Fluidization Behavior of Biomass Particles and its Improvement in a Cold Visualized Fluidized Bed

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The fluidization behavior in a fluidized bed was visualized at room temperature under different conditions for two typical lignocellulosic biomass materials (rice husk and walnut shell) as representative samples of herbage and xylophyta, respectively. The effects of initial bed height, moisture content, and addition of sand particles on the quality of fluidization were analyzed, and the optimal operating parameters were determined. The initial bed height had a negligible effect on the minimum fluidization velocity but an obvious influence on bed stability. In addition, with an increase in moisture content, the minimum fluidization velocity showed the growth of an S-shaped curve and a constant decrease in the fluidization index in the fluidized region. Fluidization when performed on binary mixtures indicated that the proportion of sand-3 (60 to 80 mesh) in biomass and sand-3 in mixtures is a main factor contributing to the fluidizing quality of a bed. With larger proportions of sand-3, the fluidizing quality of the bed improved. Meanwhile, the differences in fluidization behavior between rice husk and walnut shell have been determined.

Keywords: Biomass/sand mixtures; Fluidization quality; Initial bed height; Moisture content

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INTRODUCTION

Biomass energy is a unique renewable clean energy source that can be converted into liquid fuels, and its exploitation and utilization has been investigated widely (Panwar *et al.* 2012). A number of novel thermo-chemical and bio-chemical processes involving biomass as a raw material are under development worldwide based on combustion, gasification, pyrolysis, fermentation, *etc*. (Cui and Grace 2007; Zhong *et al.* 2008). In these processes, the fluidized bed is an important unit used for biomass conversion, especially in processes such as pyrolysis and gasification. This is because of its characteristics of violent reaction intensity, large contact area, and high heat and mass transfer, as well as uniform reactor temperature. Unfortunately, biomass particles usually have peculiar shapes, sizes, and densities, which make them difficult to fluidize and handle adequately (Rao and Bheemarasetti 2001; Zhong *et al.* 2008).

Extensive studies have been performed to improve the fluidization quality of difficult-to-fluidize materials (including pulverized coal and biomass particles), focusing on mechanical or magnetic assistance, high-pressure fluidization conditions, surface coating techniques, addition of inert particles or glidants, *etc.* Zhang *et al.* (2012) studied the fluidic properties of fly ash in a mechanically vibrating fluidized bed and found that the vibrations could reduce the minimum fluidization velocity (U_{mf}) by providing an additional power to the fluidization of material. Further studies of the effect of vibration on the fluidization behavior showed similar conclusions, in that both amplitude and frequency have crucial impacts on the fluidization of fine powder materials (Marring *et al.* 1994; Barletta *et al.* 2008). Escudero and Heindel (2013) claimed that the existence of a sound field could also effectively promote fluidization, and an increase in sound pressure and frequency could decrease the U_{mf} values. The effect of high pressure on jetting bubble and solids behavior in a two-dimensional jetting fluidized bed was investigated by Li *et al.* (2013), indicating that the excess gas velocity (U_0 -U_{mf}) and the jetting bubble size both became smaller along with the increase of pressure and solid holdup of the bubble increased at high pressure. Chen *et al.* (2008) found that a new type of surface coating process could reduce the viscosity between particles, causing the conversion of the particles from Geldart class C to class A; subsequently, an effective model was proposed for determining the minimum coating coverage required to reduce viscosity.

Recent experiments and simulations have shown that the addition of inert particles such as sand, glass beads, and alumina can effectively facilitate the fluidization of biomass (Kozanoglu *et al.* 2002; Abdullah *et al.* 2003; Suarez 2003; Zhang *et al.* 2009; Paudel and Feng 2013; Sharma *et al.* 2013; Fotovat *et al.* 2015). Sand as a medium material can also enhance the heat transfer in the process of biomass thermochemical conversion (Rao and Bheemarasetti 2001). In view of the large differences in size or density between biomass and inert particles, however, some new complexities arise when the selected components do not match. Clarke *et al.* (2005) found that mixtures of sawdust and 0.322-mm glass spheres can be completely mixed when fluidized, but mixtures of sawdust and 0.516-mm glass spheres were either partially or completely mixed, depending upon gas velocity in the fluidized bed. The fluidization of biomass/inert particles mixtures is categorized as binary mixture fluidization, and current understanding of the mechanism of multi-component fluidization is still admittedly unsatisfactory (Formisani *et al.* 2008). Segregation is a distressing but common problem in mixture fluidization that negatively affects the performance of fluidized-bed units in which chemical reactions take place (Zhong *et al.* 2008). This results in the heterogeneity of reaction product distribution as well as a non-uniform temperature profile in the bed, which in turn causes a decline in the yield of desired products, formation of tar, and emergence of cold/hot spots in the bed (Aznar *et al.* 1992a,b). In the process of biomass particle fluidization, in addition to the addition of inert particles, the initial bed height (H_0) and biomass moisture content (M) also have a critical influence on fluidization behavior. Combining the pyrolysis rate, the H_0 as an operating parameter can used to guide the feed rate of the fluidized bed effectively. In addition, the presence of moisture effects fluidization behavior by changing the biomass particle properties as well as introducing the viscosity or surface tension of the liquid and interparticle liquid bridge forces. The biomass with a high moisture content is prone to agglomeration during the fluidization process, but the demand of lower moisture content also means higher costs and difficult drying pretreatment of material. So selecting an economical and reasonable moisture content is essential for the whole fluidization pyrolysis process. However, only a few controversial studies have addressed these in detail (Clarke *et al.* 2005; Cui and Grace 2007).

In this paper, rice husk and walnut shell were used as representative samples of lignocellulosic biomass materials of herbage and xylophyta, respectively, for fluidization experiments. Three types of sands with different sizes were employed as inert particles. Fluidization index (dimensionless pressure drop P_d) and expansion ratio (R_s) were used as the evaluation indexes to quantify fluidization, and the effects of H_0, M, and the mixing ratio of sand on fluidization quality were discussed to provide a basis for the fluidization conversion of biomass.

EXPERIMENTAL

Apparatus

The self-designed cold fluidized-bed experimental setup used in this work is illustrated schematically in Fig. 1. The riser in the bed was fabricated with a plexiglass tube (2000×140×50 mm) to achieve visualization. The gas distributor with 31 caps arranged in rings for a total open area of 3.02% is located immediately below the riser. The bottom of the distributor consists of a chamber with a height of 400 mm, a cone-shaped diffuser tube with an angle of 45°, and air supply pipes with internal diameters of 40 mm. The carrier gas required for fluidization was supplied by a HBCRS-65 Roots blower (220 V rated voltage, 1940 r/min rated speed, 3.04 m^3/min air flow and 24.5 kPa pressure rise), whose flow rate was monitored by a rotameter and adjusted by ball valve 1. Ball valve 2 was used to solve the potential material spilling problem in distributor orifices rising from frequent start and stop device. The pressure drop across the bed was measured by a U-tube manometer whose two ends were connected to the top of the fluidized bed and bottom of the distributor plate, respectively. Three scale lines uniformly distributed on the riser determined the bed expansion height (*H*).

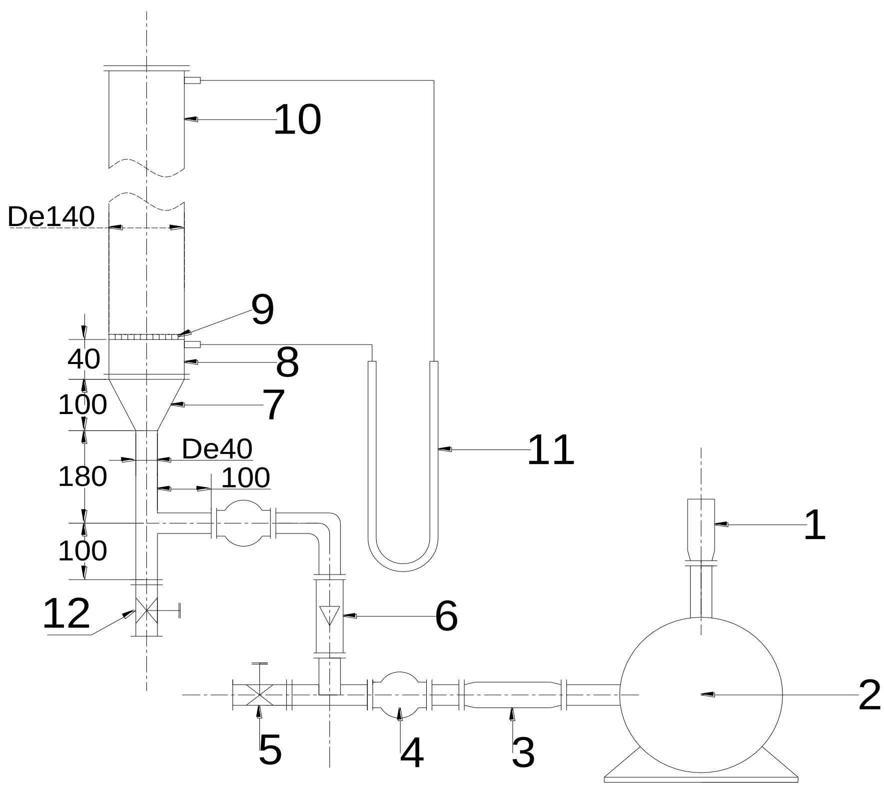

Fig. 1. Schematic diagram of a cold visualized fluidized bed experimental setup: 1-Import silencer; 2-Roots blower; 3- Export silencer; 4-Flexible joint; 5- Ball valve 1; 6-Rotameter; 7-Conic diffuse; 8- Plenum; 9- Gas distribution plate; 10- Riser; 11- U-Tube manometer; 12- Ball valve 2

Materials

The biomass materials used in this experiment, rice husk and walnut shell, were obtained from Anhui province in China, and their true densities on a dry basis were 661 and 1250 kg/m^3, respectively. Prior to use, according to the actual situation of various engineering applications, the biomass was milled and sieved to particle sizes between 30 and 40 mesh size and then dried at 105 °C for 24 h. To explore the effect of *M* on the fluidization behavior, several samples of rice husk and walnut shell with various *M* were prepared by spraying humidification on the dried biomass. Sand samples with sizes of 30 to 40 mesh, 40 to 60 mesh, and 60 to 80 mesh were sieved and selected to study the influence of the particle size on fluidization and to determine the optimal amount of inert particles for biomass fluidization. The bed bulk density was determined according to the material mass and the static bed volume (Escudero and Heindel 2013). The properties of bed materials are shown in Table 1.

During the fluidization of binary mixtures, the rice husk (*M* = 6.5%) and walnut shell (*M* = 8%) were selected as biomass and sand-3 was used as inert particles. Binary mixtures of biomass/sand-3 were prepared by thorough mechanical mixing with sand-3 weight percentage ranges from 0% to 100% in 10% increments.

Table 1. Physical Properties of the Bed Materials

Material	Mesh	Average diameter (mm)	*M* (%)	Bulk density (kg/m^3)	Geldart class
Rice hull	30~40	0.52	3.7	243	B
			6.5	272	
			8	301	
			12	331	
			16.2	447	
Walnut shell	30~40	0.52	3.3	433	B
			6.5	457	
			8	472	
			12	534	
			16.3	590	
			20.5	630	
			26.3	670	
Sand-1	30~40	0.52	0.3	1353	B
Sand-2	40~60	0.37	0.3	1290	B
Sand-3	60~80	0.23	0.3	1203	B

Procedure

Empty bed experiment

In this step, an empty bed test was carried out without any bed material to measure the resistance characteristic curve of the gas distributor. After the system leak detection, the gas flow rate in the bed was adjusted gradually from 0 to 80 m^3/h and the corresponding pressure drop was recorded. Then, the resistance characteristic curve combined with the superficial gas velocity and pressure drop was drawn, as shown in Fig. 2.

The distributor resistance coefficient ζ can be obtained by fitting these points according to the local resistance equation, as follows:

$$\Delta p_0 = \zeta \bullet \frac{1}{2}\rho v^2 = 102\zeta {u_0}^2 \tag{1}$$

where Δp_0 denotes the resistance of air distributor, v is the average flow velocity at the outlet of the blast cap, ρ is the air density, and u_0 represents the superficial velocity of the bed, defined as,

$$u_0 = \frac{4Q}{\pi D^2} \tag{2}$$

where Q is the volume flow and D is the diameter of the bed. According to calculation, ζ = 5.49.

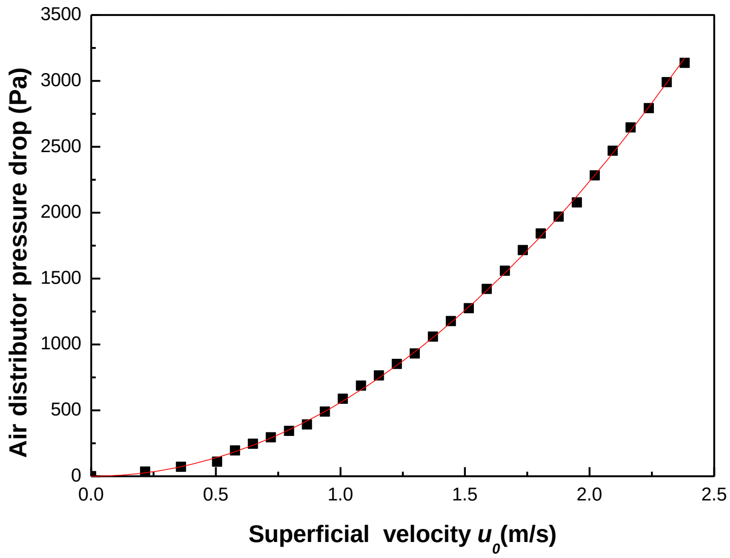

Fig. 2. Curve of resistance characteristics of gas distributor

Fluidization experiment

The experiments were carried out at three different initial bed height-to-diameter ratios (H_0/D = 0.5, 1, and 1.5) with dry biomass alone to determine the optimum H_0. Subsequently, various bed materials, such as biomass with different moisture contents, sands in various size ranges, and biomass/sand-3 binary mixtures with different weight percentages, were used for the assessment. Bed material was slowly added until it reached the desired H_0, after which the sufficient carrier gas was pumped in to fluidize the bed as much as possible. After reaching operational stability, the flow rate was decreased to zero gradually; simultaneously, the corresponding total pressure drop and bed height were recorded at each flow rate. The bed pressure drop was obtained by subtracting the empty bed pressure drop from the total pressure drop at the identical superficial gas velocity. Because the flow rates between the empty bed and fluidized-bed tests did not match exactly, the corresponding empty bed pressure drops could be calculated using Eq. 1.

RESULTS AND DISCUSSION

Effect of the Initial Bed Height on Biomass Fluidization Characteristics

Figure 3 shows the fitting curves with the data points of bed pressure drop related to superficial gas velocity for rice husk and walnut shell under various H_0 values. The U_{mf} was determined by the intersection of the fitting curves in the fluidized-bed and fixed-bed regions.

The effect of H_0 on fluidization was attributed to the interaction, coalescence, and breakup of bubbles, which was reflected in the bed pressure drop and fluctuation. In the case of 140 mm H_0, when u_0 exceeded the U_{mf} value, the bed pressure drops for rice husk and walnut shell were maintained at 370 and 590 Pa, respectively, with an inappreciable fluctuation in the fluidized-bed region. The maximum fluidized height of the dilute phase region could reach 290 and 320 mm, respectively, when u_0 was 0.58 m/s. Bubbles formed uniformly at the outlets of the gas distributor, and the bubbles grew constantly in the region of dense phase during the ascending process as a result of coalescence. Subsequently, the bubbles were broken in the dilute phase region; thus, no large bubbles were formed and a dead zone was observed in the whole bed. The dilute phase region can always be maintained at a relatively stable height for each superficial gas velocity.

The fluctuation of bed pressure drop and the behavior in the dilute phase region showed dramatic changes when the H_0 was 210 mm. This was because the relatively high H_0 resulted in the bubble rising travel too long. It can be observed that large bubbles were formed in a dense phase during the ascending process and subsequently burst in the dilute phase region, which resulted in the splashing of biomass particles, which were thrown into the freeboard. When the particles were scattered back to the surface, the new bubbles in the dense phase region just reached the dilute phase, which resulted in the instability of the dilute phase and a pressure drop for the whole bed. During the experiments, it was observed that the bed height of rice husk and walnut shell intermittently changed in the fluidization region, but that for the former varied more rapidly. In addition, the excessive initial bed height resulted in a great burden and cost of energy to run the roots blower. However, for 70 mm H_0, the pressure drop was relatively smaller throughout the gas flow ranges. Certain gas-bypassing phenomena were also observed, and the bed expansion became insufficient.

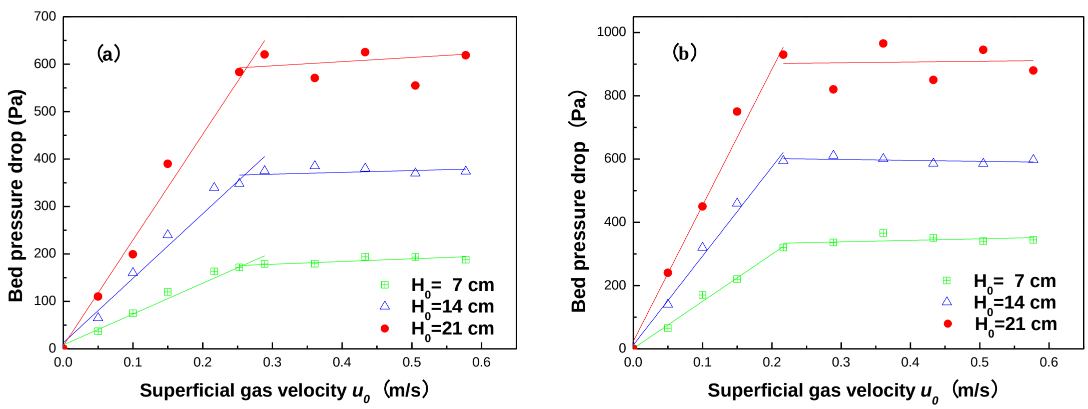

Fig. 3. Fluidization characteristic curves of biomass at various initial bed heights (a: rice husk, M = 3.7%; b: walnut shell, M = 3.3%)

As shown in Fig. 3, the minimum fluidization velocities measured at different initial bed heights were very similar, indicating that the effect of the H_0 on U_{mf} was negligible. Escudero and Heindel (2011) using different Geldart type B particles (glass beads, ground walnut shell, and ground corncob) drew similar conclusions, showing the independence of H_0 and U_{mf} in the size range of 500 to 600 µm. However, H_0 had a crucial influence on the stability of the fluidization process. To ensure a stable fluidization process, the H_0 should generally be selected at 1.0 to 1.5 D. Initial bed heights that are too low or too high are terrible for fluidization. At low bed heights, the bed can be easily penetrated by the air flow out of the distributor outlets, which would result in a low efficiency. At high values, the small bubbles would coalesce to form large bubbles during the rising process and the behavior of the dilute phase region would fluctuate violently. Therefore, the following tests were carried out at $H_0 = 1D$, that is, H_0 = 140 mm.

Effect of Moisture Content on Biomass Fluidization Characteristics

As a porous material with high moisture content (> 10%), raw biomass is prone to agglomeration during the fluidization process, which was the main reason for the occurrence of various fluidized deterioration phenomena, such as channeling, slugging, and dead regions. Decreasing the moisture content of biomass material yields higher energy efficiency and better product quality during the thermal conversion process. However, the lower moisture content also means higher costs and difficult drying pretreatment of material.

The one-component fluidization experiments were carried out using rice husk and walnut shell with various moisture contents. The fluidization index, a dimensionless pressure drop, which can reflect the fluidization quality of the bed, was defined as follows:

$$P_d = \frac{\Delta p \bullet A}{G} \tag{3}$$

where Δp is the bed pressure drop, A is the cross section area of the bed, and G is the total weight of the bed material.

In Eq. 3, the effects of the acceleration of particles and the friction of the wall surface in the bed were neglected. When $P_d > 0.95$, the bed material was considered completely fluidized. Inversely, a lower P_d indicates poor fluidization. When $P_d < 0.6$, the bed material is regarded as not fluidized. When P_d is between 0.6 and 0.95, the bed material is partially fluidized. Taking P_d as the ordinate, and u_0 as the abscissa, the fluidization curves of rice husk and walnut shell with various moisture contents were obtained, as shown in Fig. 4.

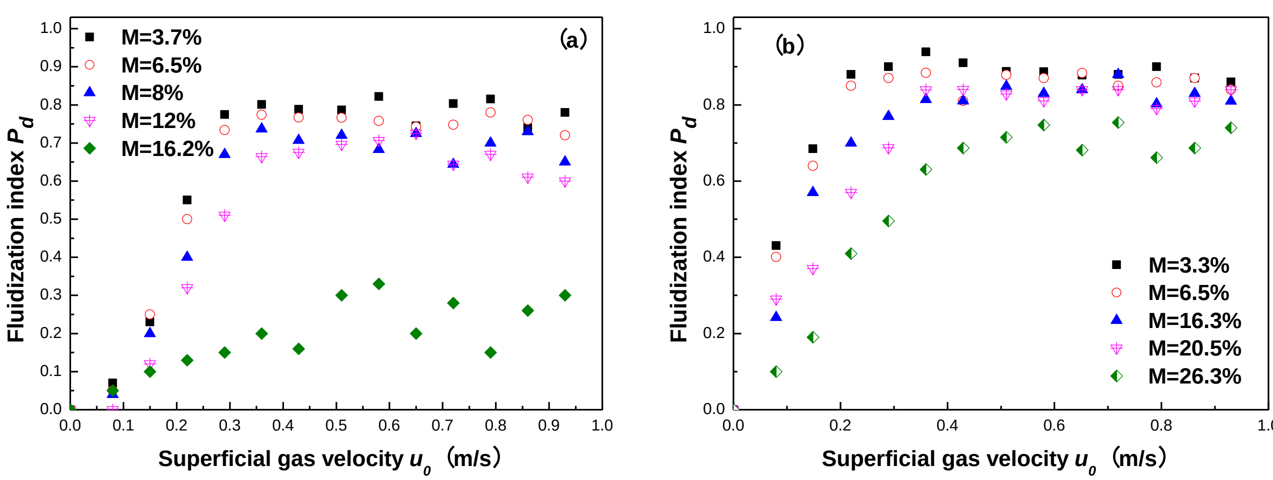

Fig. 4. Fluidization characteristic curves for biomass with various moisture contents (a: rice husk; b: walnut shell)

With increasing M, the P_d values of rice husk and walnut shell both showed a decreasing trend of different degrees until defluidization occurred completely. Comparatively, the P_d of rice husk decreased faster and more noticeably. When the M value reached 16.2%, the rice husk P_d was always less than 0.35, regardless of the increasing u_0, because a variety of particle clusters at different scales were formed in the bed. In this situation, in addition to the coalescence and breakup of the bubbles, agglomeration and disaggregation of the particles also existed, leading to serious channeling and dead regions in the whole bed, thereby affecting the rice husk fluidization. The phenomena described above are consistent with previous findings (Clarke *et al.* 2005). It seems plausible that the capillary forces between adjacent particles become significant compared to buoyant weight of the bed and create a situation whereby they do not behave as discrete particles. The fluidization phenomenon for walnut shell was similar to that of rice husk, but the maximal moisture content for walnut shell fluidization was larger, at 26.3%; in this case, partial fluidization occurred and the P_d was found to be 0.7. This value is in agreement with previous studies (Oliveira *et al.* 2013).

Figure 5 shows the relationship between U_{mf} and M as an S-shaped curve. With increasing M values, the U_{mf} of rice husk and walnut shell both increased slowly at first and then increased sharply.

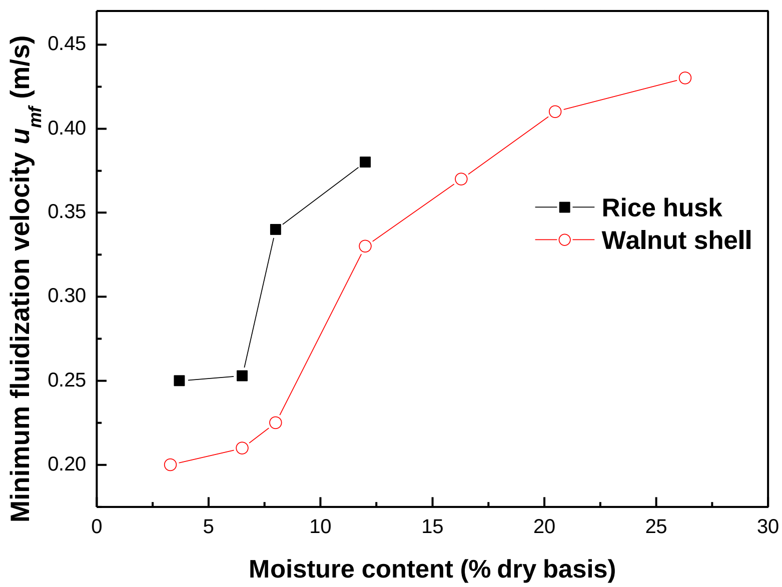

Fig. 5. The minimum fluidization velocity of biomass with various moisture contents

Once the M increased above a critical value, the fluidization failed and the U_{mf} did not exist. In contrast, the U_{mf} of rice husk was always greater than that of walnut shell, which could be attributed to its poor surface properties and sphericity. Rice husk had a lot of burrs, which led to the non-ignorable role of surface force compared with the gravity and inertia force in a small-scale fluidized bed. Simultaneously, the lower sphericity of rice husk also contributed to the increase in the U_{mf} (Fotovat *et al.* 2015; do Nascimento *et al.* 2016). Moreover, increasing the M of biomass results in increased particle density and adhesive force, which led to the U_{mf} increasing and the P_d decreasing considerably. When the M exceeded a critical value, the particle agglomeration obviously increased, which was equivalent to increasing the particle size; as a result, the fluidization gas suffered from the shielding effect to some extent. A similar conclusion was also drawn in a previous study, which focused on the effect of agglomeration on the minimum fluidization velocity (Davies *et al.* 1989). Hence, with comprehensive consideration of fluidization quality and engineering applications, the moisture content of rice husk and walnut shell should be controlled at approximately 6.5% and 8%, respectively.

Binary Fluidization of Biomass/Sand Mixtures

Fluidization of sands with different sizes

Throughout the experimental process, the manometer worked steadily and the micro bubbles were distributed homogeneously, without channeling or slugging. When the carrier gas flow was reduced to zero, the bed surface became flat. This phenomenon indicates that all three kinds of sand particles used achieved satisfactory levels of fluidization. Figure 6 shows that the P_d of sand in the fluidized region was always close to one. Additionally, with a decrease in sand particle size, the minimum fluidization velocity and the pressure drop fluctuation in the fluidized bed showed a dramatic decrease. These results are consistent with fluidized-bed theory.

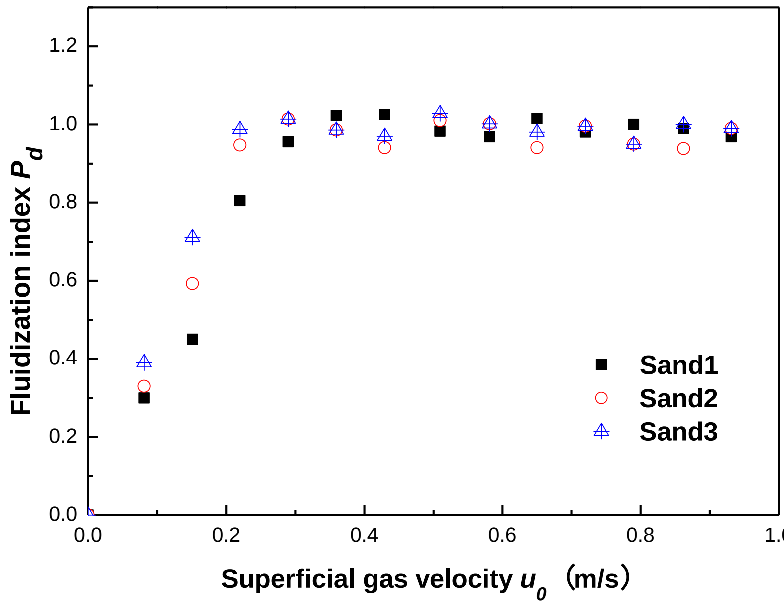

Fig. 6. Sand fluidization curve

The ratio u_0/U_{mf} was defined as the fluidization number (*N)*, which has a close relationship with the behavior and quality of the bed fluidization. The expansion height *H* is represented by a parameter R_s, called the expansion ratio, which was calculated as follows:

$$Rs = \frac{H}{H_{mf}} \tag{4}$$

where H_{mf} is the bed height in the incipient fluidization condition.

Figure 7 shows that under the same fluidization number, as the sand particle size decreased, greater R_s values were obtained. This result is related to the gas distribution between the bubble phase and the emulsion phase. Smaller particle sizes are favorable for the dispersion of gas into the emulsion phase, resulting in a higher effective volumetric flow rate and bed porosity, which also promotes bed expansion and gas-solid contact. In addition, because of the minimum fluidization velocity of sand-3, which was coincident with that of biomass, selecting sand-3 as the mixing medium can prevent the occurrence of the separation to the utmost extent.

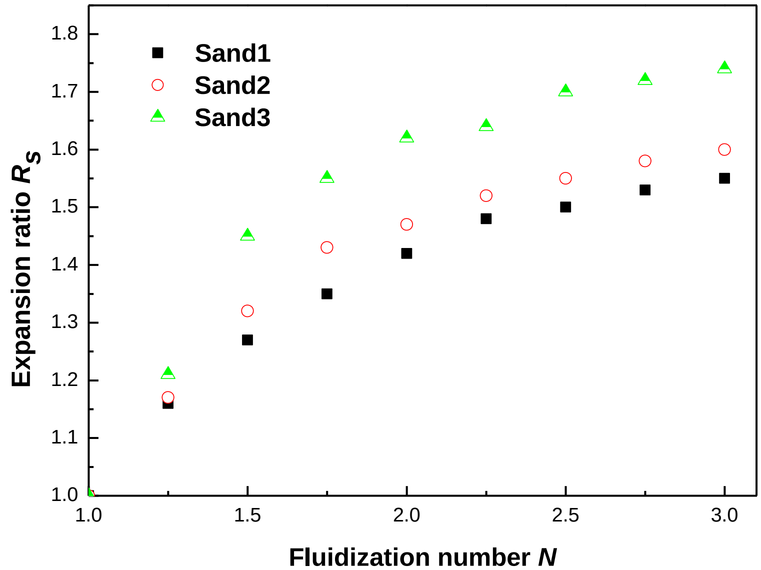

Fig. 7. Bed expansion ratio for different fluidization numbers

Fluidization of biomass/sand-3 mixtures

The fluidization experiments were carried out on biomass/sand-3 mixtures with various weight ratios, and the results are shown in Fig. 8. When the weight percentage of rice husk was at 10% and 30% levels, the two fluidization curves both showed the characteristics of piecewise linear distinctly, which means the fluidization process had an obvious initial fluidization point. The pressure drop in the fluidized region was stable at various superficial gas velocities. Because of the dominant role of sand-3, the rice husk/sand-3 mixtures can be fluidized with high quality without channeling or slugging. When the weight percentage of rice husk reached 50%, the fluidization behavior was similar to rice husk alone because of the large volume fraction (> 80%) of rice husk in the mixtures. The bed pressure drop fluctuated widely, and the fluidization of rice husk/sand-3 was poor, with a large number of channels and cavities.

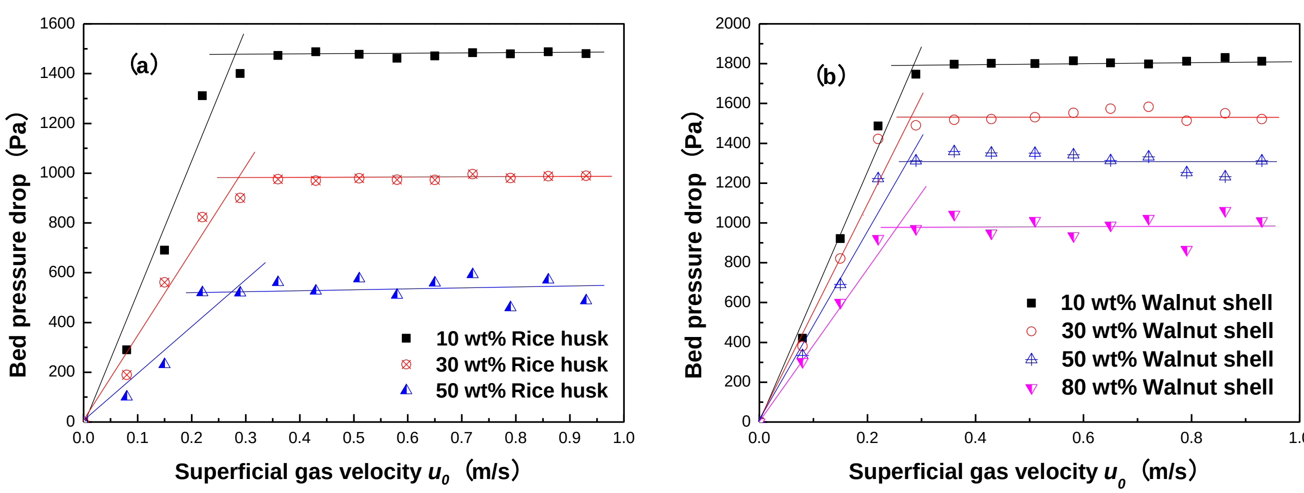

Fig. 8. Mixed fluidization characteristic curve of biomass/sand-3 (a: rice husk, M = 6.5%; b: walnut shell, M = 8%)

The results showed that the walnut shell/sand-3 had similar fluidization behavior to the rice husk/sand-3 mixture, but the density difference of the former was less than the latter, which made the walnut shell show a higher blending upper limit than rice husk. The maximum weight fraction could be up to 80%. This was consistent with the conclusions made in previous research, where effective fluidization was difficult to achieve when the sawdust volume fraction exceeded 80% in co-fluidization experiments with sand and sawdust (Zhang *et al.* 2012). Moreover, Guo *et al.* (2001) pointed out that in a non-equal density system composed of biomass and inert particles, when the weight fraction of the floating component is more than 50%, a good fluidization state cannot be formed.

Figure 9 shows the variation of the fluidization index in the fluidized region at various weight ratios of binary mixtures. It can be seen that the fluidization index of walnut shell/sand-3 mixtures was always greater than that of rice husk/sand-3 mixture at the same weight ratio. This was because of the higher spherical degree and fewer burrs on the surface of walnut shell, which are beneficial for mixtures in a dispersion system. However, the larger burrs present on the rice husk surface will cause the sand particles to be attached to it, thus weakening the mixing and fluidization of rice husk/sand-3. In addition, the proportion of sand-3 in biomass/sand-3 mixtures has a critical influence on fluidization. With an increase in the proportion of sand-3, the fluidization index also increases, thereby improving the fluidization quality was. The fluidization indices of rice husk/sand-3 and walnut shell/sand-3 were maintained above 0.9, and no marked differences with sand-3 individually in the quality of fluidization were present as long as the weight fraction of sand-3 exceeded 50% and 30%, respectively.

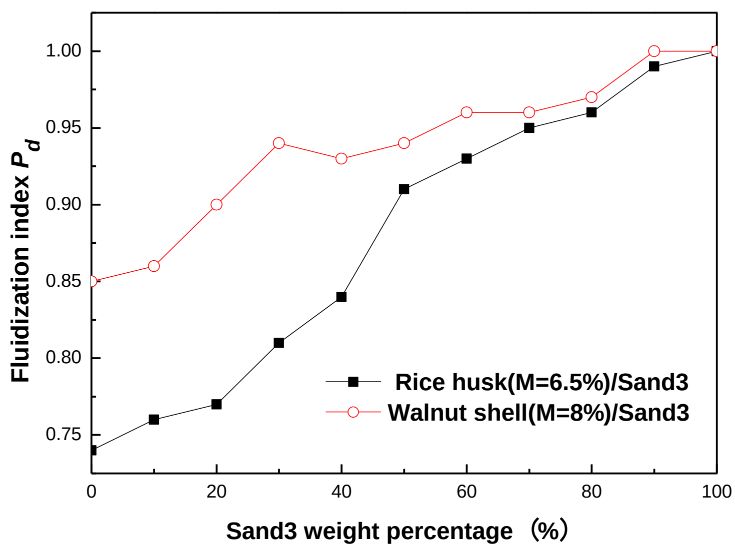

Fig. 9. Fluidization indices for mixed materials with different weight ratios

CONCLUSIONS

1. The initial bed height had a negligible impact on the minimum fluidization velocity of biomass but a considerable effect on bed stability, and the optimum value was in the range of 1.0 to 1.5 *D*. With increasing moisture content, the minimum fluidization

velocity of biomass showed a trend to increase slowly at first, then increase sharply. The fluidization index in the fluidization region decreased constantly.

2. The minimum fluidization velocity of sand-3 (60 to 80 mesh) alone was coincident with biomass and exhibited superior fluidization quality in comparison with sand-1 (30 to 40 mesh) and sand-2 (40 to 60 mesh). The proportion of sand-3 in biomass/sand-3 mixture was found to be the main factor contributing to the fluidizing quality of a bed. With increasing proportion of sand-3 in the mixture, the fluidizing quality of the bed increased. To fluidize rice husk and walnut shell efficiently, moisture content should be controlled at approximately 6.5% and 8%, respectively, and the amount of sand-3 added should be 50% and 30% by weight percentage, respectively.

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