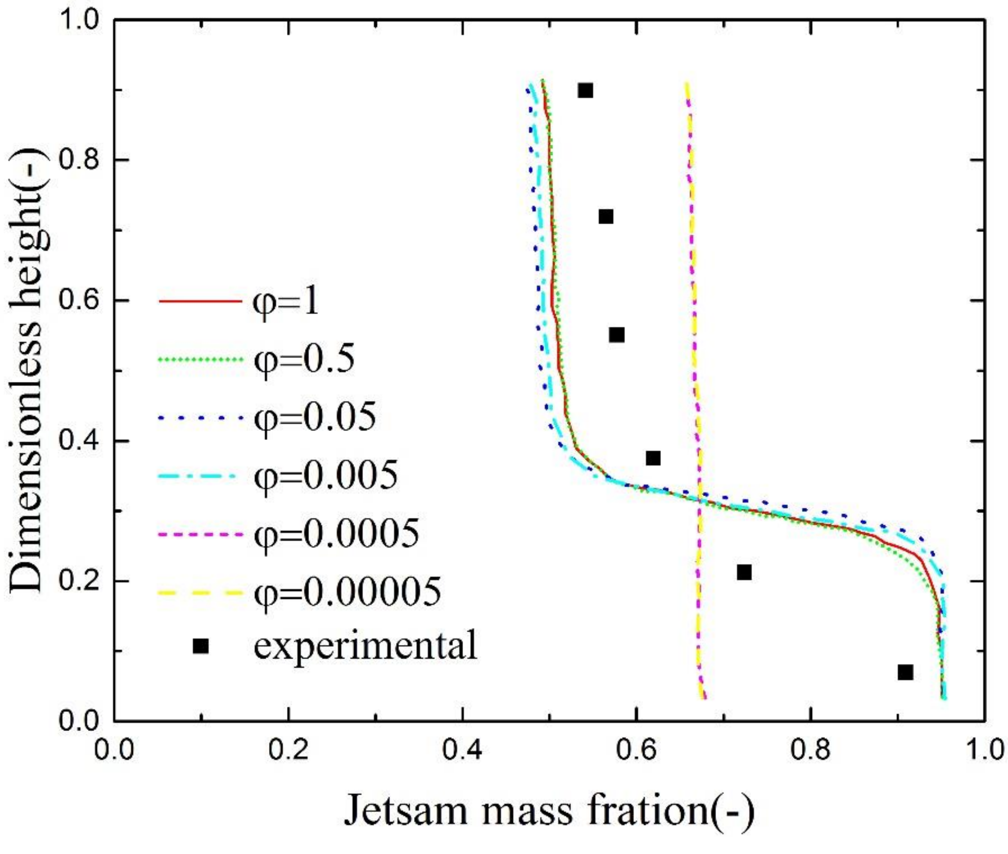


Figure 22: Axial segregation profiles for different specularity coefficients for Ug=0.0384 m/s (e_{pw}=0.90). (Zhong et al., 2012).

7 OUTLOOK

The study on the mixing and separation of multi-component particles in a fluidized bed by the Eulerian-Eulerian model is instructive in practical industry. More scholars have conducted important research in the regard. In most of the previous studies, the main focus has been on understanding the hydrodynamics of a single solid phase in the presence of a carrier gas (Shah et al., 2010, Shah et al., 2011a, Shah et al., 2011b, Shah et al., 2011c)

Based on the extension of the two-fluid CFD models of multi-component particle mixtures have been developed by some researchers, and the flow behavior of mixture particles has been predicted in fluidized bed. The success of multi-fluid Eulerian approach signifificantly depends on the proper description of inter-phase interaction (Anderson and Jackson, 1967, Feng and Yu, 2007, Chao et al., 2012). For fluidized particle mixture systems, special attentions have been paid to the influence of the interactions between particle components on the predicted mixing behavior (Owoyemi et al., 2007, Zhong et al., 2014b, Beetstra et al., 2007, Cortes and Gil, 2007). And to close the governing equations for the solid phase(s), the kinetic theory of granular flow(KTGF) is commonly used to provide the constitutive relationsfor the solid phase(s). There are some studies have been based on the kinetic theory(Fan and Fox, 2008, Goldschmidt et al., 2001, Lu et al., 2003a, Lu et al., 2007a, Annaland et al., 2009a, Annaland et al., 2009b)

In recent years, many scholars have studied the effects of different factors on particle mixing and separation in multi-component particle systems using the method of Eulerian-Eulerian. However, the current numerical simulation of gas-solid flow in a fluidized bed is mostly based on the average particle properties (including particle size and density) due to the limitations of the simulation conditions and the complex physical properties. Most hypothetical particles are mixed and separated in a fluidized bed, which greatly reduces the computational complexity and mathematical model requirements. There are obvious differences in the properties of particle size and density of actual bed materials. Only a simplified study of the simulation of single-component particles will have a great impact on the simulation results. At present, more scholars have studied the mixing and separation behaviors of two-component particles. However, the mixing and separation behaviors of three-component particles have been studied less. In addition, it is necessary to establish a new model to study the flow behavior of three-component particles. The study of the Eulerian-Eulerian model to study the three-component particles mixing and separation behavior is the urgent need for the development of the project. In addition, in the study of the drag force model, researchers have done some research on the drag force between gas-solid, but there are only a few scholars to study the drag force interaction between multi-component particles. Therefore, the study of the drag force between particles is also a major direction of follow-up research.

Notes

The authors declare no competing financial interest.

ABBREVIATIONS

d_p Particle diameter

d_b Bubble diameter

u_{mf} Minimum fluidization gas velocity (m/s)

G Gravity acceleration (m/s^2)

$\bar{u}_b$ Average velocity of bubbles

x_i Fluid-free volume fraction of its solid species defined as [Vsi/Vst]

u_{ff} Full fluidization velocity of binary mixtures (m/s)

V_b Volume fraction of RE2 in particle mixtures

u_g Inlet gas superficial velocity

e_{pp} Particle-particle restitution coefficient

e_{pw} Particle-wall restitution coefficient

φ Specularity coefficient

β_{pl-ps} Large solid-small solid drag force

β_{g-ps} Gas-small solid drag force

β_{g-pl} Gas-large solid drag force

μ_{pl} Large solid viscosity

μ_{ps} Small solid viscosity

G_{pl} Large solid gravity

G_{ps} Small solid gravity

V_g Lift force

V_{pl} Large solid lift force

V_{ps} Small solid lift force

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