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Mixing characteristic of homogeneous binary mixture of regular particles in a gas–solid fluidized bed

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Abstract

The mixing characteristic of large particles (Geldart BD type) has been investigated in a cylindrical gas–solid fluidized bed. Based on dimensional analysis, a correlation for the mixing index has been developed with the system parameters viz., average particle size of the mixture, initial static bed height, height of the particles' layer in the bed (from where the sample is drawn) and superficial velocity of the fluidizing medium. A theoretical model for the mixing index has been developed based on the counter flow of solids with circulation and horizontal dispersion. A comparison has been made for the values of the mixing index calculated by both the theoretical and the experimental models.

Keywords: Mixing index; Static bed condition; Fluidized bed condition; Horizontal dispersion coefficient; Gas–solid fluidization

1. Introduction

Generally, the gas fluidized beds have excellent and rapid mixing characteristics for non-segregating particle systems. Much effort, both experimental and theoretical, has been spent in explaining this feature [1], [2], [3], [4], [5], [6] and [7]. However, in industrial solids mixing, it is often required to mix particles differing widely in physical properties viz., size, density and/or shape. The role of particle size and density and the air flow rate on the segregation or demixing behaviour in a gas–solid fluidized bed has already been reported [8]. The previous authors have concluded that a fairly wide particle size difference can be tolerated while a small density difference leads to ready settling of the denser particles. A qualitative model for particle mixing in a gas fluidized bed has been developed by Gibilaro and Rowe [9] based on four physical mechanisms viz., overall particle circulation, interchange between the wake and the bulk phases, axial dispersion and segregation. For a size-variant, equal-density system of particles, mixing index has been proposed by Fan et al. [10] as

$$I_M = K \times \left(\frac{\bar{d}_P}{d_F}\right)^k \times \left(\frac{U}{U - U_F}\right)^n \tag{1}$$

Using two more system parameters such as the bed aspect ratio and the ratio of the height of the particles' layer in the bed (from where sample is drawn) to column diameter, the above model has been modified in the present study and has been proposed as

$$I_M = K \times \left(\frac{\bar{d}_P}{d_F}\right)^a \times \left(\frac{h_B}{D_C}\right)^b \times \left(\frac{H_S}{D_C}\right)^c \times \left(\frac{U}{U - U_F}\right)^d \tag{2}$$

Knowing the percentage of jetsam at different heights of the bed, the experimental values for the mixing index at different heights have been calculated with the help of the following expression [11],

$$I_M = \frac{X^*}{\bar{X}_{bed}} \tag{3}$$

2. Development of model

2.1. Experimental

2.1.1. Static bed condition

After fluidizing the bed with a particular fluid mass velocity, it was brought to static condition by closing the air supply. The bed was then divided into different layers each of two cm height. Each of the layers was drawn by vacuum and analyzed for particle size distribution. Such a system was referred to as the static bed condition. Using system parameters for this condition, a model has been developed as given below,

$$I_M = 0.7554 \times \left(\frac{\bar{d}_P}{d_F}\right)^{0.144} \times \left(\frac{h_B}{D_C}\right)^{-0.1322} \times \left(\frac{H_S}{D_C}\right)^{0.1596} \times \left(\frac{U}{U-U_F}\right)^{0.3111} \quad (4)$$

2.1.2. Fluidized bed condition

The bed was fluidized at a fixed mass velocity and under steady state condition, the samples of the materials were drawn through the side ports of the column which are located at intervals of two cm height on either side alternately. The samples drawn in such a manner were analyzed for particles' distribution. This system was referred to as the fluidized bed condition. The model developed for such a condition is,

$$I_M = 0.3725 \times \left(\frac{\bar{d}_P}{d_F}\right)^{0.3679} \times \left(\frac{h_B}{D_C}\right)^{-0.4864} \times \left(\frac{H_S}{D_C}\right)^{0.8258} \times \left(\frac{U}{U-U_F}\right)^{0.5084} \quad (5)$$

2.2. Theoretical

In the present study, an attempt has been made to analyze the vertical as well as horizontal dispersion in case of gas–solid fluidization. Considering the counter flow of solids and circulation model [12] together with the horizontal displacement of the particles in the column (which cannot be neglected for a column of 100 cm height), a model for concentration of jetsam particles has been developed. For static condition, the motion of particles which leads to axial mixing is described as a function of bed height by dividing the total bed height equally into a number of sections in series in the vertical direction with the last section being the adjacent one to the gas distributor. Uniform concentration is assumed for a layer of particles, from where the sample is drawn for analysis in case of the fluidized condition. With this approach, the developed model for both static and fluidized conditions is,

$$\left(\left(\frac{W}{V_B \times \rho_s}\right) \times D_{SV} + 2D_{SH}\right) \times \frac{d^2 C_j}{dZ^2} + \left(\frac{W \times U}{V_B \times \rho_s}\right) \times \frac{dC_j}{dZ} = 0 \qquad (6)$$

Solving the above differential equation, the concentration of the jetsam particles is expressed as,

$$C_j = \int e^{-\int \left(\frac{F \times U}{F \times D_{SV} + D_{SH}}\right) dZ} dZ \qquad (7)$$

Where Z is height of any layer of particle in the bed measured from the distributor, (varying from 0 to 0.2 m).

The mixing index can be calculated from the above concentration using the following expression,

$$I_M = C_j \times \left(\frac{W}{J}\right) \qquad (8)$$

Thus the mixing index can be evaluated theoretically as a function of height from the above relation.

3. Experimentation

A mixture of Sago particles (white coloured spherical cereals having density of 1304 kg/m^3) having particle sizes of 3.375 mm and 1.355 mm and minimum fluidization velocities of 1.0335 m/s and 0.465 m/s, respectively, is fluidized in a 15 cm × 100 cm perspex column (Fig. 1). The above two particle sizes have been mixed in the ratio of 10 : 90, 25 : 75, 40 : 60 and 50 : 50. For a particular mixture, the initial static bed height and the superficial velocity of the fluidizing medium have been altered. The scope of the experiment is given in Table 1A. The samples drawn at different heights for both the static and fluidized conditions have been analyzed for the distribution of particle sizes (Table 1B).

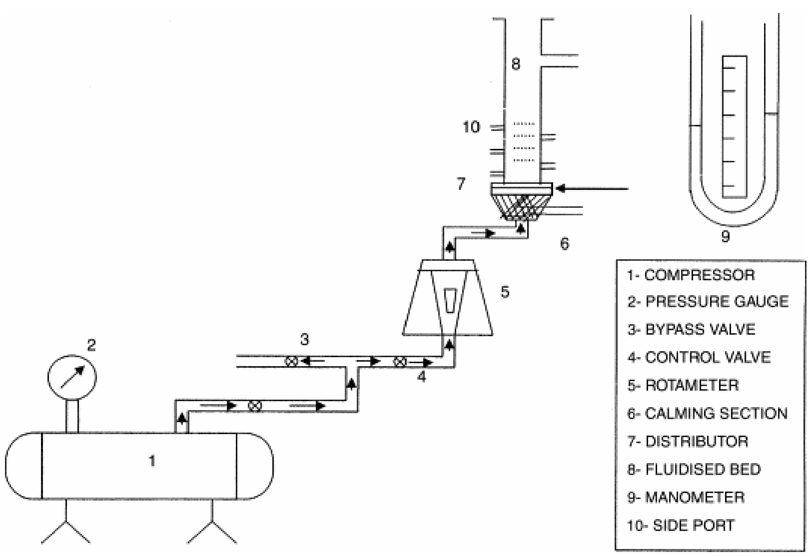

Fig. 1. Experimental set-up.

Table 1A.

Scope of the experiment

Serial number	**Average particle size, $\bar{d}_P \times 10^3$ (m)**	**Initial static bed height, $H_S \times 10^2$ (m)**	**Superficial velocity of gas, U (m/s)**	**Heights of any layer of particles, $h_B \times 10^2$ (m)**
1	1.860	12	1.30823	2,4,6,8,10,12
2	1.860	16	1.30823	2,4,6,8,10,12,14,16
3	1.860	20	1.30823	2,4,6,8,10,12,14,16,18,20
4	1.860	24	1.30823	2,4,6,8,10,12,14,16,18,20
5	1.860	20	0.7714	2,4,6,8,10,12,14,16,18,20
6	1.860	20	0.9275	2,4,6,8,10,12,14,16,18,20
7	1.860	20	1.1188	2,4,6,8,10,12,14,16,18,20
8	1.557	20	1.30823	2,4,6,8,10,12,14,16,18,20
9	2.163	20	1.30823	2,4,6,8,10,12,14,16,18,20
10	2.365	20	1.30823	2,4,6,8,10,12,14,16,18,20

Table 1B.

Particle properties

Component	**Particle size, $\bar{d}_P \times 10^3$ (m)**	**Minimum fluidization velocity, U_{MF} (m/s)**
Larger one	3.375	1.0335
Smaller one	1.355	0.465
Ratio	2.491	2.2226

4. Result and discussion

The correlation plots based on dimensional analysis for the static and fluidized bed conditions are presented in Fig. 2 and Fig. 3, respectively.

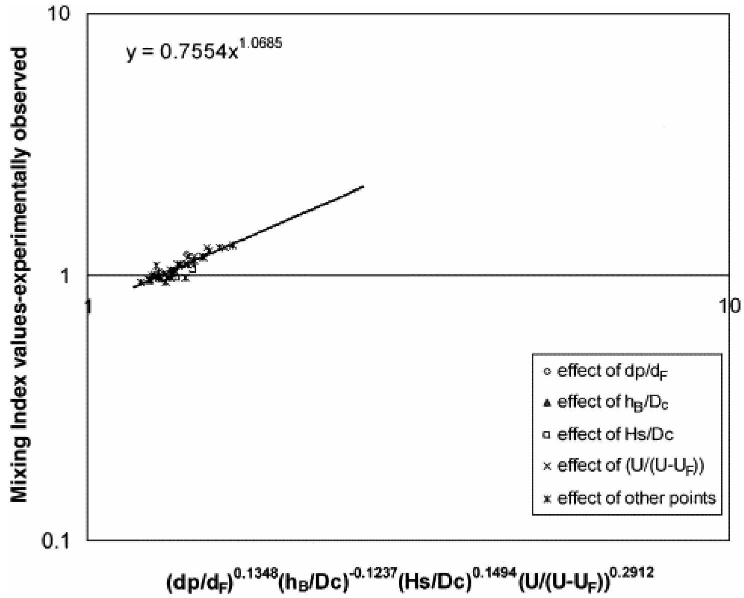

Fig. 2. Correlation plot (experimental mixing index vs. system parameters) for static bed condition (dimensionless analysis approach).

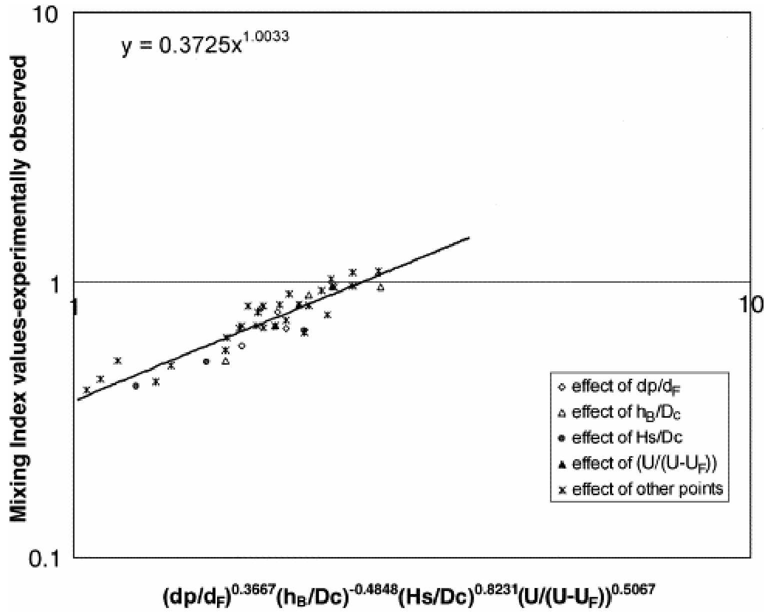

Fig. 3. Correlation plot (experimental mixing index vs. system parameters) for fluidized bed condition (dimensionless analysis approach).

The calculated values of the mixing index by the theoretical model as well as by the dimensional analysis approach together with the experimental ones both for static and fluidized conditions are listed in Table 2. It is observed from Table 2 that the calculated values of the mixing index by the theoretical model are lower than the experimental ones obtained for both static and fluidized conditions.

Table 2.

Comparison of the values of mixing index (I_M)

Dimensionless parameters				**I_M**				
$\bar{d}_P/d_F$	**h_B/D_C**	**H_S/D_C**	**$U/(U-U_F)$**	**Static bed condition**		**Theoretical model**	**Fluidized bed condition**	
				I_M-exp	**I_M-cal[a]**	**I_M-th**	**I_M-exp**	**I_M-cal[b]**
1.3727	0.7143	1.7143	1.5515	1.0396	1.0329	0.2603	0.8224	0.8168
1.3727	0.5714	1.7143	1.5515	1.0464	1.0638	0.2962	0.8810	0.9097
1.3727	0.4286	1.7143	1.5515	1.0480	1.1050	0.3416	0.9650	1.0453
1.3727	0.7143	1.4286	1.5515	1.0232	1.0033	0.2628	0.8920	0.7426
1.3727	0.5714	1.4286	1.5515	1.0404	1.0333	0.3009	0.9172	0.8271
1.3727	0.4286	1.4286	1.5515	1.0992	1.0733	0.3444	0.9492	0.9504
1.3727	0.2857	1.4286	1.5515	1.1280	1.1324	0.3943	0.9532	1.1559
1.3727	0.7143	1.1429	1.5515	0.9636	0.9681	0.2629	0.5844	0.6609
1.3727	0.5714	1.1429	1.5515	0.9664	0.9971	0.3010	0.6132	0.7361
1.3727	0.4286	1.1429	1.5515	0.9768	1.0358	0.3445	0.7428	0.8458
1.3727	0.2857	1.1429	1.5515	0.9802	1.0928	0.3944	0.8638	1.0287
1.3727	0.4286	0.8571	1.5515	0.9736	0.9893	0.3448	0.5972	0.7278
1.1491	1.2857	1.4286	1.5515	0.6960	0.9048	0.3827	0.4450	0.5239
1.1491	1.14286	1.4286	1.5515	0.8170	0.9190	0.4382	0.5180	0.5546
1.1491	1.0000	1.4286	1.5515	0.8850	0.9353	0.50160	0.5810	0.5915
1.1491	0.8571	1.4286	1.5515	0.9080	0.9546	0.5742	0.6640	0.6373
1.1491	0.7143	1.4286	1.5515	0.9180	0.9779	0.6574	0.6780	0.6959
1.1491	0.5714	1.4286	1.5515	1.0120	1.0072	0.7525	0.9025	0.7751
1.1491	0.4286	1.4286	1.5515	1.0484	1.0462	0.8615	0.9240	0.8906
1.1491	0.2857	1.4286	1.5515	1.1010	1.1038	0.9862	0.976	1.0832
1.5963	0.7143	1.4286	1.5515	0.9460	1.0253	0.1642	0.7873	0.7847
1.5963	0.5714	1.4286	1.5515	0.9558	1.0560	0.1880	0.8403	0.8740

Dimensionless parameters				I_M				
$\bar{d}_P/d_F$	h_B/D_C	H_S/D_C	$U/(U-U_F)$	Static bed condition		Theoretical model	Fluidized bed condition	
				I_M-exp	I_M-cal[a]	I_M-th	I_M-exp	I_M-cal[b]
1.5963	0.4286	1.4286	1.5515	0.9690	1.0969	0.2152	0.9593	1.0042
1.5963	0.2857	1.4286	1.5515	0.9840	1.1573	0.2464	1.0145	1.2214
1.3727	1.14286	1.4286	1.7112	0.9116	0.9720	0.1946	0.6784	0.6218
1.3727	1.0000	1.4286	1.7112	0.9156	0.9893	0.2214	0.6888	0.6632
1.3727	0.8571	1.4286	1.7112	0.938	1.0097	0.2518	0.6932	0.7145
1.3727	0.7143	1.4286	1.7112	0.9512	1.0343	0.2865	0.7288	0.7802
1.3727	0.5714	1.4286	1.7112	0.9580	1.0653	0.3259	0.7364	0.8690
1.3727	1.2857	1.4286	2.0050	0.7725	1.0054	0.1982	0.8160	0.6363
1.3727	1.14286	1.4286	2.0050	0.8128	1.0211	0.2237	0.8202	0.6736
1.3727	1.0000	1.4286	2.0050	0.846	1.0393	0.2524	0.8220	0.7184
1.3727	0.8571	1.4286	2.0050	0.8736	1.0607	0.2847	0.8330	0.7740
1.3727	0.7143	1.4286	2.0050	0.8940	1.0866	0.3213	0.8736	0.8452
1.3727	0.5714	1.4286	2.0050	0.9192	1.1191	0.3625	0.8744	0.9414
1.3727	0.4286	1.4286	2.0050	0.9256	1.1625	0.4090	0.9488	1.0817
1.3727	1.2857	1.4286	2.5176	0.8548	1.079171	0.2323	0.8934	0.7138
1.3727	1.1429	1.4286	2.5176	0.9408	1.096106	0.2598	0.9608	0.7556
1.3727	1.0000	1.4286	2.5176	0.9548	1.115627	0.2907	0.9624	0.805932
1.3727	0.8571	1.4286	2.5176	0.9728	1.138595	0.3252	1.0240	0.8682
1.3727	0.7143	1.4286	2.5176	0.9824	1.1664	0.3638	1.0755	0.9481
1.3727	0.5714	1.4286	2.5176	0.9916	1.2013	0.4070	1.0864	1.0560
1.3727	0.4286	1.4286	2.5176	0.9956	1.2479	0.4553	1.0948	1.2134

[a] Calculated with the help of Eq. (4).
[b] Calculated with the help of Eq. (5).

It is also evident that, higher values of mixing index are obtained in static bed condition when compared with its fluidization counterpart. Higher values of I_M for the static condition establish that, the mixing is better in this case. This may be due to the fact that, initial fluidization followed by settling to a static bed condition (in which state the samples have been drawn) has resulted in a better mixing as against the fluidized bed condition, where particle distribution in continuous and dispersed phases are different to affect the ultimate mixing phenomenon.

Lower values of mixing index have been obtained from the theoretical model (Table 2) when compared with those obtained from the experimental measurements in case of both the static and the fluidized conditions. The reason for high experimental value for static condition may be due to ‘gulf-streaming’ effect during fluidization in the bed. For fluidized condition, the samples were drawn from the ports made on either side of the column alternately and were analyzed based on the assumption of uniform concentration for a particular layer of particles across the cross-section of the column at any height. This may not be true in totality which in turn results in higher values of the mixing index over the theoretical values.

Theoretical model has been developed on the assumption that 50% of the bed material move up as the upward stream and the balance 50% move down as the downward stream during fluidization. Lower values of mixing index by the theoretical model might have been obtained due to this assumption which may not be true in an operating fluidized bed.

From Table 2 it is further observed that, the values of the mixing index are better in case of the theoretical model with the binaries containing less percentage of jetsam components in the mixture in comparison with the higher percentages of the same. This in turn implies that mixing is better with less jetsam and more flotsam components in a mixture, while segregation is better when the situation is reversed.

From the velocity point of view it is observed from Table 2 that the values of the mixing index from the theoretical model decreases with the increase of the velocity. The requirement of the ratio of minimum fluidization velocity of the jetsam to that of flotsam for segregation to be greater than two [13] is justified in this case as it is 2.22 in the present study (Table 1B). However, out of selected four velocities (velocity parameter), two are greater than the minimum fluidization velocity of the jetsam and two are less than that in the present case. As a result, some more jetsam particles are found in the upper portion of the bed in case of higher velocity parameter during fluidization which may be one of the reasons for higher experimental mixing index values than the theoretical ones.

5. Conclusion

The developed experimental models can be used widely for analyzing the mixing and segregation characteristics of the homogeneous binary mixtures of particles over a good range of the operating parameters. The developed theoretical model establishes that, the concentration of jetsam (and hence the mixing index) decreases with the height of the particle layer in the bed measured from the distributor. This needs more work to improve upon the model so that the difference between the values of the mixing index for the experimental and the theoretical can be minimized. Further work is being carried out to fix up an optimum fraction of the bed material with respect to its distribution in the upward and the downward streams during the fluidization process, so that the theoretical model can be improved. This will ultimately reduce the difference in values of the mixing index obtained from the theoretical and the experimental models.

Nomenclature

a, b, c, d, k, n

Exponents for the variables

C_j

Concentration of jetsam particles at any height in the bed (amount of jetsam particle in the sample drawn at a height in kg/amount of that in the original mixture in kg)

d_F

Diameter of the flotsam particle (m)

$\bar{d}_P$

Average particle size of the mixture (m)

D_C

Diameter of the column (m)

D_{SH}

Horizontal dispersion coefficient (m^2/s)

D_{SV}

Vertical dispersion coefficient (m^2/s)

F

Flow rate of solids moving up or down per bed volume (m^3) of the solid (m^3) of the bed volume [= $((W/2 * \rho_s)/V_B)$]

h_B

Height of particles layer in the bed from the distributor (m)

H_S

Initial static bed height (m)

I_M

Mixing index, dimensionless

J

Weight of jetsam particles taken in the bed (kg)

K

Coefficient of the correlation

M.I.-exp

Experimentally observed Mixing Index values

U

Superficial velocity of the fluidizing medium (m/s)

U_F

Minimum fluidization velocity of the flotsam particles (m/s)

V_B

Volume of the bed (m^3)

W

Weight of the total bed material (kg)

*X**

Percentage of jetsam particle in any layer

$\bar{X}_{bed}$

Percentage of jetsam particle in the bed

ρ_s

Density of the solid (kg/m^3)

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