

# Minimum Fluidization Velocities of Mixtures of Palm Oil Residues and Sand

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**ABSTRACT:** Understanding and knowledge on the hydrodynamics of fluidization is vital in obtaining an efficient fluidized bed system. The minimum fluidization of mixtures of palm oil residues with inert material (silica sand) in a cold gas fluidized bed has been studied. Oil palm residues consist of palm pressed fibre and palm kernel shell were used as the feed material in a 150mm internal diameter fluidized bed test rig with 1000mm in height. The percentage of palm oil residues in the mixture were: 5, 10, 15, 20, 25 and 30% by weight. It is proven that the appropriate design value of the superficial gas velocity to be used in the operation of biomass gasifier is to take  $U_{cf}$  twice the  $U_{mf}$  for mixture of palm kernel shell with silica sand and thrice the  $U_{mf}$  for mixture of palm pressed fibre with silica sand. The experimental  $U_{mf}$  values were compared to several correlations established by previous researches and it was found that Bilbao et al., 1987 was suitable to be used to predict  $U_{mf}$  for binary mixture of palm pressed fibre with silica sand.

**Keywords:** Binary mixture, minimum fluidization velocity, hydrodynamic, palm kernel shell, palm pressed fibre

## NOMENCLATURE

|            |                                            |
|------------|--------------------------------------------|
| $\rho_M$   | Mixture density                            |
| $d_M$      | Mean particle diameter of mixture          |
| $\rho_p^F$ | Particle density of fluid component        |
| $\rho_p^P$ | Particle density of packed component       |
| $x^F$      | Weight fraction of fluid component         |
| $x^P$      | Weight fraction of packed component        |
| $d_p^P$    | Mean particle diameter of packed component |
| $d_p^F$    | Mean particle diameter of fluid component  |
| $\rho_p^P$ | Particle density of packed component       |
| $\rho_p^F$ | Particle density of fluid component        |
| $U_{mf}$   | Minimum fluidization velocity              |
| $U_{cf}$   | Complete fluidization velocity             |
| FI         | Fluidization index                         |
| $\Delta P$ | Pressure drop                              |
| $U$        | Superficial gas velocity                   |

## 1. INTRODUCTION

Conversion of biomass to intermediate energy carriers like gases or oils is much more attractive than direct combustion. This is when gasification technology comes in. Fluidized bed gasification has been preferred to gasify biomass for its good heat and material transfer between the gas and solid phase with the best temperature distribution, high specific capacity and fast heat-up. They tolerate wide variations in fuel quality and a broad particle size distribution which were the main characteristics of most biomass particles.

However, the fundamental knowledge of biomass fluidization which is the governing process inside the gasifier is not well understood. Fluidization of biomass is complicated due to their unusual

morphology, wide particle distribution and high moisture content besides the main characteristics of its peculiarity in shapes, sizes and densities. A common practice to ease the fluidization is to add a second, inert material forming binary particle system.

Fluidization of palm oil residues consists of palm kernel shell and palm pressed fibre with inert material (silica sand) was conducted in this work. The aim of the research is to imitate gasification process inside a fluidized bed biomass gasifier using a fluidized bed cold rig. Understanding and knowledge on the hydrodynamics of fluidization is vital in obtaining an efficient fluidized bed system since reported values of fluidization hydrodynamics for biomass are scarce [1].

## 2. THEORY

Binary mixture involves two components with the same or different properties. For fluidization of particles with different sizes and densities, it is useful to define two other velocities which is velocity for beginning fluidization for fine particles or  $U_{mf}$  and velocity for total or complete fluidization for coarser particles,  $U_{cf}$ .

Yang and Keairns, 1982 as cited in [2] have proposed a method for estimating the minimum fluidization velocity as the intersection of the horizontal line representing the bed pressure drop, calculated by dividing the total bed weight by the bed cross-sectional area, with the pressure drop curve after the maximum pressure drop is attained. The common graphical representation for minimum fluidization velocity,  $U_{mf}$  in  $\Delta P$  versus  $U$  curve is defined as corresponding to the intersection of the fully fixed and fully fluidized straight lines. Noda et al., 1986 [2] obtained the representation of  $\Delta P$ - $U$  by increasing and decreasing  $U$  and observed that the values for  $U_{mf}$  so obtained are somewhat higher in the second case. The

higher of the values is recommended for  $U_{mf}$ .

Formisani, 1991 [3] suggests taking the minimum fluidization velocity value at increasing velocities for a perfect mixed initial state rather than during defluidization when segregation may occur. Work from Aznar et al., 1992 [4, 5] 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 [6] obtained the minimum fluidization velocity from the intersecting point of the defluidization curve with the constant pressure line. Patil et al., 2005 [7] determined  $U_{mf}$  at the point when the pressure drop across the fluidizing bed became constant. In this study, definition by Yang and Keirns, 1985 [2] have been used in determining the  $U_{mf}$  while definition set by Aznar [4, 5] is applied in determining  $U_{cf}$ .

Another important part of fluidization hydrodynamics is to model the  $U_{mf}$  correlations. The methods used to develop correlations in the case of minimum fluidization velocity of gaseous systems can involved either fixed bed pressure drop, a void fraction velocity or a completely empirical procedure [8]. A large amount of analysis has been devoted to the study of the behaviour of beds constituted of particles of mixed sizes or densities. The objective is generally being to determine the mechanism of solids motion and the degree of mixing.

A bed of mixed solids can be considered as a bed of particles of uniform size only by defining a convenient mixture diameter and densities. Goossens et al., 1971 [9] assumed the mixture density to be:

$$\frac{1}{\rho_M} = \frac{x^F}{\rho_p^F} + \frac{x^P}{\rho_p^P} \quad (2.1)$$

and found that the smallest deviation between experimental and calculated values was obtained by adopting a mixture diameter definition such as to give the same total surface area per unit weight of the binary system:

$$\frac{1}{d_M \rho_M} = \frac{x^F}{d_p^F \rho_p^F} + \frac{x^P}{d_p^P \rho_p^P} \quad (2.2)$$

Meanwhile, Kumar and Sen Gupta, 1974 which was cited in [8] define it as:

$$d_M = \frac{1}{\frac{x^F}{d_p^F} + \frac{x^P}{d_p^P}} \quad (2.3)$$

$$\rho_M = x^F \rho_p^F + x^P \rho_p^P \quad (2.4)$$

These definitions of mixture sizes and densities have been widely used as can be seen in the compilation of various correlations for calculating the minimum fluidization velocity of binary mixture as listed in table 1 in appendix. In this study, list of equations in the table were applied to find the most suitable model for the present study.

### 3. METHODOLOGY

Biomass used was taken on weight basis and the mixture studied basically contains 5, 10, 15, 20, 25 and 30 weight percent of biomass. However, there were mixtures which cannot fluidize before reaching 30 weight percent of biomass and some of the mixtures can fluidize even though it reached more than 30 weight percent of biomass. Two distinct types of bed arrangement i.e. layer and random mixture methods were applied in this work. In layer mixture method, sand was placed at the bottom of the Perspex tube and oil palm residues were

put on top of the sand. In random mixture method, oil palm residues and sand were weight according to their respective percentage. A Z-blade mixer was used to randomly mix the pre-weighted oil palm residues and silica sand for a period of 10 minutes prior feeding into the Perspex tube. The total weight of the biomass material and silica sand in the bed was kept constant at 3 kg in all experiments. Air was passed to the bed increasingly from zero to fluidization stage. Then, the gas flowrate was gradually decreased (defluidization stage). At each gas flowrate, either in fluidization or defluidization stage, the pressure loss across the bed was recorded. Bed expansion and fluidization behaviour were also observed and recorded.

## 4. RESULTS AND DISCUSSION

### 4.1 Design value of superficial gas velocity

Ratio of  $U_{cf}/U_{mf}$  is derived from  $U_{cf}$  and  $U_{mf}$  values for both types of bed arrangement. The ratio of  $U_{cf}/U_{mf}$  decreases as the weight percentage of palm kernel shell increases in layer mixture method and the ratio vary between 1.5-1.9 as exhibited on Figure 1. In the meantime,  $U_{cf}/U_{mf}$  values for mixture of palm kernel shell and silica sand in random mixture method lies between 1.94-1.99, which show little dependency upon biomass content in the mixture in random mixture method. The findings give a good practical guide as given by [1], where they suggested selecting the appropriate design value of the superficial gas velocity to be used in the operation is to take it as twice the minimum fluidization velocity.

Meanwhile,  $U_{cf}/U_{mf}$  ratio for mixture of palm pressed fibre and silica sand is higher in random mixture method compared to mixture of palm kernel shell with silica sand using the same bed arrangement. It can be clearly seen on Figure 2 where the ratio falls between 2.2 – 2.8. A different pattern is

observed for the mixture of palm pressed fibre and silica sand. As the weight percentage of the palm pressed fibre in the mixture increases, the ratio of  $U_{cf}/U_{mf}$  is also increases sharply due to large difference in superficial gas velocity between  $U_{mf}$  and  $U_{cf}$  in every weight fraction. 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. Therefore, higher velocity is needed to fluidize all the particles in the bed vigorously.

From figure 1 and 2, it is concluded 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 palm kernel shell which has a 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.

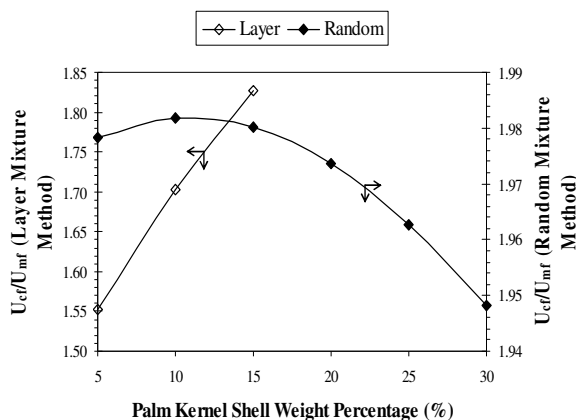


Figure 1:  $U_{cf}/U_{mf}$  ratio for mixture of silica sand and palm kernel shell

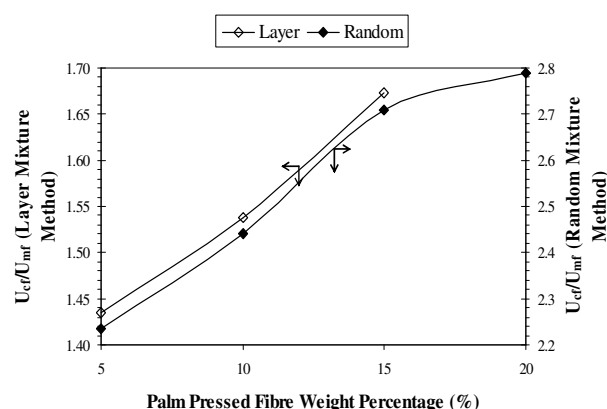


Figure 2:  $U_{cf}/U_{mf}$  ratio for mixture of silica sand and palm pressed fibre

## 4.2 Comparison of theoretical $U_{mf}$ Values

A number of equations have been established to predict  $U_{mf}$  of binary mixture as summarized on table 1 on appendix. Courdec et al., 1985 [8] stated that correlation for  $U_{mf}$  is sensitive to the particle shape, size and density. Most of the authors did not include sphericity factor and bed porosity associated with minimum fluidization velocity due to the difficulty in determining it. They have proposed generalized equations by correlating experimental data in the form of  $Re_{mf} = f(Ar)$ . However, empirically derived correlations are useful only to describe the behaviour of analogous particle system under constrained operating conditions. Hence, the minimum fluidization concept has a precise sense only for a bed of particles that are all of the same nature, shape and size.

Figure 3 shows comparison of experimental and theoretical  $U_{mf}$  values for mixture of palm pressed fibre with silica sand. The experimental hydrodynamics determination carried out in this study has proven that the empirical correlation proposed by [10] is the most suitable equation to be used to predict the  $U_{mf}$  values for mixture of palm pressed fibre with silica sand. However, the application of the equation to the mixtures used in this work

gives a significant deviation. This is due to the following reasons which are similar with work done by [10]. They fluidized sand with wheat straw which is fibrous in nature as palm pressed fibre.

- i) The maximum amount of palm pressed fibre that can be added to a fluidizing mixture was found to be of 15%<sup>w/w</sup> in layer mixture method and 20%<sup>w/w</sup> in random mixture method. Beyond this point, slugging and vertical rat holes formations were observed respectively.
- ii) Since palm pressed fibre does not fluidize on its own, its minimum fluidization velocity cannot be determined. Therefore, correlations established by [11-13] cannot be used since the correlations need the value of  $U_{mf}$  for palm pressed fibre.

The difference between experimental and calculated values can be attributed to the high content of fine particles and to the materialization of agglomerates of particles due to interlacing promoted by fluid forces [14].  $U_{mf}$  predictions were much lower than experimentally determined. This is due to the value of constant  $k$  which is not suitable to be used in this work since it is the value for rice husk, sawdust and groundnut shell [6]. These materials are differing from palm fibre in terms of density, material's structure and shape. Prediction by [9, 15] were also not in the 20% range.

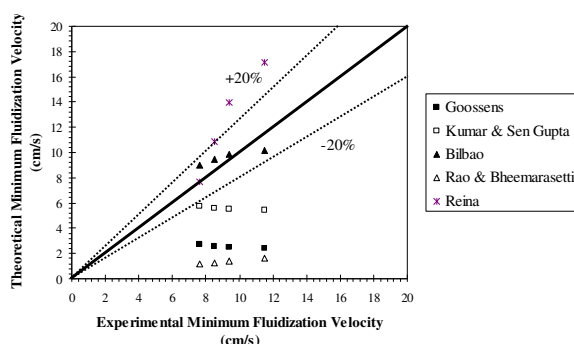


**Figure 3:** Comparison of experimental and theoretical  $U_{mf}$  values for mixture of palm pressed fibre with silica sand

Figure 4 shows comparison of experimental and theoretical  $U_{mf}$  values for mixture of palm kernel shell with silica sand. In this case,  $U_{mf}$  predictions by [11, 13-15] falls within 20% range set. Correlations [14] include sphericity factor and bed porosity which strongly influences hydrodynamic behaviour of the bed. The use of the correlations is believed to be the best way to correlate the characteristic parameters of the fluidized bed which involves Archimedes and Reynolds numbers, because it considers the type of particle as well as the hydrodynamics of the fluidizing agent. Different correlations have been specified for particle's  $Re_{mf}$  less than 20 and more than 20 [13]. Galileo number and density ratio has been included in the correlation. Correlations by [15] has been observed to include the fluidizing gas characteristics; the density of the gas as well as the viscosity. Meanwhile, correlation by [11], have set different forms for completely segregating system and perfectly mixed system. In this case, correlation for completely segregating system has been applied.

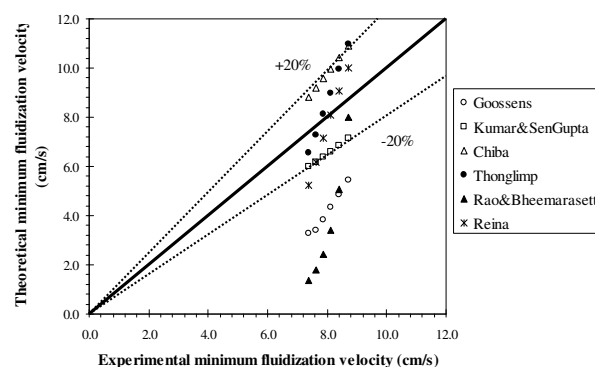


**Figure 4:** Comparison of experimental and theoretical  $U_{mf}$  values for mixture of palm kernel shell with silica sand

## 5. CONCLUSION

Ratio of  $U_{cf}/U_{mf}$  of binary fluidization of oil palm residues with silica sand showed a different pattern for different type of residues used. Increment pattern is observed

in the mixture of palm pressed fibre and silica sand while decrement 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. In general, it can be concluded that the appropriate design value of the superficial gas velocity to be used in the operation is to take it as twice the  $U_{mf}$  for mixture of palm kernel shell with silica sand and thrice the  $U_{mf}$  for mixture of palm pressed fibre with silica sand.

The suitability of empirical correlations to predict  $U_{mf}$  that have been established by previous researchers depends on many critical factors such as sphericity factor, bed porosity, type of particle and characteristic of fluidizing agent. Predicted results indicated that the values are either too high or low. It is suggested that modification has to be made to previous correlations to suit the experimental data in this study.

## ACKNOWLEDGEMENT

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## APPENDIX

Table 1: Various correlations for calculating the minimum fluidization velocity of binary mixture

| Author                  | Correlations                                                                                                                                                                                                                                                      | Definitions and comments                                                                                                                                                                                                                                                                                      |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Otero & Corella, 1971   | $u_{mf} = u_{mf}^F x^F + u_{mf}^P x^P$                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                               |
| Goosen et al., 1971     | $u_{mf} = \frac{\mu}{\rho_G d_M} \left\{ \begin{array}{l} (33.7^2 + 0.0408 Ga Mv)^{0.5} \\ - 33.7 \end{array} \right\}$                                                                                                                                           | $Ga = \frac{d_M^3 \rho_G^2 g}{\mu^2};$<br>$Mv = \frac{\rho_M - \rho_G}{\rho_G}$<br>$\frac{1}{d_M \rho_M} = \frac{x^F}{d_p^F \rho_p^F} + \frac{x^P}{d_p^P \rho_p^P}$<br>$\frac{1}{\rho_M} = \frac{x^F}{\rho_p^F} + \frac{x^P}{\rho_p^P}$                                                                       |
| Kumar & Sen Gupta, 1974 | $u_{mf} = 0.0054 \frac{d_M^{1.34} (\rho_M - \rho_G)^{0.78} g^{0.78}}{\mu^{0.56} \rho_G^{0.22}}$                                                                                                                                                                   | $d_M = \frac{1}{\frac{x^F}{d_p^F} + \frac{x^P}{d_p^P}};$<br>$\rho_M = x^F \rho_p^F + x^P \rho_p^P$<br>Not restricted to binary mixtures                                                                                                                                                                       |
| Chiba et al., 1979      | For a completely mixed bed:<br>$u_{mf} = u_{mf}^F \frac{\rho_M}{\rho_p^F} \left( \frac{d_M}{d_p^F} \right)^2$<br><br>For a completely segregated bed:<br>$u_{mf} = \frac{u_{mf}^F}{\left( 1 - \frac{u_{mf}^F}{u_{mf}^P} \right) x^F + \frac{u_{mf}^F}{u_{mf}^P}}$ | $\rho_M = V^F \rho_p^F + (1 - V^F) \rho_p^P$<br>$d_M = \left[ N^F d_p^{F3} + (1 - N^F) d_p^{P3} \right]^{1/3}$<br><br>$N^F = \frac{1}{\left[ 1 + \left( \left( \frac{1}{V^F} \right) - 1 \right) \left( \frac{d_p^F}{d_p^P} \right)^3 \right]}$<br><br>- similar with definition by Kumar and Sen Gupta, 1974 |

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Thonglimp,  
1981

First form:

$$\text{Re}_{mf} = 3.4 \times 10^{-3} Ga^{0.20} Mv^{0.10},$$

$$\text{Re}_{mf} < 20$$

$$\text{Re}_{mf} = 2.88 \times 10^{-2} Ga^{0.63} Mv^{0.626},$$

$$\text{Re}_{mf} > 20$$

Second form:

$$\text{Re}_{mf} = (19.9^2 + 0.03196 Ga Mv)^{0.5} - 19.9$$


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$$\rho_M = \frac{\rho_p^F \rho_p^P}{x^F \rho_p^F + x^P \rho_p^P}$$

$$d_M = \frac{x^F \rho_p^P + x^P \rho_p^F}{x^F \rho_p^P d_p^P + x^P \rho_p^F d_p^F} d_p^P d_p^F$$

- similar with definition by  
Kumar and Sen Gupta, 1974

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Bilbao et al.,  
1987

$$u_{vf} = u_{mf}^P - (u_{mf}^P - u_{mf}^F) X^F$$

Where  $u_{mf}^P$  is calculated:

$$u_{mf}^P = (50 d_p^P)^{0.84}$$

$$X^F = \frac{x^F}{x^F + \left( \frac{\rho_p^F}{\rho_p^P} \right) x^P}$$


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