

Fluidization Characteristics of Rice Husk in a Bubbling Fluidized Bed

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Abstract

In this study, the fluidization characteristics of rice husk was investigated experimentally in a 0.17 m ID, 0.9 m high laboratory scale fluidized bed by analyses of mean bed pressure drop, pressure fluctuations, power spectrum of pressure fluctuations, and visual observation with a digital camera. The results show that pure rice husk cannot be fluidized uniformly due to the occurrence of severe channeling. One of the possible methods to facilitate fluidization is to mix rice husk with an easily fluidizable solid. In this study, mixing 700 μm glass bead particles ($\rho_p = 2500 \text{ kg/m}^3$) with rice husk improved the fluidization characteristics significantly. The minimum fluidization velocity of the binary mixture decreased and approached to that of glass bead particles as the mass fraction of the rice husk in the mixture was decreased. Power spectrum of pressure fluctuations was used as a tool to determine the quality of fluidization and estimate the onset of fluidization for the rice husk-glass beads mixture. Furthermore, it was found that with intermittent (pulsed) supply of fluidization air, the fluidization characteristics of pure rice husk could be substantially enhanced. In a frequency range of 0-10 Hz, flow pulsation resulted in turbulent bed-like behavior with improved gas-solid contact.

Introduction

Gasification of biomass is an economically significant process that is used for obtaining syngas, producer gas, pure hydrogen and chemicals such as methanol and ammonia. In power generation, the resulting gaseous fuel is easy to clean, transport and can be burned efficiently in gas turbines, furnaces, and reciprocating engines, and used in fuel cells. Fluidized bed technology is especially suitable for gasification of biomass due its salient features such as feedstock flexibility and excellent gas-solid contact characteristics. However, the uniform fluidization of most biomass such as sawdust, rice husk, straw and bagasse is difficult because of their characteristic shapes, sizes, densities, and moisture contents. However, for successful design of a fluidized bed gasifier, the fluidization characteristics of the feedstock should be well understood.

It has been suggested that the mixing of biomass with a fluidizable solid can improve its fluidization quality and the determination of the minimum fluidization velocity for the resulting binary mixture and effects of moisture on the fluidization characteristics of biomass have been subjects of recent investigations [1-4]. On the modeling side, Sun *et al.* simulated the segregation patterns of a binary rice husk-sand mixture using Eulerian-Eulerian approach coupled with kinetic theory of granular flow [5]. Clearly, more work is required in this area for in-depth understating of fluidization behavior of biomass.

In this study, the fluidization characteristics of pure rice husk and rice husk-glass beads mixture under continuous and intermittent gas supply conditions were investigated by means of measuring mean bed pressure drop, pressure fluctuations,

and analyzing the corresponding power spectrum. A digital camera was also utilized to aid the visual analysis of the fluidization behavior.

Experimental Set-up and Procedure

Experiments were performed in a cast acrylic fluidized bed column of 17 cm in internal diameter and 90 cm in height as shown in Fig.1. A polyethylene porous sheet by Porex was used as the distributor plate. The distributor pressure drop varied between 1000-8100 Pa with superficial gas velocity providing sufficient pressure drop for uniform air distribution. A wind filter was installed at the top of the column to prevent fine particles flying out. The fluidization air was obtained from the university air supply and controlled by a pressure regulator. Four flowmeters with different scales were used to measure the volumetric flowrate of the fluidization air. For pulsed flow experiments, a 2-way normally open solenoid valve (ASCO 8210) was employed. A 36 L surge tank was placed between the solenoid valve and the flowmeters to prevent significant oscillation of the flowmeter float and intense vibration of the bed. The frequency of the solenoid valve was controlled by a 5 MHz Function Generator by BK Precision in the range of 0 – 10 Hz. The input excitation voltage to the valve was 6 VDC and the response time of the valve was approximately 20 ms. A differential pressure transducer by Omega was used in pressure measurements. A 12-bit DAQ card by National Instruments (AT-MIO-64E-3) was utilized for data acquisition and corresponding analyses were carried out with LabVIEW software. Table 1 shows the properties of the bed materials used in this study.

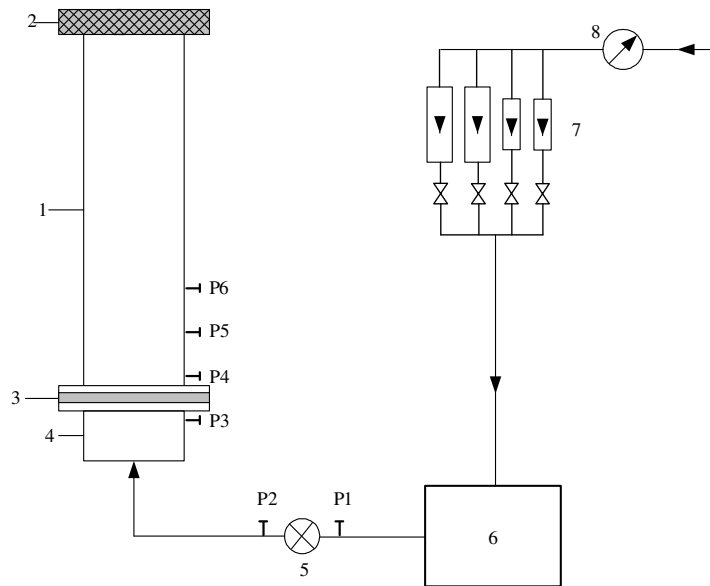


Figure 1. Schematic diagram of the experimental apparatus. 1. fluidized bed, 2. filter, 3. distributor plate, 4. windbox, 5. solenoid valve, 6. surge tank, 7. flowmeter, 8. pressure regulator with filter, P1-6. pressure port locations.

Table 1. Material properties

| Material | Dimension(s) (mm) | Bulk density (kg/m ³) | Particle density (kg/m ³) |
|-------------|----------------------|--------------------------------------|------------------------------------------|
| Rice husk | 8×1×0.2 | 143 | - |
| Glass beads | 0.7 (sieve diameter) | 1467 | 2500 |

Results and Discussion

Experiments were carried out at four different stages: fluidization of rice husk in continuous flow, fluidization of rice husk-glass bead binary mixture in continuous flow, fluidization of rice husk in pulsed flow, and fluidization of rice husk-glass bead binary mixture in pulsed flow. Since the gross hydrodynamic behavior of the bed was of interest, the bed pressure drop and its fluctuation were quantified by the pressure difference between a port just above the distributor plate and the ambient ($P_4 - P_{atm}$). It should be noted that $P_4 - P_{atm} \approx P_4 - P_6$ since the weight of the solids is the dominant contributor to the pressure drop. Scaling was not considered in this work. The total mass of the solids during the experiments for pure rice husk and binary mixtures is given in Table 2.

Table 2. Total mass of the solids in the bed

| Bed | Weight |
|------------------------------------------|--------|
| Pure rice husk – 10 cm bed | 355 g |
| 90vol%, 89wt% rice husk-glass bead mixt. | 400g |
| 70vol%, 23wt% rice husk-glass bead mixt. | 1540g |
| 60vol%, 15wt% rice husk-glass bead mixt. | 2367g |
| 50vol%, 10wt% rice husk-glass bead mixt. | 5463g |

1. Fluidization Characteristics of Pure Rice Husk

When we first attempted to fluidize the pure rice husk in a bubbling fluidized bed at room conditions, two distinct alternating flow patterns were obtained as shown in Fig. 2. After the fluidization air was supplied to the bed, severe channeling was observed (Fig. 2a) marked by small “cracks” near the bed wall. After 5-6 s, the cracks grew in size into a “spouting-like” behavior where rice husk particles were thrown to the freeboard from one side of the bed (Fig. 2b). Fig. 3 shows the bed pressure drop data for rice husk at $U_o = 66$ cm/s. The initial channeling resulted in low mean bed pressure drop values, whereas the spouting-like behavior of rice husk led to sudden increase in mean pressure drop and larger pressure fluctuation. The lower pressure drop values during the initial channeling process can be attributed to the fact that part of the fluidization gas takes a shortcut without lifting the bed material. It should be noted that the signal in Fig. 3 strongly depends on the placement of the pressure port. When the spouting-like behavior (Fig. 2b) occurred on the same side of the pressure port, the pressure drop attained a low value (~ 80 Pa). When the channels grew and spouting-like pattern occurred, the rice husk formed ballistic flow patterns (see Fig. 2c) in the freeboard with rest of the bed staying in de-fluidized condition.

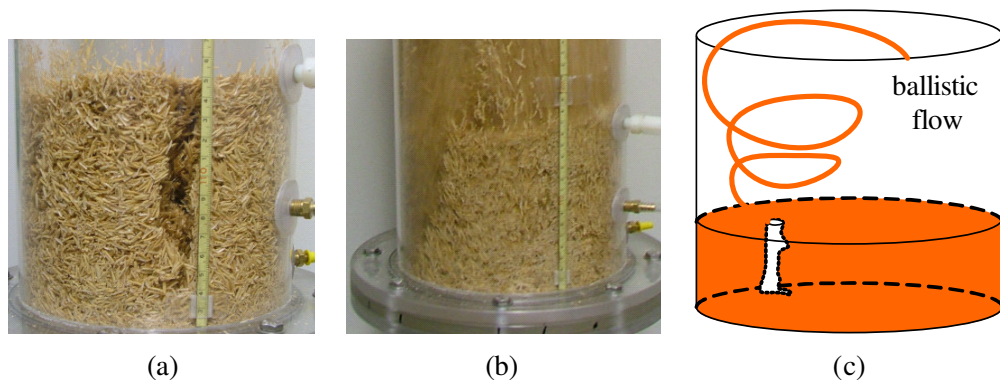


Figure 2. Channeling phenomenon in a bed of pure rice husk

Fig. 4 shows the mean bed pressure drop for rice husk at the static bed heights of 8 cm, 17 cm and 24 cm, which corresponds to bed aspect ratios (H/D) of 0.5, 1 and 1.5, respectively. As can be seen, the mean bed pressure drop increases almost linearly as the superficial gas velocity increases, regardless of the static bed height. Thus, a constant mean bed pressure drop value, which marks the onset of fluidization for a typical fluidizable solid material is never reached. The higher the static bed height, the larger the bed pressure drop is obtained, up to a superficial gas velocity of 45 cm/s beyond which severe spouting-like behavior as described in Fig. 2b alters the expected pattern. The increase in static bed height tends to increase the severity of the channeling phenomenon. Therefore, it can be concluded that pure rice husk used in current study cannot be fluidized. Similar [5] and contradictory [6] findings have been reported in the literature.

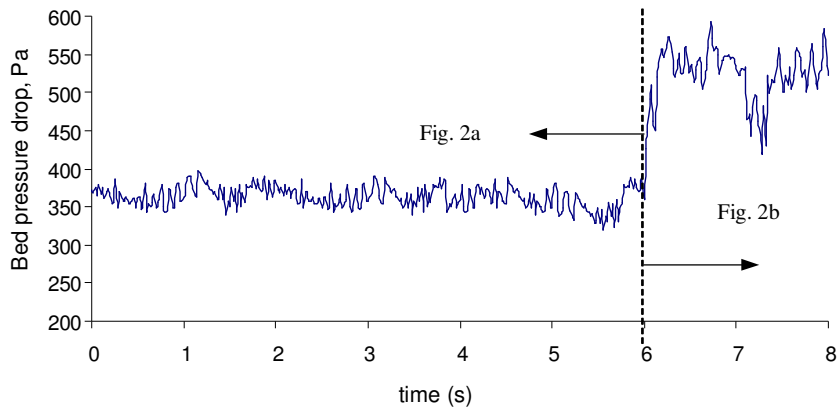


Figure 3. Time series of bed pressure drop, $U_0 = 66$ cm/s.

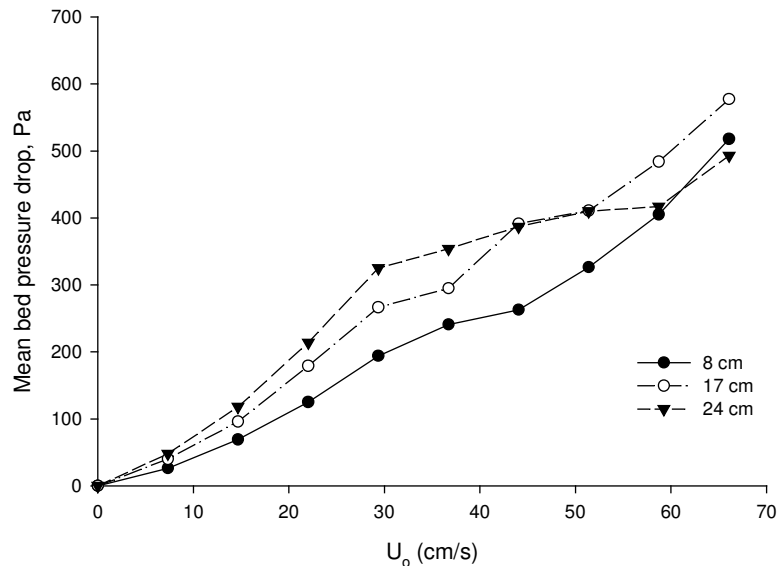


Figure 4. Variation of mean bed pressure drop with superficial gas velocity for different static bed heights, bed material: rice husk.

2. Fluidization of Rice Husk-Glass Bead Binary Particle System

It has been reported in the literature that the fluidization of biomass such as rice husk can be achieved by mixing it with a fluidizable solid [1]. In current study, attempts to

fluidize the binary mixtures have been made with rice husk and different solid particles, i.e. 94 μm ceramic particles ($\rho_p = 700 \text{ kg/m}^3$), 160 and 700 μm glass bead particles. Preliminary experiments showed that 94 μm ceramic particles and 160 μm glass bead particles did not result in substantial improvement of the fluidization quality. Another problem encountered, especially at high superficial gas velocities, was the carryover of the ceramic and 160 μm glass bead particles through the voids of rice husk to the freeboard and their subsequent entrainment from the bed. Therefore, only the results obtained with 700 μm glass bead particles are presented.

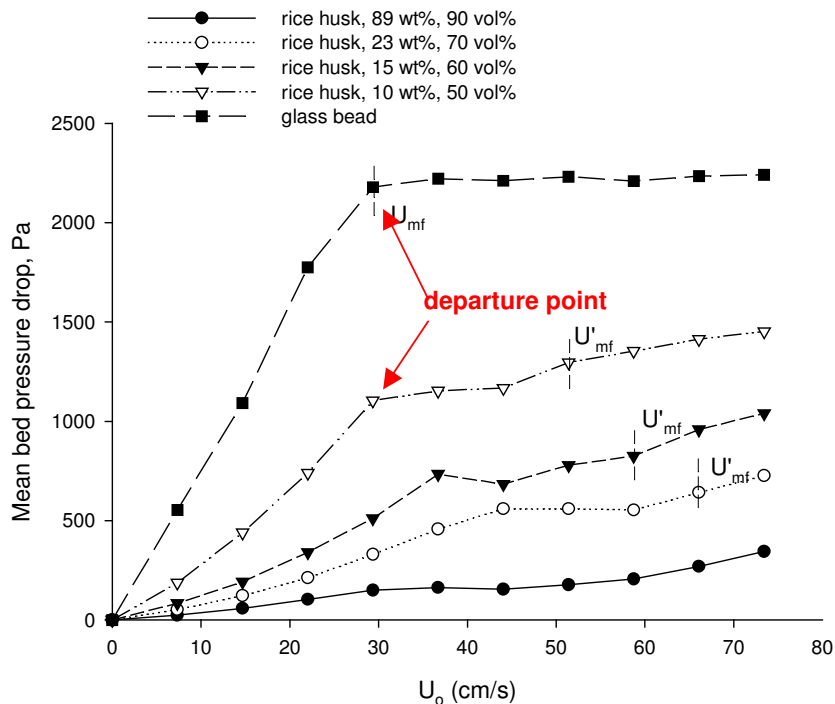


Figure 5. Variation of mean bed pressure drop with superficial gas velocity for the rice husk-glass bead binary mixture.

Fig. 5 shows the mean bed pressure drop in the bubbling bed of binary mixture of rice husk and 700 μm glass bead particles at different mass fractions of rice husk. The corresponding volume fractions are also presented in the same figure. When the mass fraction of the glass beads in the mixture increases, the mean bed pressure also increases due to the increased weight of the mixture. Uniform fluidization was achieved for all tested binary mixture cases except when the mass fraction of the rice husk was higher than 25%. As can be seen, for the case of pure glass beads, the departure from the linear relationship between the pressure drop and the superficial gas velocity in the packed bed is quite clear and marks the onset of fluidization. For the binary mixtures, the departure point is also present, however, the pressure drop still continues to increase after the departure point (although not as marked as in the case of pure rice husk) with superficial gas velocity. This departure point has been used to determine the U_{mf} in a previous study [3]. Aznar *et al.* indicated that the existing mathematical equations for estimating U_{mf} of binary mixtures could not be applied to binary mixtures of biomass and a second solid, because the experimental determination of U_{mf} for the non-fluidizable biomass is impossible [1].

First, we have tried to determine the minimum fluidization velocity of the binary mixture by visual observation. The observed values of minimum fluidization velocity

are indicated by U'_{mf} for each binary mixture case in Fig. 5. It should be noted that the presented values for minimum fluidization velocity can be slightly higher than the actual values since gentle bubbling was being observed at these velocities. This was done to ensure that fluidization was actually achieved. Furthermore, it is known that for coarse particles, the minimum bubbling velocity is almost the same as the minimum fluidization velocity. However, the observed U'_{mf} was much larger than the value indicated at the departure point, especially when the mass fraction of rice husk was high. The U'_{mf} of the binary mixture decreases as the mass fraction of glass bead particles increases and it tends to approach to the U_{mf} of pure glass bead particles. It is evident that the visual approach is rather subjective and relies heavily on researcher's individual experience. Furthermore, in an actual industrial system, it may not be possible at all to use this approach.

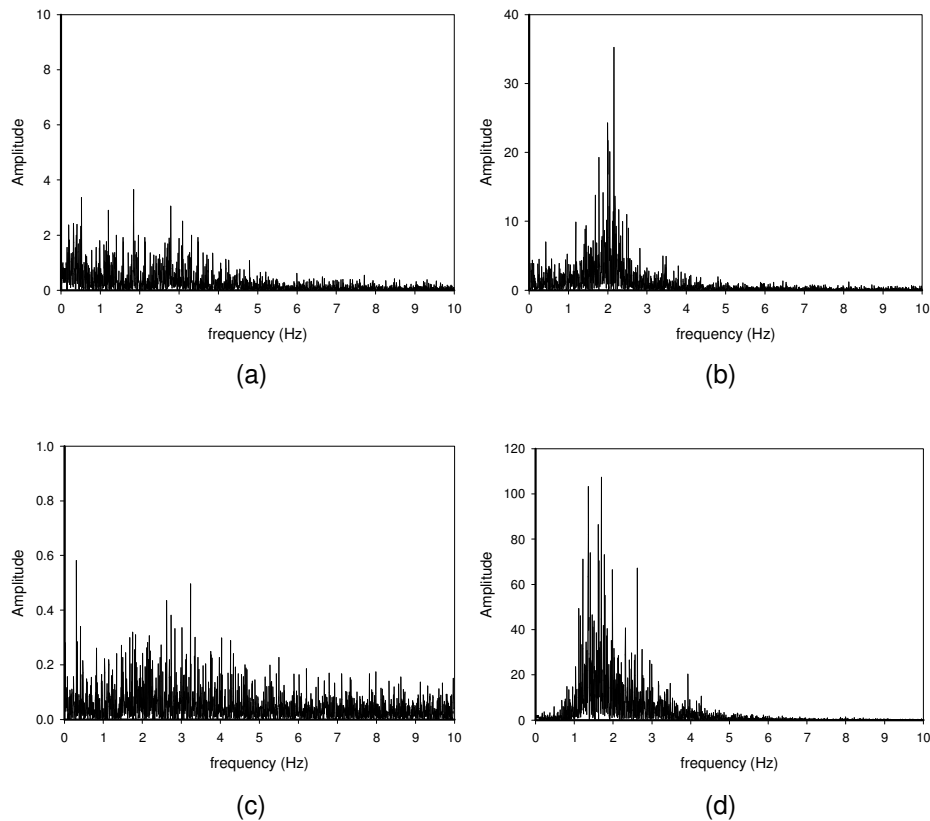


Figure 6. Power spectrum of the bed pressure fluctuation for rice husk-glass bead binary mixture, (a) 15 wt% rice husk, $U_o = 51.4$ cm/s, (b) 15 wt% rice husk, $U_o = 58.7$ cm/s, (c) 10 wt% rice husk, $U_o = 44.1$ cm/s, (d) 10 wt% rice husk, $U_o = 51.4$ cm/s.

It is known that power spectrum of pressure fluctuations in a typical bubbling fluidized bed shows a frequency distribution in a range of 0 – 15 Hz with peaks observed in the range of 1 – 6 Hz. The peak value is sometimes referred as dominant frequency. Thus, the frequency spectrum of bed pressure drop is a deterministic characteristic of a bubbling fluidized bed and can be utilized to determine the fluidization quality and deduce the onset of fluidization [7].

Fig. 6 shows the power spectrum of bed pressure drop for the binary mixtures of 15 wt% rice husk and 10 wt% rice husk, respectively at two different superficial gas velocities for each case. These superficial gas velocities are higher than the

minimum fluidization velocities that could be inferred from the departure point and U_0 of 58.7 cm/s and 51.4 cm/s are the exact velocities that were determined as U'_{mf} by visual inspection for 15 wt% and 10 wt% rice husk cases (Fig. 5). As can be seen, for both cases, at velocities lower than U'_{mf} , the power spectrum is uniform along the frequency band without showing a distinguished peak. On the other hand, for $U_0 = U'_{mf}$, typical expected power spectrum patterns are obtained with peaks around 2 Hz. These power spectrum patterns confirm that the bed is essentially fluidized with uniform bubbling. It should again be noted that the velocities corresponding to these cases can be slightly higher than the actual U_{mf} , however, U_{mf} obtained from the departure point (29 cm/s for 10 wt%, 37 cm/s for 15 wt%) would significantly underestimate the actual U_{mf} . Therefore, the power spectrum analysis is a viable approach.

3. Effects of Flow Pulsation on Fluidization of Rice Husk

As shown, fluidization of pure rice husk cannot be achieved in a conventional bubbling fluidized bed due to its peculiar shape, size and density. Intermittent supply of fluidization gas or the so-called pulsation can be a method to break up the channels observed in pure rice husk beds and improve fluidization quality. When the fluidization gas is pulsed, the gas flow to the bed is cut off for a specified period of time (off period) and then supplied again (on period). The frequency of this pattern is the pulsation frequency and the overall gas throughput does not change. Although, the variation of the gas input to the bed with time is ideally a step function, practically a solenoid valve produces a triangular pattern [8]. Bubble size reduction, more uniform bubble patterns and improved bed-to-surface heat transfer were previously achieved with flow pulsation [8-9].

According to the visual observations, when the bed of rice husk is pulsed at low superficial gas velocity (below 30 cm/s), it cannot be fluidized but tends to pack firmly forming a whole lump. With increasing gas velocity, the lump can be pushed upwards and broken by the strong flow in the *on* period, and a turbulent bed like behavior is obtained with intense particle motion. As in the case of a classical turbulent bed, there are gas voids present in the bed, the bed is highly expanded and the bed surface is not clear. The rice husk in this condition can be fluidized at a superficial gas velocity as low as 37 cm/s, with varying the pulsation frequency constantly from low to high in the range of 0.5 and 5 Hz. The low frequency pulsation mainly pushes the lump of rice husk up and loosens its packing. The high frequency, on the other hand, breaks the lump and moves the rice husk particles up and down at the imposed frequency.

With further increase in gas velocity, above 44 cm/s, the frequency does not need to be varied and a fixed frequency is adequate as seen in Fig. 7. Fig. 7a shows the snapshots of the pulsed bed behavior in one second at $U_0 = 44.1$ cm/s with 1 Hz pulsation. As can be seen, the bed material is fluidized during the *on* period of pulsation and the rice husk is thrown to the freeboard due to the sudden release of accumulated gas. The bed collapses afterwards and the particles settle down and get de-fluidized due to the rather long *off* period. Thus, the fluidization is periodic.

The bed can be continuously fluidized at a higher pulsation frequency as the gas velocity increases. Fig. 7b shows a full cycle for 3 Hz pulsation at $U_0 = 58.7$ cm/s. The bed of rice husk can be completely fluidized without any de-fluidization and channeling. Large gas voids (distorted shape bubbles) are continuously generated by the pulsed flow and the frequency of the formation of these voids is essentially equal to the imposed pulsation frequency.

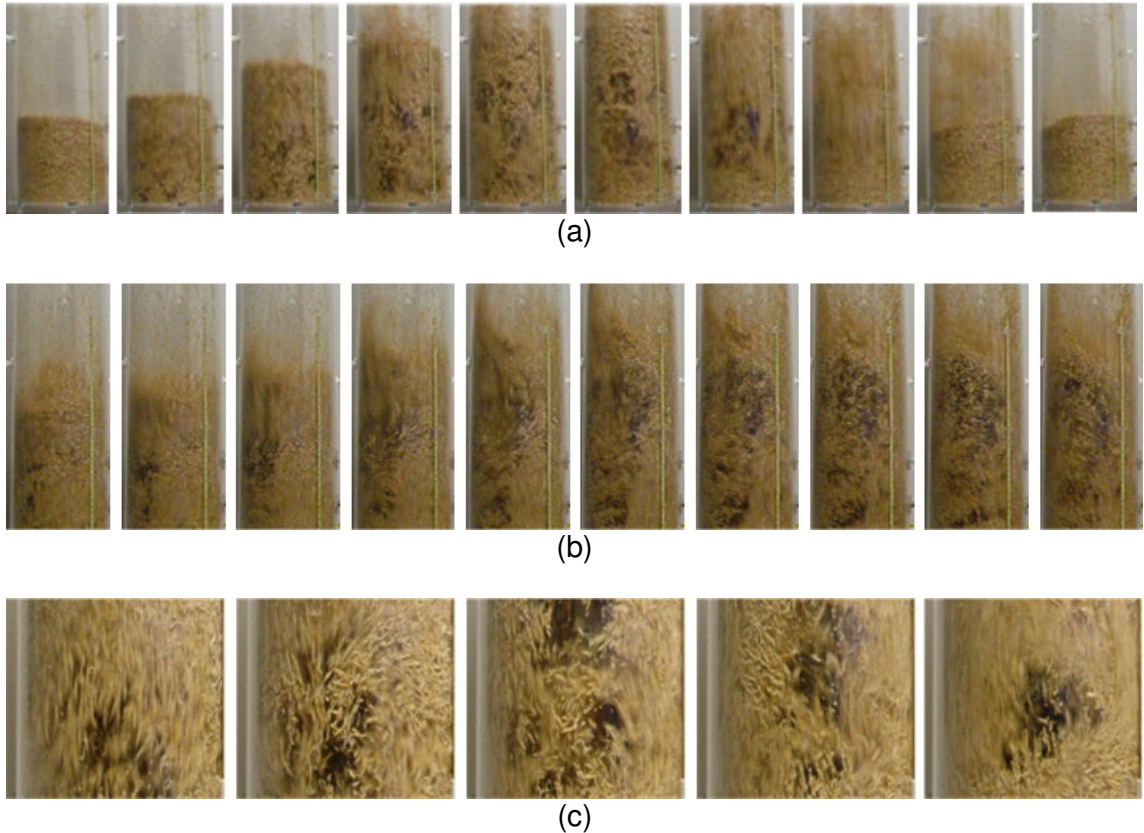


Figure 7. Snapshots of fluidization of pure rice husk, (a) $U_o = 44.1$ cm/s, $f_p = 1$ Hz, $\tau = 0.1$ s, (b) $U_o = 58.7$ cm/s, $f_p = 3$ Hz, $\tau = 0.033$ s, (c) $U_o = 58.7$ cm/s, $f_p = 5$ Hz, $\tau = 0.067$ s.

Fig. 7c shows the close-up of particle and bubble motion with 5 Hz pulsation at $U_o = 58.7$ cm/s in 0.33 second. As can be seen, bubbles form and rise up one after another and the particles never settle down at this pulsation frequency. The size of bubbles at 5 Hz is smaller compared to the voids observed in 3 Hz pulsation and a more uniform behavior can be achieved because the bubbles are generated more frequently and distributed more evenly. With even further increase in gas velocity, the rice husk can still be fluidized as long as the pulsation frequency is also increased. Referring to the continuous flow case and Fig. 4, it might be possible to get a similar turbulent bed behavior with continuous flow at quite high superficial gas velocities (above 90 cm/s) and break the channels. The pulsation essentially achieves the same result at a much lower superficial gas velocity.

Fig.8 shows the time series of pressure fluctuations and the corresponding power spectrums in the bed of rice husk for both continuous and pulsed flows. As can be seen, the amplitude of pressure fluctuation in the continuous flow is much smaller than that of the pulsed flow, and the maximum pressure drop in the pulsed bed is significantly larger than the conventional bed. Meanwhile, a dominant frequency corresponding to the pulsation frequency is found in the pulsed bed as expected, whereas no dominant frequency exists in the conventional bed.

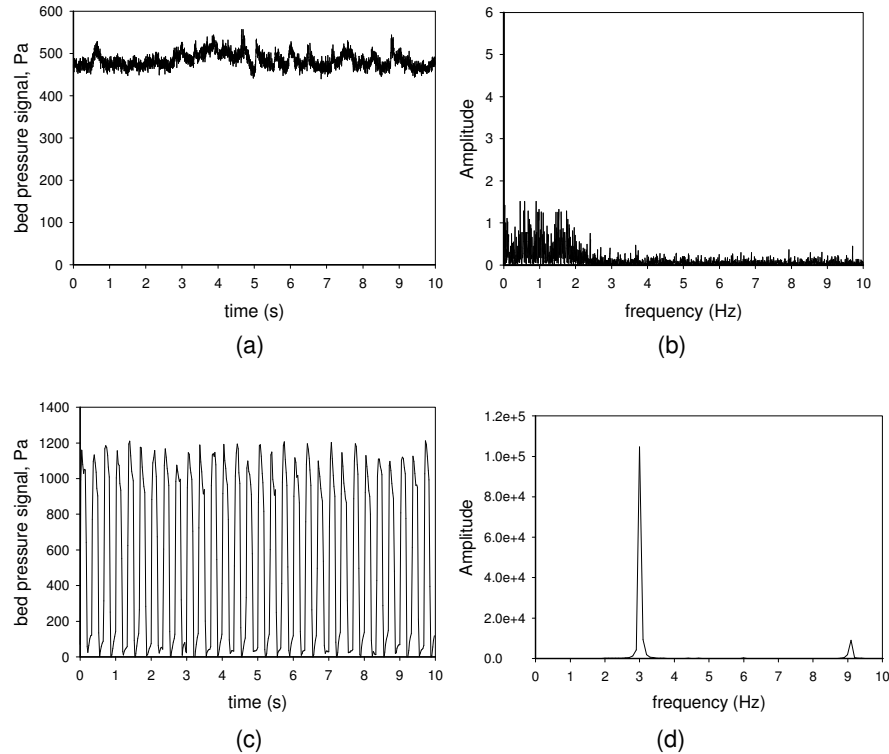


Figure 8. Time series of pressure fluctuation and the corresponding power spectrum in the bed of pure rice husk, $H_{\text{bed}} = 17 \text{ cm}$, $U_o = 58.7 \text{ cm/s}$ (a) pressure fluctuation in the conventional bed, (b) power spectrum of the conventional bed, (c) pressure fluctuation in the pulsed bed at 3 Hz, (d) power spectrum of the pulsed bed at 3 Hz.

The effect of flow pulsation on the binary mixture of rice husk and $700 \mu\text{m}$ glass bead particles was also investigated. Results indicate that pulsation can assist fluidization of the binary mixture by achieving complete fluidization at a much smaller superficial gas velocity compared to conventional fluidization. For the mixture of 10wt% rice husk, fluidization could be achieved at a superficial gas velocity as low as 30 cm/s range compared to 51 cm/s in the conventional bed. However, the segregation of the mixture during the *off* period especially at low pulsation frequencies was observed. Better mixing was achieved at high superficial gas velocities.

In an industrial system, instead of a solenoid valve, which would create significant pressure drop, pulsation can be achieved with a mechanical pulse flow generator such as a rotational disk connected to a motor or a moving double plate distributor [9] where the ratio of the on-off periods as well as the pulsation frequency can be easily controlled. Furthermore, the pulsation frequency can be varied during the operation to further improve the fluidization quality for pure biomass.

Conclusions

From the results of this study, the following conclusions can be drawn:

1. Pure rice husk cannot be fluidized in a conventional bubbling fluidized bed due to severe channeling.
2. Binary mixture of rice husk and a coarse fluidizable solid such as glass beads can be fluidized and the minimum fluidization velocity decreases as the amount of the

fluidizable solid in the mixture increases. The minimum mass fraction of 700 μm glass beads used in this study necessary for complete fluidization of the binary mixture was 75%.

3. Power spectrum analysis of pressure fluctuations is a viable tool to deduce the onset of fluidization for binary mixture of biomass and a fluidizable solid.
4. Flow pulsation can assist fluidization of pure rice husk and the binary mixture in a frequency range of 0-10 Hz. The pulsed supply of fluidization gas results in a behavior similar to a turbulent bed with intense particle motion and mixing. The required pulsation frequency increases with increasing superficial gas velocity.

Acknowledgements

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Nomenclature

| | | |
|-----------|--------------------------------------------|----------------------|
| H/D | ratio of static bed height-to-bed diameter | [-] |
| f_p | pulsation frequency | [Hz] |
| P | pressure | [pa] |
| U_o | superficial gas velocity | [cm/s] |
| U_{mf} | minimum fluidization velocity | [cm/s] |
| U'_{mf} | observed minimum fluidization velocity | [cm/s] |
| ρ_p | particle density | [kg/m ³] |
| τ | time lag between each snapshot | [s] |

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