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Minimum Fluidization Velocities of Binary-Solid Mixtures: Model Comparison

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***Abstract*—**An accurate prediction of the minimum fluidization velocity is a crucial hydrodynamic aspect of the design of fluidized bed reactors. Common approaches for the prediction of the minimum fluidization velocities of binary-solid fluidized beds are first discussed here. The data of our own careful experimental investigation involving a binary-solid pair fluidized with water is presented. The effect of the relative composition of the two solid species comprising the fluidized bed on the bed void fraction at the incipient fluidization condition is reported and its influence on the minimum fluidization velocity is discussed. In this connection, the capability of packing models to predict the bed void fraction is also examined.

***Keywords*—**Bed void fraction, Binary solid mixture, Minimum fluidization velocity, Packing models

I. INTRODUCTION

THE first known application of the liquid fluidization of a solid mixture has been reported long ago in the mineral dressing for the separation of ores [1]. It was noted that when solid particles differ in the size, the classification dominates. The difference in the density, on the other hand, leads to the phenomenon of sorting. The potential application of the liquid fluidization of mixtures nowadays is cited in the separation of plastics [2]–[3]. Even more diverse is the application of the fluidization of solid mixtures is in the gas-solid systems. An important application in this connection, for example, has been the thermo-chemical processing of the biomass as can be seen from the work of Corella and co-worker [4]–[5] and Berruti *et al*. [6]. In this application, an inert solid species, often sand, is used to achieve the fluidization of the biomass and control its residence time besides improving the heat transfer. Another interesting application has been the addition of the Geldart's group B particles to improve the fluidization of group D particles which show slugging behavior [7]. Similarly, it has also been shown that the quality of fluidization can be significantly improved by introducing a small amount of Group A particles in the cohesive powder which falls under the Geldart's group C classification [8].

The minimum fluidization velocity is a crucial hydrodynamic feature of fluidized beds as it marks the transition at which the behavior of an initially packed bed of solids changes into a fluidized bed. Its accurate specification is therefore indispensable for a successful initial design and subsequent scale-up and operation of the reactors or any other contacting devices based on the fluidized bed technology. Industrial practice on fluidized beds usually involves the fluidization of solids over a wide range of particle-sizes and/or systems with two or more components. In these cases, each particle fraction or each solid species has its own minimum fluidization velocity. Characterizing the minimum fluidization velocity in cases where the fluidization mass consists of different kinds of solid particles is quite challenging in view of the complex particle-particle and fluid-particle interactions. Several approaches have been recommended in the literature, which can be broadly classified into the following two main categories.

The first category is the direct extension of the approach being commonly used for determining the minimum fluidization velocity of the single solid species, which consists of equating the effective bed weight with the pressure drop predicted by the Ergun equation [9]. Substituting the averaged values of particle properties, i.e. the mean diameter and the mean density instead of the mono-component properties lead to the minimum fluidization velocity of the solid particle mixtures. This can be written as:

$$1.75\varepsilon_{mf}^{-3}\overline{\mathrm{Re}_{mf}^{2}}+150\varepsilon_{mf}^{-3}\left(1-\varepsilon_{mf}\right)\overline{\mathrm{Re}_{mf}}-Ga=0 \qquad (1)$$

where the Reynolds number and the Galileo number are defined as follows:

$$\overline{\mathrm{Re}_{mf}}=\left(\rho_f\overline{U_{mf}}\,\overline{d}\big/\mu\right) \qquad (2)$$

$$\overline{Ga}=\left(\overline{d}^{3}\rho_f\left(\overline{\rho_s}-\rho_f\right)g\big/\mu^{2}\right) \qquad (3)$$

Note that the over-bar represents the mean, and the subscript 'mf' represents the incipient or minimum fluidization condition. Symbols ρ_f and ρ_s are fluid and solid densities, respectively while other symbols have the usual significance. The following definitions of the mean-diameter and the mean-density are used in the above equation:

$$\overline{\rho_s}=\left[X_1\rho_{s1}+\left(1-X_1\right)\rho_{s2}\right] \qquad (4)$$

$$\frac{1}{\overline{d}}=\left[\frac{X_1}{\psi_1 d_1}+\frac{1-X_1}{\psi_2 d_2}\right] \qquad (5)$$

where, X_1 and ψ_1 are the volume fraction and the sphericity

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shape factor of the solid component 1 of the binary-solid mixture, respectively. Note that (4) represents the surface-to-volume mean-diameter whereas (5) is the volume-average particle density. Since the above-mentioned approach is based on averaging the physical properties, namely the diameter and density of the two solid species, it is also commonly termed as the property-averaging approach.

However straightforward, the property-averaging approach is reported to be limited for cases where the solid species do not significantly differ in their properties. One reason for the failure of this approach may be due to the fact that when the solid particle species that differ significantly in their sizes are present together in the same packing environment, the mixture shows a substantial degree of the volume contraction. As a consequence, the pressure drop in the packing, being a strong function of the void fraction, is also affected. This in turn leads to an incorrect prediction the minimum fluidization velocity of the mixture. Although this issue has been apparently realized sometimes ago [10], any attempt in this direction appears to be relative recent [11]. What is therefore needed for the correct prediction of the minimum fluidization velocity of the mixture using this approach is to have a priori reasonable estimate of the void fraction of the mixture besides averaged particle properties.

It is worthwhile at this stage to discuss the literature concerning the apparent total volume that a packing of a mixture of two or more solid species will occupy. A good deal of literature concerning packing models depending upon the perceived mechanism of packing behavior of the solid mixture containing two or more components has been reported [12]–[16]. However, two models based on the Westman [17] equation, which is valid for a binary-solid mixture, are presented here. The well-known Westman equation is given as:

$$\left(\frac{V-V_1X_1}{V_2}\right)^2+2G\left(\frac{V-V_1X_1}{V_2}\right)\left(\frac{V-X_1-V_2X_2}{V_1-1}\right)+\left(\frac{V-X_1-V_2X_2}{V_1-1}\right)^2=1 \quad (6)$$

where,

$$V=\left(1-\varepsilon\right)^{-1}$$

is the specific volume of the packing of binary solid mixture while V_1 and V_2 are specific volumes of mono-component beds of species 1 and species 2, respectively. The parameter G depends upon the size ratio of the two components of the packing. It is easy to see that setting G = 1 in the above equation yields the well-known serial model:

$$V=X_1V_1+X_2V_2 \quad (7)$$

which simply states that the volume occupied by the bed of a mixture of solids is the sum of volumes occupied by mono-component beds. Using a large base of data, Yu *et al*. [18] have proposed the following functional form of the parameter G in the Westman equation:

$$\frac{1}{G}=\begin{cases}1.355\,r^{1.566} & \left(r\le 0.824\right)\\ 1 & \left(r>0.824\right)\end{cases} \quad (8)$$

where r is the size ratio (smaller to larger) of the two solid species. On the other hand, Finkers and Hoffmann [19] have recently suggested another expression for the parameter G in the Westman equation. Their approach makes use of the structural ratio rather than the diameter ratio, and is equally applicable for both spherical and non-spherical particles. This is given by:

$$G=r_{str}^k+\left(1-\varepsilon_1^{-k}\right);\quad r_{str}=\left[\frac{\left(\left(1/\varepsilon_1\right)-1\right)r^3}{1-\varepsilon_2}\right] \quad (9)$$

where a value of exponent k = - 0.63 has been recommended by the authors.

The second category of approaches consists of applying the averaging approach directly to the minimum fluidization velocity data of mono-component beds. Among early researchers, Otero and Corella [20] proposed the following averaging procedure involving the minimum fluidization velocities of the constituent solid phases:

$$\overline{U_{mf}}=\left[X_1U_{mf1}+\left(1-X_1\right)U_{mf2}\right] \quad (10)$$

where U_{mf1} and U_{mf2} are minimum fluidization velocities of components 1 and 2, respectively. And, X_1 is the fluid-free volumetric fraction of the larger component. On the other hand, assuming the binary-solid fluidized bed as consisting of two completely segregated mono-component layers, others recommended using the following harmonic averaging of minimum fluidization velocities [21]:

$$\frac{1}{\overline{\overline{U_{mf}}}}=\left[\frac{X_1}{U_{mf1}}+\frac{X_2}{U_{mf2}}\right] \quad (11)$$

Though inherently perceived to be applicable for segregated beds, this approach has been shown to hold good even if the components are substantially mixed [22]. Introducing a more general expression for such averaging approaches, Asif and Ibrahim [23] suggested the following general expression for averaging:

$$\overline{U_{mf}}^{\,p}=\left[X_1U_{mf1}^p+\left(1-X_1\right)U_{mf2}^p\right] \quad (12)$$

where p = -1 yields the harmonic averaging, whereas p = 1 leads to the arithmetic averaging. Using the data of their own experiments, they found that p = -0.5 in general gave superior predictions. Although based on minimum fluidization velocities of constituent solid phases, Cheung et al. [24] proposed a slightly different approach. Their empirical correlation is given by:

$$\frac{\overline{U_{mf}}}{U_{mf2}} = \left(\frac{U_{mf1}}{U_{mf2}}\right)^{X_1^2} \qquad (13)$$

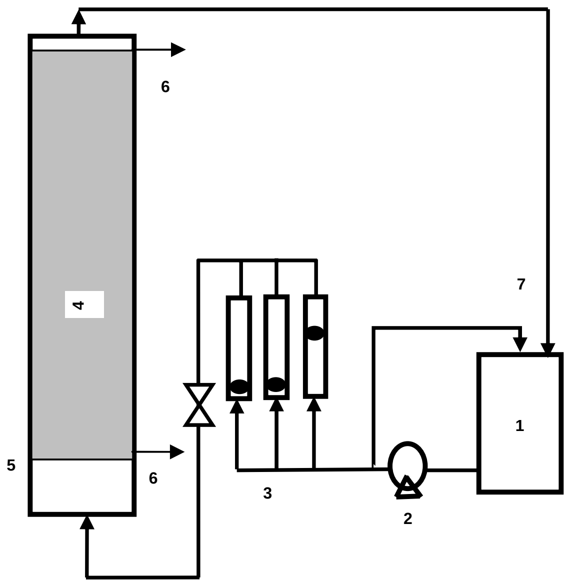
The experimental data of Formisani [10] were found to show good agreement with the above equation. Having briefly reviewed both types of approaches presented above, it is worthwhile to compare their predictive capability using carefully obtained data for the binary-solid fluidization.

II. EXPERIMENTAL

The test section used in the present experimental investigation consisted of a 1.5-m tall transparent Perspex column of 60-mm internal diameter. It was preceded by a perforated plate distributor covered with a 105-µm mesh. As an added precaution to eliminate entry effects, a 0.5-m long calming-section was employed preceding the distributor. A schematic is shown in Fig. 1. A flow-through circulation cooler was used to maintain the temperature of the tap water at 20±0.2 °C in the recirculation water tank. This was important in view of the fact that any change in the water temperature affects the viscosity, and consequently the pressure drop and the bed height. The flow rate of the water was adjusted using one of three calibrated flow-meters of a suitable range. The bed heights were read visually with the help of a ruler along the length of the column. The pressure drop along the bed was measured using two different manometers of significantly different ranges. For small pressure drop measurements, an inverted air-water manometer was used. A mercury manometer, on the hand, was employed for measuring high pressure drops. The observation included measuring the flow rate, the bed height and the pressure drop across the bed.

Two different solid species were used. The larger plastic particles were cylindrical in shape with equivalent volume diameter of 2.95-mm and the density of 1761-kg/m^3. Its sphericity was 0.87. The smaller particle species was a closely-sized sand sample retained between adjacent sieves with opening of 600-µm and 500-µm. Its density was found to be 2664- kg/m^3.

Different amounts of solid masses were charged into the test column and several runs for different experiments were carried out as summarized in Table I. The bed composition as well as the mean-diameter and the mean-density of the resulting solid mixture are also shown in the table. Both fluidization and defluidization runs were carried out. Since the defluidization runs provided reproducible results in most cases, the minimum fluidization velocities and the bed void fraction at the incipient fluidization condition were evaluated using the pressure drop data during the defluidization. This can be seen in Fig. 2. The minimum fluidization velocity in this case is found to be 20.7-mm/s and the bed void fraction, evaluated from the bed height, is 0.518.



1. Water tank, 2. Pump; 3. Flow-meters; 4. 1.5-m long test section
5. Distributor; 6. Manometer taps; 7. Recirculation to water tank

Fig. 1 Schematic of the experimental setup

TABLE I SUMMARY OF EXPERIMENTAL RUNS CARRIED OUT

Mass of solid (g)		Fraction	Diameter	Density
Sand	Plastic	X_1	(m)	(kg/m^3)
318	0	0.00	0.00055	2664
1200	140	0.15	0.00062	2529
636	140	0.25	0.00068	2438
319	140	0.40	0.00080	2303
318	315	0.60	0.00104	2122
318	630	0.75	0.00134	1987
318	1290	0.86	0.00169	1887
260	2000	0.92	0.00198	1833
0	2000	1.00	0.00255	1761

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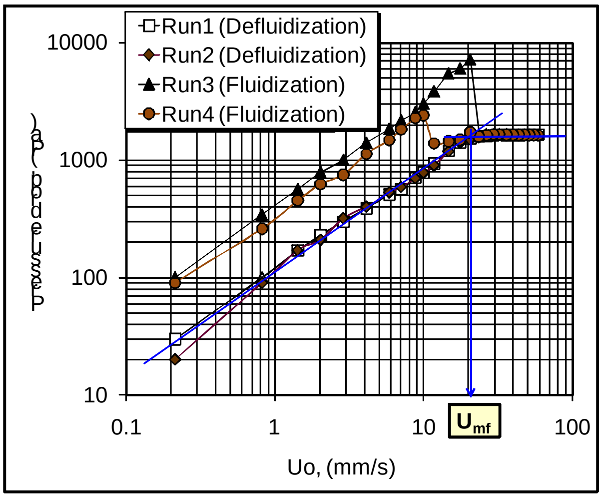

Fig. 2 Dependence of pressure drop on liquid velocity for $X_1 = 0.75$

III. RESULTS AND DISCUSSION

In the following, the results of the present experimental investigations are first presented in Table II. The minimum fluidization velocity and the bed void fraction are both reported in the table for different compositions of the bed. Note that the bed void fraction for the larger particles (Plastic) is much higher than the one of the smaller (sand) particles. It is seen that as the fraction of the larger component increases, the minimum fluidization velocity also increases. On the other hand, the bed void fraction also shows a progressive increase as the fraction of larger particles is increased.

In the following, we first present the comparison for both categories of approaches discussed before. This is shown in Fig. 3. Also reported in the chart window is the average percent error. It is seen here that predictions of (12) with p = 1 is better than p = -0.5 and p = -1. This is in variance with what was reported before that p = - 0.5 provides better description [23]. This can be attributed to the greater difference in the physical properties of binary mixture considered in their work. Here, the property-averaging model however provides the best predictions. The mean percentage error is seen to be 10% in this case. Predictions of both p = -1 as well as (13) are seen to be poor here.

It is important to point out at this stage that none of the models presented above are fully predictive. While (12)–(13) depend upon mono-component values for the prediction of the minimum fluidization velocities of the mixture, the property averaging approach (using Eqs. 1-5) strongly depends upon the bed void fraction at the incipient fluidization condition. This issue needs to be properly addressed in order to make the property-averaging model fully descriptive and exploit its superior predictive capability. For the case of binary mixtures, one can use (6) in conjunction with one of (7) to (9) to predict the mixture void fraction. The predictions are shown in Fig. 4. It is clear from the figure that (7) does not account for the volume contraction or volume expansion effects associated with mixing of two or more solid species in the same packing environment. On the other hand, both (8) and (9) are capable of describing the contraction phenomenon. But, the degree of contraction predicted by both models is higher as compared to actual values, while (7) providing a better description of the mixture void fraction.

TABLE II EXPERIMENTAL RESULTS FOR THE DEPENDENCE OF THE VOID FRACTION AND VELOCITY AT INCIPIENT FLUIDIZATION CONDITIONS FOR THE BINARY-MIXTURE

Fraction	Incipient fluidization	
X_1	Voidage	Velocity
0.00	0.418	3.6
0.15	0.415	4.0
0.25	0.429	6.0
0.40	0.432	9.0
0.60	0.506	17.7
0.75	0.518	20.7
0.86	0.526	23.6
0.92	0.528	26.6
1.00	0.506	26.5

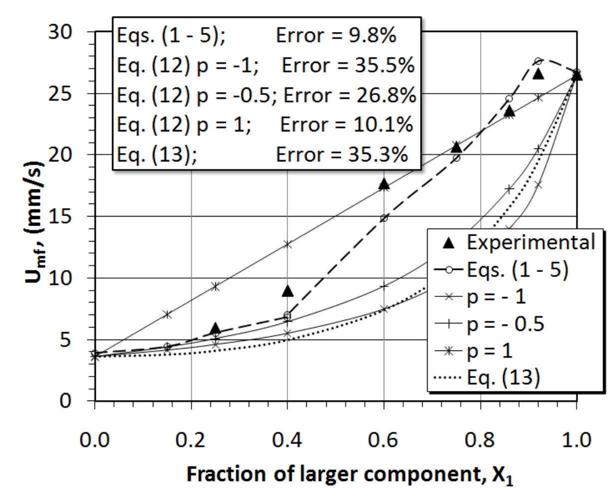

Fig. 3 Predictions of minimum fluidization velocities using different approaches

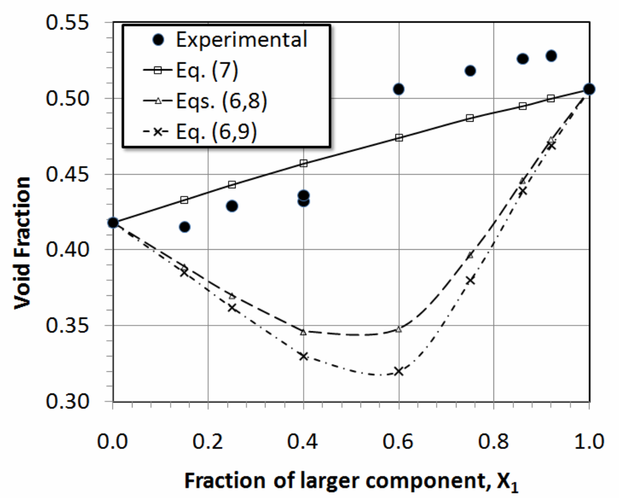

Fig. 4 Predictions of bed void fractions using different equations at incipient fluidization conditions

The prediction of U_{mf}, when ε_{mf} is calculated from (7)–(9) are shown in Fig. 5. The average error associated with each model is also presented in the chart window. The trend already seen in Fig. 4 is once again in fact gets highlighted in this figure. The error associated with (7) is less than both (8) and (9). This is clear indication of superior predictive capability of (7).

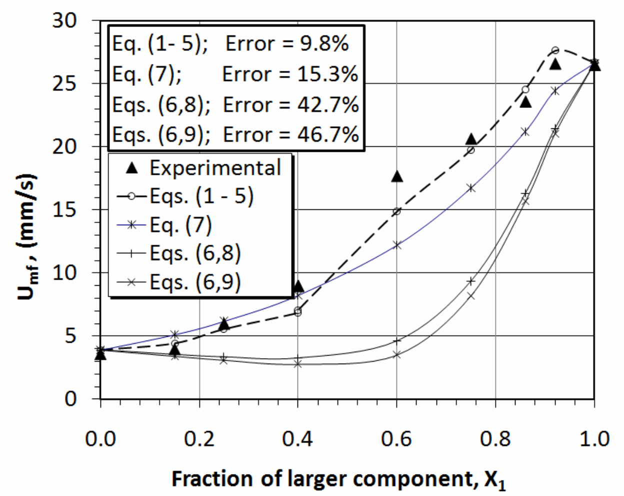

Fig. 5 Comparison of predictions of U_{mf} using the property averaging approach. Eq. (1–5) legend refers to experimental values of ε_{mf}.

IV. Conclusion

It becomes obvious that while the property averaging approach is inherently capable of providing a good description of the minimum fluidization velocity here, it is mainly the accurate prediction of the bed void fraction at the minimum fluidization condition that proves to be the main stumbling block. Its importance can be easily gauged from the fact that the Ergun equation contains terms with third order dependence on the bed void fraction. As a result, even a small error in the bed void fraction can lead to a significantly higher error in the prediction of the pressure drop. This, in turn, introduces the error in the prediction of the minimum fluidization velocity. This issue assumes even greater importance due to the occurrence of the higher degree of volume contraction as the size ratio of mixture constituents increases.

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