Cold Flow Binary Fluidization of Oil Palm Residues Mixture in a Gas-Solid Fluidized Bed System

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ABSTRACT

Fluidized bed gasification of biomass is a promising technology. However, significant development work is required before large-scale implementation can be realized. In this work, binary mixture fluidization of silica sand and oil palm residues were accomplished to visualize the fluidization behavior of the mixture in a cold rig. The most critical characteristics for biomass gasifier operation, the minimum (U_{mf}) and complete (U_{cf}) fluidization velocity of the mixtures were determined. The mixtures were prepared by adding $70\%^{w/w}$, $75\%^{w/w}$, $80\%^{w/w}$, $85\%^{w/w}$, $90\%^{w/w}$ and $95\%^{w/w}$ of silica sand to palm kernel shell and/or palm pressed fiber. Experiments were performed in a 0.15 m diameter by 1.0 m height cylindrical column gas-solid fluidized bed system, at a constant 3 kg bed weight. The mixture was pre-mixed before being fed in to the column. The U_{cf}/U_{mf} ratio was found to decrease with increasing weight percentage of palm kernel shell in the mixture while the ratio increased as the weight percentage of palm pressed fibre increased in the mixture. It was also observed that segregation was reduced when the content of silica sand was increased in the binary mixture.

Keywords: Binary mixture, minimum fluidization velocity, complete fluidization velocity, segregation

INTRODUCTION

Fluidization is the principal process that governs gasification technology. The fluidization characteristics of biomass materials are very important for the modelling and design of the reactors (Sun *et al.*, 2005). However, reported values of fluidization hydrodynamics for biomass are scarce (Gomez and Lora, 1995). As stated by Sadaka *et al.* (2002), most works done on biomass gasification did not include the hydrodynamic parameters.

The most important aspects in fluidization hydrodynamics are minimum fluidization velocity and pressure drop across the bed. The minimum fluidization velocity of biomass particles is important for the preliminary sizing in designing the biomass gasifier. As an example, the gasifier diameter can be calculated by using an estimation of the superficial gas velocity which is often related to the minimum fluidization velocity of the bed (Enden and Lora, 2004).

Oil palm residues are wastes that can be turned into gold when appropriate process is applied to extract energy. Looking at the prospects, gasification of oil palm residues

is the most suitable and promising technology which can be exploited in Malaysia. It is a common practice in gasification process where silica sand is used as a starting 'burning' material, in which the heated fluidizing silica sand is used to gasify the biomass supplied to the reactor. Hence, the purpose of this study is to investigate the fluidization behaviour of oil palm residues when fluidized with silica sand in order to understand and predict the gasification process.

THEORY

Pressure Drop Across the Bed

According to Geldart (1986), pressure drop across the bed is the only parameter that can be predicted accurately. Then, a dimensionless index for fluidization was adopted (Marring *et al.*, 1994), where ratio between experimental and theoretical pressure drop was calculated. The Fluidization Index, FI, is defined as:

$$\text{FI} = \frac{\Delta PA}{0.1M_B} \tag{1}$$

where M_B is mass of solid in bed, ΔP is pressure drop across the bed and A is the cross-sectional area of the bed.

Definitions of Minimum and Complete Fluidization Velocity for Mixture

Determination of minimum fluidization velocity, U_{mf}, is a complex process when binary mixtures are involved in the fluidization process. Peculiarities in sizes, shapes and densities of biomass particles are the main contributors for this complexity.

There are numerous discussions on determination of the minimum and complete fluidization of binary mixtures. For a monodisperse system, U_{mf} is defined as the superficial velocity at which the packed bed becomes a fluidized bed. According to Chiba *et al.* (1971) (Nienow and Chiba, 1985) fluidization of a binary particles system can be divided into three categories; (a) perfect segregation; (b) partial mixing; (c) perfect mixing; as illustrated in *Fig. 1(i)*. Binary mixtures involve two components with the same or different properties. Component 1 will have a lower Umf compared to component 2. Components 1 and 2 will fluidize at U_F and U_P respectively. F and P refer to more and less fluidizable components. When the mixture is fluidized at U>>Up, and then U is reduced at a steady rate to zero (the defluidizing procedure), the settled bed will generally have one of the three mixing-segregation states. When more fluidizable particles are in large proportion in the mixture, superficial gas velocity will be close to U_F (Delebarre *et al.*, 1994).

For mixtures with small difference in size and equal density components, a good mixture may be obtained throughout the bed regardless of the defluidizing procedure. $\Delta P/\Delta P_{fluidized}$ against superficial gas velocity, U provides a unique measure of minimum fluidization velocity, U_M.

If one component is bigger and more dense than the other, the system remains completely segregated independent of the defluidizing procedure as illustrated in *Fig. 1(i)(a)*. In this case, $\Delta P/\Delta P_{fluidized}$ plotted against U will be the sum of contributions from the pure components (*Fig. 1(ii)(a)*). However, in order to obtain U_{mf} value, some special definition must be adopted, since at $U_F<U<U_P$, the upper part of the bed is well fluidized

while the bottom is packed. The U_{mf} is obtained from the velocity at the intersection of the two extrapolated linear portions of the plot corresponding to the regions where the whole bed is first, fluidized ($U>U_P$) and second, packed ($U<U_F$). This apparent minimum fluidization velocity is shown as U_S.
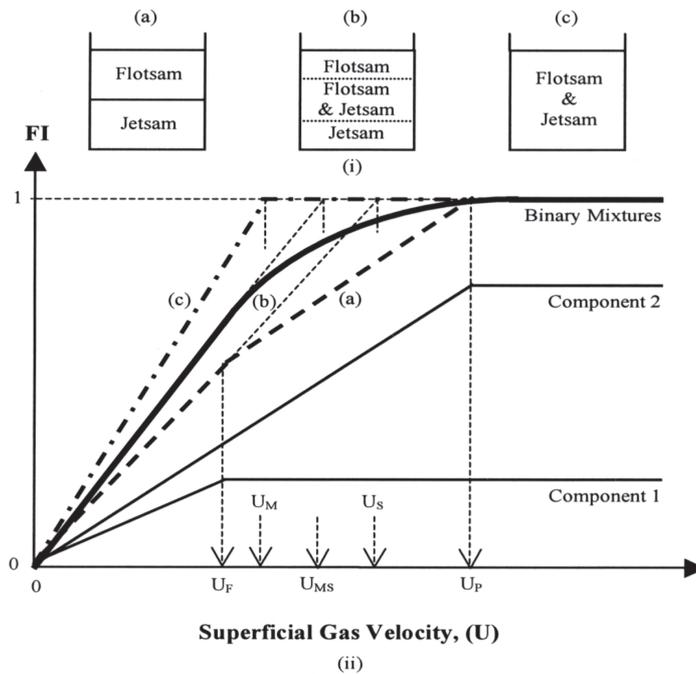

Fig. 1: Relationship between bed pressure drop and gas velocity for fluidization of binary particles system

Generally, the upper part of the bed is flotsam-rich, the lower jetsam-rich and there is a mixed region in the middle as shown in *Fig. 1(i)(b)*. Ongoing from U_P to U_F, a steadily decreasing amount of the bed will be fluidized, but as long as at least some of it is still fluidized, particle rearrangement can occur. If defluidization is slow and the species differ in density, *Fig.1(i)(b)* will tend towards *Fig. 1(i)(a)*. If the species only differ in size and defluidization is rapid, *Fig. 1(i)(b)* will tend towards *Fig. 1(i)(c)*. In each case, FI versus U will in general be as shown in *Fig. 1(ii)(b)* with U_{MS} being a function of the defluidization procedure.

The common graphical representation for minimum fluidization velocity, U_{mf} in ΔP versus U curve is defined as corresponding to the intersection of the fully fixed and fully fluidized straight lines. Formisani (1991) suggests obtaining the value of the minimum fluidization velocity at increasing velocities for a perfect mixed initial state rather than during defluidization when segregation may occur. Work from Pilar Aznar *et al.* (1992) observed U_{mf} as common graphical presentation and U_{cf} by observation at which the entire bed (biomass and second solid) is in motion, independently of where this velocity starts or whether or not all the biomass is segregated in the upper or lower part of the bed, or the movement of the biomass is different (small plugs, for example) from the movement of the second fluidizing solid. Rao and Bheemarasetti (2001) obtained the

minimum fluidization velocity from the intersecting point of the defluidization curve with the constant pressure line. Patil *et al.* (2005) determined U_{mf} at the point where the pressure drop across the fluidizing bed became constant.

MATERIALS AND METHODS

Sample Pre-treatment

Biomass sample was dried using a MEMMERT GmbH universal oven model g604.0435 to achieve biomass moisture content to be below 10-20% for gasification (Cummer and Brown, 2002). The oven-drying was performed according to technical specification CEN TC335 Solid Biofuels (Samuelsson *et al.*, 2006). The temperature of the oven was set to 1050C and left to be dried for 24 hours. Moisture content in the biomass sample was measured by using Precisa moisture analyzer, model XM 60 before and after oven-drying. Oil palm biomass was then ground to particle size by using the Retsch cutting mill model SM 100 with a bottom sieve of perforation size of 2 mm. Silica sand used in the experiment was sieved and separated. The mean particle size of the sand used in this work was 287.5 μm. This size range was chosen as the most suitable for the pilot plant gasifier as proven in the work done by Pilal Aznar *et al.* (1992). Table 1 shows the properties of materials used as the feed to the fluidized bed and *Fig. 2* exhibits photos of oil palm residue when received and after pre-treatment processes.

FLUIDIZATION

Fig. 3 shows the experimental set-up of the fluidized bed and the apparatus comprises of a 150 mm diameter Perspex tube 1000mm in height. The distributor was made from PVC with 36 holes, 8mm in diameter each. A layer of gauze cloth was placed over the distributor. The top end of the Perspex tube was covered with filtration material to prevent the particles from elutriating out. A transparent scale was attached on the bed wall to provide direct bed expansion measurement. Air at ambient temperature and with a relative humidity of 50% was used as the fluidizing agent and was supplied from a 0.5hp blower.

TABLE 1
Properties of materials used in the experiment

Material		Mean Diameter (μm)	Bulk Density, ρ_b (kg/m³)	Particle Density, ρ_p (kg/m³)	Voidage, ε_{mf}	Geldart's Classification
Palm Shell	Kernel	1425	150	398.7	0.62	B
Palm Fibre	Pressed	675	73*	407.4*	0.82	A
Silica Sand		287.5	554	1086.8	0.49	B

*Values taken from Abdullah *et al.* (2003)

(a)

(b)

Fig. 2: (a) Palm kernel shell as received; (b) Palm pressed fibre as received

Oil palm residues used in this experiment were taken on weight basis and the mixture studied contains 5, 10, 15, 20, 25 and 30 weight percent of oil palm residues. The total weight of oil palm residues and silica sand in the bed was kept constant at 3 kg in all experiments. Sand and oil palm residues were weighed according to their respective percentage. Random mixture method is chosen in this work where a Z-blade mixer was used to randomly mix the pre-weighed oil palm residues and silica sand for a period of 10 minutes to ensure uniformity for all the mixtures prior to feeding into the Perspex tube. Air was passed to the bed increasingly from zero to fluidization stage (when all
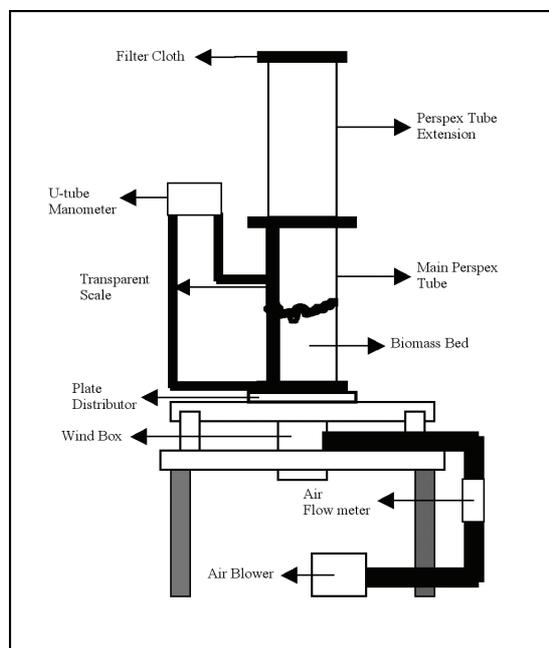
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Fig. 3: Schematic diagram of fluidized bed apparatus

particles in the bed move vigorously). Two ranges of air velocity were set; 0-19 cm/s and 0-29 cm/s for mixtures of palm kernel shell or palm pressed fibres with silica sand respectively. Then, the gas flow rate was gradually decreased (defluidization stage). At each gas flow rate, either in fluidization or defluidization stage, the pressure loss across the bed and the bed height was recorded. The important parameters, minimum fluidization velocity, U_{mf} and complete fluidization velocity, U_{cf} were observed and recorded. All of the experiments were repeated at least three times to ensure reproducibility.

RESULTS AND DISCUSSION

Fluidization Behaviour

Palm pressed fibre is considered as polydisperse material which has wide particle size distributions. Each of the fractions has their own U_{mf} (Reina *et al.*, 2000). When fluidized with silica sand (jetsam), palm pressed fibre (flotsam) will move to the upper bed. At $U_{mf}<U<U_{cf}$, fraction of smaller flotsam will elutriate out from the bed and some of it will stick to the wall of the Perspex tube extension. However, most of the particles will circulate back into the bed since the fluidization column is covered with a filter cloth. These fractions of particles fluidize vigorously in their own region at the upper part of the bed without any mixing with silica sand. Larger fraction of flotsam is observed to mix and segregate simultaneously.

Figs. 4 and *5* display the profile of the dependency of pressure drop across the bed to superficial gas velocity of the mixture of 85% silica sand and 15% palm pressed fibre

and palm kernel shell respectively. From the graphs, the mixture of palm pressed fibre and silica sand show that complete fluidization occurs at FI value of 1.3, which is higher than FI indicated in complete fluidization for mixture of palm kernel shell and silica sand (FI = 1.2). This is probably due to high interparticle forces in palm pressed fibre particles where a higher pressure drop and superficial gas velocity are noticeable for the mixtures to reach complete fluidization. It was observed that the palm pressed fibre has high tendency to stick to the column wall which indicates the presence of high electrostatic charge. The charges build-up resulting in particle agglomeration causing stagnant spots in the bed, which later increase the value of U_{mf} and subsequently U_{cf}. These charges were generated as a result of repeated particle contact and separation, supplemented by the friction of particles rubbing against each other and the column wall (Mehrani *et al.*, 2007). High electrostatic charge also was suspected to contribute to the limitation of fluidization capabilities of palm pressed fibre mixture where the bed can only be fluidized if the fibre content is less than 20 weight percent of the total bed weight. Fluidizing mixture of palm pressed fibre with higher than 20 weight percent results in the formation of channels across the bed, and later the formation of vertical rat hole from the bottom to the surface of the bed. The rat hole became bigger as U increased and the palm pressed fibre starts to be blown out of the column. As for the fluidization of the palm kernel shell and sand mixture, segregation is observed to be more visible. This is probably due to its free-flowing nature of ground palm kernel shell, where fluidization occurs up to 30 weight percent of residues in the bed.
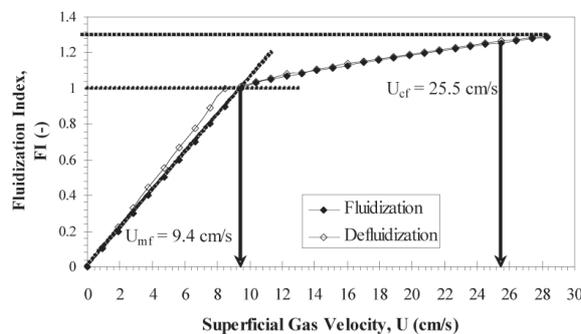

Fig. 4: Fluidization index versus superficial gas velocity for mixture of 85% silica sand and 15% palm pressed fibre

According to Cheung *et al.* (1974), segregation through percolation occurs if packing arrangements that allow the smaller spheres to pass through the other particles are between $\dfrac{d_s}{d_B}$ = 0.417 for the loosest packing and $\dfrac{d_s}{d_B}$ = 0.154 for closest packing. In this experiment, binary mixtures of silica sand and palm kernel shell and silica sand and palm pressed fibre have $\dfrac{d_s}{d_B}$ values of 0.201 and 0.426 respectively. In both cases, segregation is visually observed to be more severe when silica sand content is reduced in the mixture. However, no indicative measurement was done to investigate the mixing/segregation phenomena in this work.
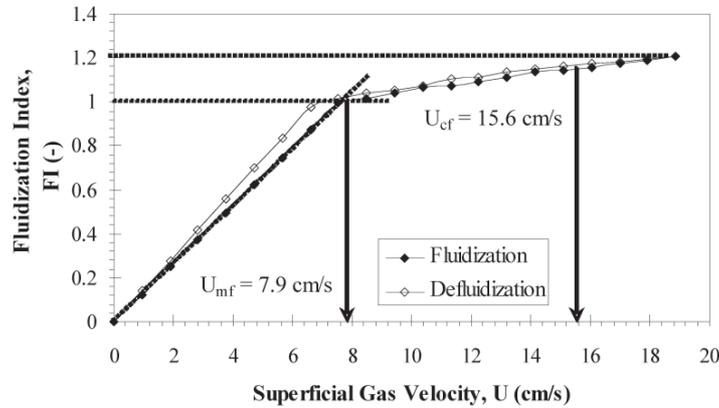
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Fig. 5: Fluidization index versus superficial gas velocity for mixture of 85% silica sand and 15% palm kernel shell

Determination of U_{mf} and U_{cf}

Figs. 4 and *5* are typical plots of fluidization and defluidization curves for mixtures of oil palm residue and silica sand. As shown in both figures, U_{mf} values are taken at the intersection of fluidization curve from point 0 and FI equals to 1. During this time, the upward drag force exerted by the gas on the particles is equal to the apparent weight of particles in the bed. Theoretically, the particles will be lifted up by the gas, the separation of the particles increases and bed becomes fluidized. This is observed by the commencing of bubbles or expansion of the bed according to their respective group of powders classified prior to the experiment. U_{cf} is determined when all the particles in the bed are observed to move (Pilar Aznar *et al.*, 1992; Patil *et al.*, 2005). Both the U_{mf} and U_{cf} values for fluidization of the palm kernel shell mixture were found to be smaller than for the palm pressed fibre. This result is as expected as both the U_{mf} and U_{cf} are heavily affected by physical characteristics of the fluidizing materials used. As discussed in section 4.2, the palm kernel shell behaves as free-flowing particles and hence contributes to less particle-particle interactions in the bed, which results in smaller U_{mf} and U_{cf}. Meanwhile, physical characteristics of palm pressed fibre results in higher velocity needed to break the interparticle forces of the fibrous materials (Fauziah *et al.*, 2006).

As can be seen in *Fig. 4*, the defluidization curve is almost the same as the fluidization curve when $U_{mf}<U<U_{cf}$. A dynamic equilibrium state may have been reached where mixing and segregation occurs simultaneously. Furthermore, a large amount of sand was used in the mixture and it belongs to free-flowing group B particles; hence, it is expected that the fludization - defludization profile of this bed mixture does not show much difference between one other in that specified region. However, the defluidization curve for both types of mixtures is slightly higher than the fluidization plot especially after passing U_{mf} values. This is because the bed is less permeable in the defluidization stage due to segregation, as well as due to the effect of flotsam and jetsam of particles with different densities and shape.

Ratio of U_{cf}/U_{mf}

As exhibited in *Fig. 6,* the ratio of U_{cf}/U_{mf} decreases as the percentage of palm kernel shell mixture increases. Meanwhile, a different pattern is observed for the mixture of

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palm pressed fibre and silica sand. As the percentage of the palm pressed fibre in the mixture increases, the ratio of U_{cf}/U_{mf} also increases sharply as displayed on *Fig. 7*. However, as can be seen in Table 2, the U_{cf} and U_{mf} trends for both mixtures (palm kernel shell/palm fibre with silica sand) only demonstrate increment pattern with increasing percentages of residue in the mixtures. A large difference in superficial gas velocity between U_{mf} and U_{cf} in every weight fraction is noticed in Table 2(b) and these explained the sharp increment of the U_{cf}/U_{mf} ratio for mixtures of palm pressed fibre and silica sand. The trend dissimilarity in U_{cf}/U_{mf} ratio for both mixtures is probably due to the physical characteristic of this residue material where palm pressed fibre is physically light weighted, sustained rod shape after grinding and have a very high voidage. The interparticle forces are known to be very high as explained in previous section. Therefore, higher velocity is needed to fluidize all the particles in the bed vigorously.

From *Figs. 6* and *7*, it is clear that U_{cf}/U_{mf} ratio of palm kernel shell and silica sand is much lower than mixtures of palm pressed fibre. This is due to the physical characteristics of the palm kernel shell which has lower voidage and retains a more free-flowing nature in comparison to fibrous palm pressed fibre. Mixture of palm kernel shell and silica sand is also observed to start fluidizing at a lower gas velocity.
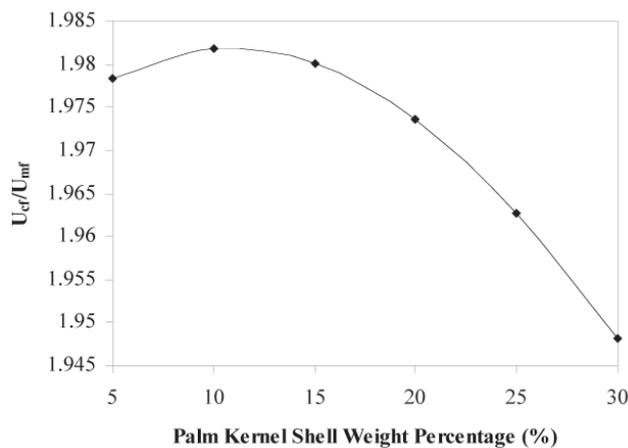

Fig. 6: U_{cf}/U_{mf} ratio for mixture of silica sand and palm kernel shell

TABLE 2(a)

U_{mf} and U_{cf} for different mixtures for palm kernel shell with silica sand

Palm Kernel Shell Weight Percentage (%)	U_{mf} (cm/s)	U_{cf} (cm/s)
5	7.4	14.6
10	7.6	15.1
15	7.9	15.6
20	8.1	16.0
25	8.4	16.5
30	8.7	17.0

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TABLE 2(b)

U_{mf} and U_{cf} for different mixtures for palm pressed fibre with silica sand

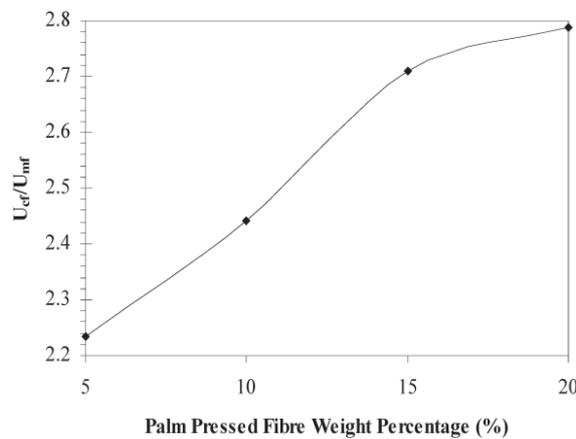| Palm Pressed Fibre Weight Percentage (%)	U_{mf} (cm/s)	U_{cf} (cm/s)
5	7.6	17.0
10	8.5	20.8
15	9.4	25.5
20	11.5	32.1

Fig. 7: U_{cf}/U_{mf} ratio for mixture of silica sand and palm pressed fibre

CONCLUSIONS

Ratio of U_{cf}/U_{mf} of binary fluidization of oil palm residues with silica sand shows a totally different pattern for different types of residues used. Increment pattern is observed in the mixture of palm pressed fibre and silica sand while a decreasing pattern is obtained in the fluidization of palm kernel shell and silica sand, which is contributed by the physical characteristics of the materials used. The inequality of patterns is determined by the amount of superficial gas velocity necessary for the particle to reach complete fluidization from minimum fluidization velocity at the initial stage. It is also observed by visual observation that segregation is reduced when the content of oil palm residues used in the mixture is in small amounts.

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