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Mixing Characteristics of Irregular Binaries in a Promoted Gas-Solid Fluidized Bed: A Mathematical Model

By

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Abstract

The vertical as well as horizontal dispersion for the gas-solid fluidization has been analyzed in the present work. The fluidization and solids mixing characteristics of large irregular particles (Geldart-BD type) for both homogeneous and heterogeneous materials (size-variant and density-variant respectively) have been investigated in a 15×100cm cylindrical column. A theoretical model for concentration of jetsam particles has been developed as a function of height of any layer of particles (measured from the grid) by considering the counter flow of solids and circulation model together with the dispersion model for the vertical and the horizontal displacement of the particles in the fluidized bed. The mixing index at any position in the bed has thereby been expressed as a function of the concentration of the jetsam. The values of mixing index calculated from the above model as well as the experimentally measured ones for both the homogeneous and the heterogeneous systems have been compared with each other. Attempt has also been made to develop correlations for the mixing index using various system parameters based on the dimensional analysis approach for the un-promoted and the promoted beds. The mixing index values thus obtained through the dimensional analysis approach have been compared with those obtained from the developed theoretical model. The values of the mixing index calculated for promoted beds have also been compared with the corresponding values for the un-promoted beds. Segregation effect is found to be stronger

for the heterogeneous systems than the homogeneous ones. The density difference is the major factor affecting the segregation.

***Keywords**: Co-axial promoters, Mixing index, Jetsam concentration, Homogeneous and Heterogeneous binaries, Gas-solid fluidization and dispersion coefficient.*

Article Outline

1. Introduction

Solid mixing is a common mixing operation widely used in different industries. In fact, this operation is almost always practiced wherever particulate matter is processed. This is strongly influenced by different mobilities of the mixed components, which depend on the particle properties. 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 (Nienow et al., 1972). The degree of axial mixing of particles in fluidized beds is important for many continuous or batch processes, and control thereof is desirable. In fluidized beds consisting of particles with different size and/or density a concentration profile will develop over the height of the bed at moderate gas velocities (Hartholt et al., 1997). Most of the investigators who discuss the problem of solid mixing in a fluidized bed have assumed that the solid mixing stems from random movements of particles and this assumption has rarely been questioned. If it is correct it follows that solid mixing will occur by inter-particle diffusion or eddy diffusion as in true fluids (Rowe et al., 1965) and bubble rise. Because of the bubble rise, some solids are seen flowing up and others flowing down the bed.

2. Literature

Solid exchange between a bubble wake and the emulsion phase is one of the fundamental rate processes that directly affect the direct mixing of fluidized beds (Chiba& Kobayashi, 1977 and Kunii and Levenspiel, 1969). Work relating to the mixing of segregating particles in a fluidized bed is scanty. Nicholson and Smith, (1966) studied the axial mixing of particles differing in density in a fluidized bed and thereof proposed a first order rate equation to describe the progress of mixing in the short mixing time. Gibilaro and Rowe, (1974) formulated a qualitative model of particle mixing in fluidized beds based on four physical mechanisms viz. overall particle circulation, interchange between wake and bulk phases, axial dispersion and segregation. Fan and Chang, (1979) studied the fluidization and solid mixing characteristics of very large particles where bubble or slug induced drift and gross solid circulation appeared to be the predominant solid mixing mechanisms. The degree of axial mixing of particles in fluidized beds is important for many continuous as well as batch processes and the control thereof is desirable.

2.1 Correlations for Mixing Index

Naimer et al., (1982) have developed the general expression for mixing index which is widely used for all systems in the form as given below.

$$I_M = \frac{X^*}{\overline{X}_{bed}} \qquad (1)$$

Nienow et al., (1978) have proposed the correlation for the equilibrium mixing index for an equal-size, density-variant binary mixture in a three dimensional fluidized bed as follows.

$$M = \left(1 + e^{-z}\right)^{-1} \qquad (2)$$

Where,

$$Z = \left(\frac{U - U_{TO}}{U - U_F} \right) e^{U/U_{TO}} \tag{3}$$

For a size variant, equal density system of particles, Fan et al., (1990) have developed the following model for the mixing index.

$$I_M = K \times \left(\frac{\bar{d}_P}{d_F} \right)^k \left(\frac{U}{U - U_F} \right)^n \tag{4}$$

2.2 Role of Bubbles on Mixing

It is a well known fact that some solids flow up and others flow down because of bubble rise during fluidization in a gas-solid fluidized bed. This up-flow and down-flow with an interchange between the streams is the basis for various counter flow models that have been proposed to account for the vertical mixing of solids. Van Deemter, (1967) divided the solids into two streams for a tall enough bed of solid particles and developed two models for up-flowing stream and for down-flowing stream. The horizontal movement of solids was first studied by Brotz, (1954) in a shallow rectangular bed from where he got the information to evaluate the horizontal dispersion coefficient D_{sh}. A similar approach was used by other investigators (Mori et al., 1965; Hirama et al., 1975 and Borodulya et al., 1982). Heertjes et al., (1967) suggested that the wake material scattered into the freeboard by the bursting bubbles could contribute significantly to the horizontal movement of solids. Hirama et al., (1975) and Shi and Gu, (1986) used partition plates in the freeboard just above the bed to study this effect. All of these investigators used rather shallow beds of height between 5 and 35cm. In contrast, Bellgardt and Werther, (1984) made measurements in a much larger bed, namely a 2m×0.3m bed about one meter deep. Quartz sand (dp=450µm) was fluidized, and careful measurements confirmed that vertical mixing was much faster than the horizontal mixing, thus justifying the use of a one dimensional dispersion model in the horizontal direction. Kunii and Levenspiel, (1991) developed a mechanistic model based on the Davidson's bubble model and proposed the following expression for the horizontal dispersion coefficient for both fast and intermediate bubbles.

$$D_{sh} = \frac{3}{16}\frac{\delta}{1-\delta}\alpha^2 d_b u_{br}\left[\left(\frac{u_{br}+2u_{fl}}{u_{br}-u_{fl}}\right)^{1/3} - 1\right] \quad (5)$$

For fast bubbles with thin clouds typical of fine particle systems, or $u_{br} >> u_{fl}$, the above equation simplifies to

$$D_{sh} = \frac{3}{16}\left(\frac{\delta}{1-\delta}\right)\left(\frac{\alpha^2 u_{mf} d_b}{\varepsilon_{mf}}\right) \quad (6)$$

3. Development of Mathematical Model (Sahoo, A., 2005)

An attempt has been made to develop a theoretical model with the above system parameters on the basis of 'Counter flow Solid Circulation Models' (Kunii and Levenspiel, 1991). Considering both vertical and horizontal movement of the jetsam particles as some particles displace horizontally due to the bursting of bubbles the dispersion model in the form of the differential equation can be written as follows,

For solids upward motion i.e. in upward direction:

$$f_u D_{sv}\left(\frac{\partial^2 C_{ju}}{\partial z^2}\right) + f_u u_u \frac{\partial C_{ju}}{\partial z} + K_s\left(C_{ju} - C_{jd}\right) + D_{sh}\frac{\partial^2 C_{ju}}{\partial z^2} = 0 \quad (7)$$

For solids downward motion i.e. in downward direction:

$$f_d D_{sv}\left(\frac{\partial^2 C_{jd}}{\partial z^2}\right) + f_d u_{jd}\frac{\partial C_{jd}}{\partial z} + K_s\left(C_{jd} - C_{ju}\right) + D_{sh}\frac{\partial^2 C_{jd}}{\partial z^2} = 0 \qquad (8)$$

when the superficial velocity of the fluidizing medium is more than that of jetsam/flotsam particles, assuming that the whole solid materials is divided into two streams; one stream having fraction f_u moves up and the other stream with fraction f_d moves down. Thus the movement of solids is a continuous process during fluidization. It is almost impossible to determine the exact fraction of solids moving up or down. Therefore it has been assumed that always half of the whole bed material moves in upward direction while the other half moves in the downward direction during fluidization.

Again with the assumption of $f_d = f_u$, $u_u=u_d$, $C_{ju} = C_{jd}$ and writing f, u and C_j for these variables respectively in the above equations-7 and 8, then adding these two equations the following equation is obtained where $(W/2\rho_s)/V_B$ is used for f

$$\frac{\partial^2 C_j}{\partial z^2} + \frac{W u_o}{W D_{sv} + 2 D_{sh}\rho_s V_B}\frac{\partial C_j}{\partial z} = 0 \qquad (9)$$

This is the differential equation describing the concentration of jetsam as a function of bed height. Vertical mixing rate as a function of gas velocity in rather small beds is given (Kunii and Levenspiel, 1991) as under.

$$D_{sv} = 0.06 + 0.1 u_o \qquad (10)$$

Horizontal dispersion coefficient as mentioned in the book (Kunii and Levenspiel, 1991) is given by equation-6. For Geldart-BD solids α has been taken as 0.77.

Equation-6 has been simplified using the expressions for the bubble diameter, bubble rise velocity, bed voidage fraction, minimum fluidization velocity and fraction of bed in bubbles etc. (Kunii and Levenspiel, 1991).

Equation-6 in simplified form is as under

$$D_{sh} = \frac{3}{16}\left(\frac{u_o - u_{mf}}{u_b - u_o + 2u_{mf}}\right)\left(\frac{\alpha^2 u_{mf}\left(d_b/100\right)}{\varepsilon_{mf}}\right) \tag{11}$$

Now equation-9 can be written as

$$\frac{\partial^2 C_j}{\partial z^2} + \frac{Fu_o}{FD_{sv} + D_{sh}}\frac{\partial C_j}{\partial z} = 0 \tag{12}$$

Where, $F = \frac{W}{2\rho_s V_B}$

Now describing the coefficient of $\frac{\partial C_j}{\partial z}$ as a function of height as

$$\frac{Fu_o}{FD_{sv} + D_{sh}} = f(z) \tag{13}$$

The equation-12 can be written as

$$\frac{\partial^2 C_j}{\partial z^2} + f(z)\frac{\partial C_j}{\partial z} = 0 \tag{14}$$

Solving the above differential equation by variable separable method the concentration of jetsam particles can be written as

$$C_j = \int e^{-\int f(z)\,dz}\,dz \tag{15}$$

Now substituting the D_{sh} and D_{sv} from eq-11 and eq-10 respectively, the equation-13 can be expressed as under

$$f(z) = \frac{A + Bz}{C + Dz} \tag{16}$$

Where, $A = Fu_oC_1 + Fu_oD_2$

$$B = 0.0414 \times Fu_o D_2$$

$$C = (0.06 + 0.1u_o)FC_1 + (0.06 + 0.1u_o)FD_2 + KK_1$$

$$D = (0.06 + 0.1u_o)0.0414 \times FD_2 + 0.0828KK_1$$

The solution of equation-15 in terms of A, B, C, D can thus be written as

$$C_j = \int e^{-\left(\frac{B}{D}\right)z} \times \left(1 + \frac{D}{C}\right)^{\frac{BC-AD}{D^2}} dz \qquad (17)$$

Again on simplification, equation-17 can be written as

$$C_j = -\frac{D}{B} e^{-\left(\frac{B}{D}\right)z} - \frac{(BC-AD)}{BC} e^{-\left(\frac{B}{D}\right)z} z - \frac{(BC-AD)}{CD} \times \frac{D^2}{B^2} e^{-\left(\frac{B}{D}\right)z} \qquad (18)$$

This gives the idea for the concentration of jetsam particles for any system at any height of the bed from the distributor. Thus the mixing index at any height can be written as

$$I_M = C_j \times \frac{W}{J} \qquad (19)$$

4. Experimentation

Fig.-1 gives a schematic diagram of the experimental set up. The binary mixtures of irregular particles are fluidized in a 15cm×100cm Perspex column. The components of the mixture have been mixed in the ratio of 10:90, 25:75, 40:60 and 50:50. For a particular composition of the mixture, the initial static bed height and the superficial velocity of the fluidizing medium have been altered four times. The process has been repeated for four different size/density ratios of the homogeneous/heterogeneous binary mixtures respectively in un-promoted as well as promoted beds. The samples have been drawn for analysis for the static bed condition as well as for the fluidized bed condition.

In the static bed condition the samples have been drawn layer wise by applying vacuum after the fluidized bed is brought back to static bed condition by shutting off the air supply suddenly. In the fluidized bed condition the samples have been drawn through the side ports during fluidization process. The samples drawn at different heights have been analyzed for the distribution of jetsam particles and calculation of their concentration. The scope of the experiments is presented in Table-1and 2.

5. Development of Experimental Models

The model developed from dimensional approach for the un-promoted and promoted fluidized beds are as follows.

1. For Homogeneous binary mixtures

A. Un-promoted Fluidized bed

(i) Static bed condition

$$I_M = 0.8995 \times \left[\left(\frac{d_j}{d_f} \times \frac{d_m}{d_f} \right)^{0.046} \left(\frac{H_S}{D_C} \right)^{0.059} \left(\frac{H_b}{D_C} \right)^{-0.207} \left(\frac{U}{U - U_{mf}} \right)^{-0.036} \right] \quad (20)$$

(ii) Fluidized bed condition

$$I_M = 0.92 \times \left[\left(\frac{d_j}{d_f} \times \frac{d_m}{d_f} \right)^{-0.140} \left(\frac{H_S}{D_C} \right)^{0.028} \left(\frac{H_b}{D_C} \right)^{-0.135} \left(\frac{U}{U - U_{mf}} \right)^{0.021} \right] \quad (21)$$

B. Promoted Fluidized bed

$$I_M = 1.086 \times \left[\left(\frac{d_j}{d_f} \times \frac{d_m}{d_f} \right)^{-0.091} \left(\frac{H_S}{D_E} \right)^{0.096} \left(\frac{H_b}{D_E} \right)^{-0.271} \left(\frac{U}{U - U_F} \right)^{-0.067} \right] \quad (22)$$

2. For Heterogeneous binary mixtures

A. Un-promoted Fluidized bed

(i) Static bed condition

$$I_M = 2.761 \times \left[\left(\frac{\rho_f}{\rho_j} \times \frac{\rho_m}{\rho_j} \right)^{1.301} \left(\frac{H_S}{D_C} \right)^{0.549} \left(\frac{H_b}{D_C} \right)^{-0.148} \left(\frac{U}{U - U_{mf}} \right)^{-0.152} \right] \quad (23)$$

(ii) Fluidized bed condition

$$I_M = 2.403 \times \left[\left(\frac{\rho_f}{\rho_j} \times \frac{\rho_m}{\rho_j} \right)^{1.343} \left(\frac{H_S}{D_C} \right)^{0.326} \left(\frac{H_b}{D_C} \right)^{-0.234} \left(\frac{U}{U - U_{mf}} \right)^{-0.052} \right] \quad (24)$$

B. Promoted Fluidized bed

$$I_M = 4.44 \times \left[\left(\frac{\rho_f}{\rho_j} \times \frac{\rho_m}{\rho_j} \right)^{1.599} \left(\frac{H_S}{D_E} \right)^{0.258} \left(\frac{H_b}{D_E} \right)^{-0.548} \left(\frac{U}{U - U_{mf}} \right)^{-0.295} \right] \quad (25)$$

6. Results and Discussion

1. Experimental Validation

The developed model for the concentration of jetsam particles, thereby for the mixing index has been verified with a number of homogeneous and heterogeneous binary mixtures by varying the system parameters. Finally the values of the mixing index obtained through the theoretical model for un-promoted and promoted beds have been compared with both the homogeneous and heterogeneous binary mixtures. On comparing the values of the mixing index at different heights for the promoted beds with those of un-promoted ones for both the systems, it is found that the un-promoted fluidized beds are having higher jetsam concentration in almost all cases indicating more mixing index than the promoted beds. A sample plot for the homogeneous binary mixture is shown in **Fig.2**. This in turn implies that better mixing is obtained with the un-promoted bed than the promoted ones, where resistance is offered in the horizontal plane. Reason for this may be that with the promoter the bubble rise is obstructed by the discs of the promoter, which in turn reduce the rise of jetsam particles upwards with the bubbles. Some particle transport might occur from the upper side of the lower disc to the bottom of the next upper disc.

The values of the mixing index calculated by the dimensional analysis approach have been compared with those obtained from the experimental observations as well as from the theoretical model for different types of beds with both the systems (homogeneous and heterogeneous binary mixtures). The average error values for mixing index obtained from the comparison of calculated mixing index values by the dimensional analysis approach and the experimental methods are listed in **Table-3**

Mixing index values obtained from the theoretical model (eq. no.-19) and the numerical models (developed by the dimensional analysis, eq. nos. 20-25) have been compared with the experimental ones for different types of fluidized beds for both homogeneous and heterogeneous binary mixtures in **Figs.-3** and **4** respectively. It was observed that the values obtained with the developed theoretical model are lower than both, the experimental ones as well as the developed dimensional correlations for all types of fluidized beds in both the systems. The reason for this may be due to the "gulf-streaming effect" and the assumption of the uniform concentration in a layer of particles at any height of the bed, which may not be true in reality.

During the process of fluidization some particles move upwards and some downwards inside the fluidizer. It is difficult to known that at any instant of time how much portion of the bed materials is moving upward and how much downward. For the simplification of the modeling it was assumed that at any instant of time during the process of fluidization 50% of the bed materials is moving up and the balance 50% of the bed materials is moving in the downward direction.

Theoretical model has been developed on the assumption that 50% of the bed materials move up as the upward stream and the balance 50% move down as the downward stream during fluidization. Apparently, segregation in the axial direction might have been resulted from preferential transportation of lighter particles upwards with rising bubbles and from inter particle competition to fill the voidage created by the rising bubbles (Fan and Chang, 1979).The samples were drawn from the ports made on either side of the column alternately and were analyzed on the basis of 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. Lower values of mixing index by the theoretical model might have been obtained due to these assumptions which may not be true in an operating fluidized bed.

2. Theoretical Analysis for the model

Effect of various system parameters viz. size/density of the particles, initial static bed height, composition of the mixture and the superficial velocity of the fluidizing medium on the jetsam concentration have been studied for both the systems with the un-promoted and promoted fluidized beds respectively. A sample plot for the heterogeneous binary mixtures is shown through **Fig.5** (A, B, C and D) with the promoted bed. It is observed that with the increase of flotsam density or in other words decreasing the ratio of jetsam to flotsam densities the jetsam concentration decreases at any height and also the jetsam concentration decreases with the increase of bed height. Although the same tendency is observed with the homogeneous binaries but the effect of jetsam and flotsam size ratio on jetsam concentration at any height is insignificant in comparison with the heterogeneous binaries. In both the systems, the distribution of jetsam particles in any layer of the bed has been found to decrease with the increase of jetsam percentage in the overall mixture, with the increase of the initial static bed height and with the decrease of size/density ratio of the binary mixture. Also the distribution of the jetsam was found to decrease with the increase of the superficial velocity above the minimum fluidization velocity (**Fig.5**). It is also observed that the concentration of jetsam decreases with the height of the bed irrespective of the any system parameter involved. This implies that the segregation tendency is observed with all the system parameters for the developed model as the jetsam concentration gradually decrease with the increase of bed heights for any system. It is also noted from the **Tables-1-(B)** and **2-(B)** that the ratio of minimum fluidization velocity of jetsam to that of flotsam for three mixtures in case of homogeneous binaries and one mixture in case of heterogeneous binaries is greater than 2.0 whereas it is less than 2.0 in case of other mixtures indicating clear segregation tendency with the former mixtures compared to other mixtures in both the systems studied (Chen and Keairns, 1975). It was also observed that the mixing index for the homogeneous binaries is better than the heterogeneous binary mixtures indicating the better mixing operation in the former case.

Conclusion

The degree of mixing depends very much on gas velocity and even strongly segregating system can either be separated or well mixed by controlling this. Knowledge of the minimum fluidization velocity is crucial if the behaviour of a fluidized bed is to be properly analysed. The U_{mf} is a simple concept and easy to measure in a mono-component fluidized bed however, it is complex in both definition and measurement for any binary system. In a well-mixed bed of two solids, the void fraction depends strongly on the mean size ratio and volumetric fractions of its components and its values can be significantly lower than for a monosized bed of particles.

The developed model has been tested against the existing experimental data. The distributions of the jetsam particles are variable in the direction of the bed height. The numerical results are in satisfactory agreement with the existent experimental data.

The depth of the jetsam layer, the fluidization velocity and the particle properties, especially the minimum fluidization velocities of the two components, determines the concentration of jetsam in the upper stratum of a strongly segregating bed at steady state.

The developed experimental models can be used widely for analyzing the mixing and segregation characteristics of both the homogeneous and the heterogeneous 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. The presence of promoter/baffle reduces the mixing aspect for both the homogeneous and the heterogeneous binaries. 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.

Figure Caption:

Fig-1: Experimental set-up

Fig.2: Comparison plots for mixing index values for promoted and un-promoted beds for Homogeneous binary mixtures.

Fig.-3: Comparison plots for the mixing index values calculated from the theoretical model and the semi-empirical model against the experimental ones for the homogeneous binaries

- **(A)** For Un-promoted Static bed condition
- **(B)** For Un-promoted Fluidized bed condition
- **(C)** For Promoted Fluidized bed condition

Fig.-4: Comparison plots for the mixing index values calculated from the theoretical model and the semi-empirical model against the experimental ones for the heterogeneous binaries

- **(A)** For Un-promoted Static bed condition
- **(B)** For Un-promoted Fluidized bed condition
- **(C)** For Promoted Fluidized bed condition

Fig.5: Comparison plots for effect of system parameters on concentration of jetsam particles obtained through the theoretical model for the heterogeneous binaries in promoted fluidized bed.

- (A): Effect of mixture property (smaller/larger or lighter/heavier)
- (B): Effect of composition of the mixtures
- (C): Effect of bed height
- (D): Effect of fluidization velocity (u_o)

Notation

Cj	: 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 kg)
d	: Diameter of particle, m
d_b	: Bubble diameter, cm
D_C	: Diameter of the column, m
D_E	: Equivalent 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
f	: fraction of solids moving up or down per bed volume, m^3 of the solid /m^3 of the bed volume
Hb	: Height of particles layer in the bed from the distributor, m
Hs	: 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
Ks	: Interchange coefficient
K	: exponent of parameter
M	: equilibrium mixing index
N	: exponent of parameter
u	: velocity of the stream of particles moving up or down, m/s
u_b	: Bubble velocity, cm/s
u_{br}	: Bubble rise velocity, cm/s

U, u_o	: Superficial velocity of the fluidizing medium, m/s
U_F	: Minimum fluidization velocity of the mixture, m/s
U_{TO}	: take over velocity defined as the value of U corresponding to M = 0.5.
V_B	: Volume of the bed, m^3
W	: Weight of the total bed material, kg
X*	: Percentage of jetsam particle in any layer
$\overline{X}_{bed}$	: Percentage of jetsam particle in the bed
Z	: Height of any layer of particle in the bed measured from the distributor, (varying from 0 to 0.2 m).

Greek letters

δ	: fraction of bed in bubble
α	: a factor, the ratio of wake diameter to bubble diameter
ε	: Bed voidage fraction
ρ	: Density of particle, kg/m^3

Suffixes

F, f	: flotsam
fl	: fluidizing condition
j	: jetsam
m	: mixture
mf	: minimum fluidization condition
u	: upward component
d	: downward component
o	: operating condition
p	: particle
s	: solids
w	: wake solids

Abbreviations:

Dia_ratio	: $(dj/df) \times (dm/df)$
Dens_factor	: $\rho_f/\rho_j \times \rho_m/\rho_j$
M.I.-cal	: Calculated values of mixing index
M.I.-exp	: experimental values of mixing index

M.I.-th : Mixing index values obtained from the theoretical model

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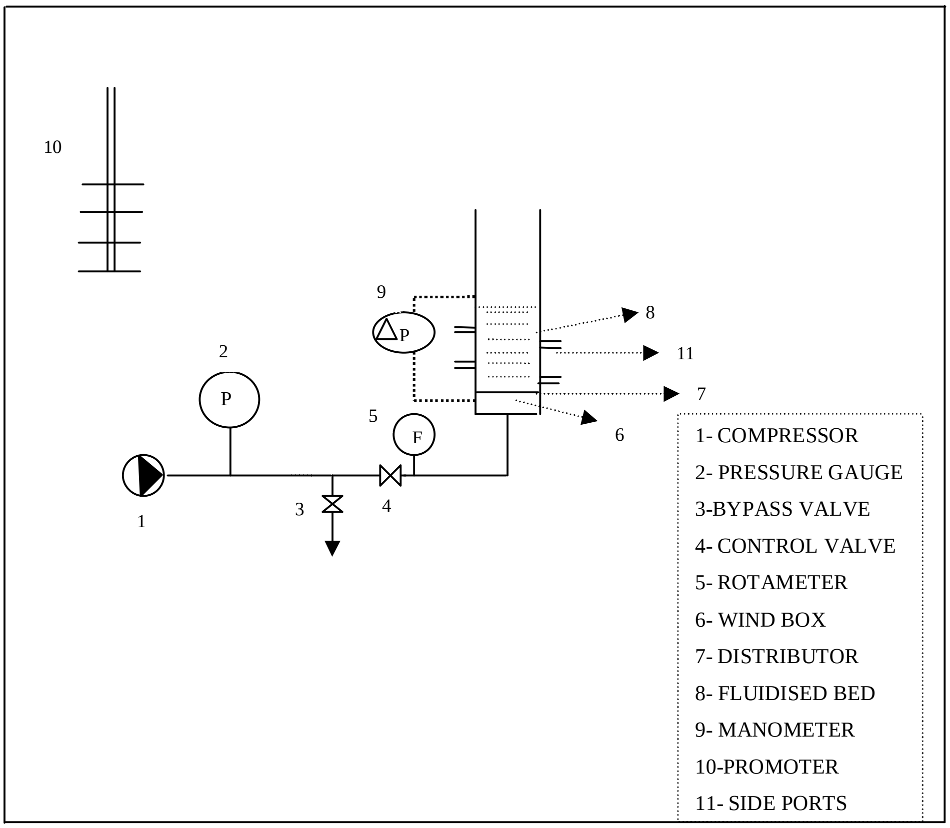

Fig-1

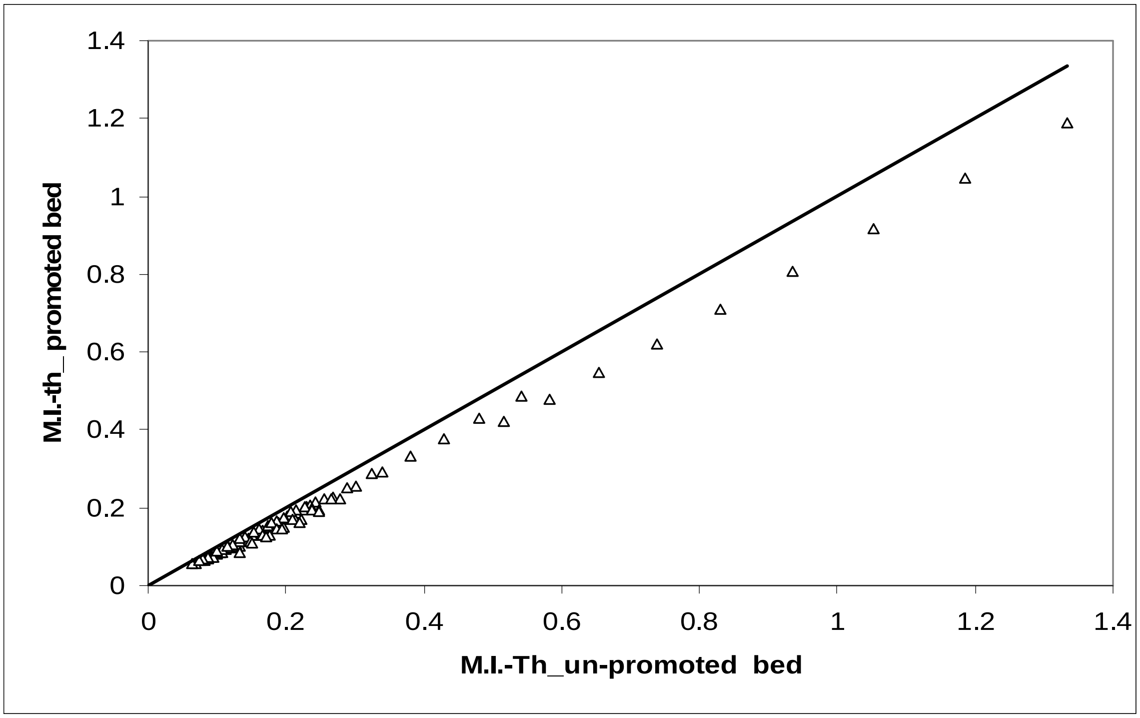

Fig.2

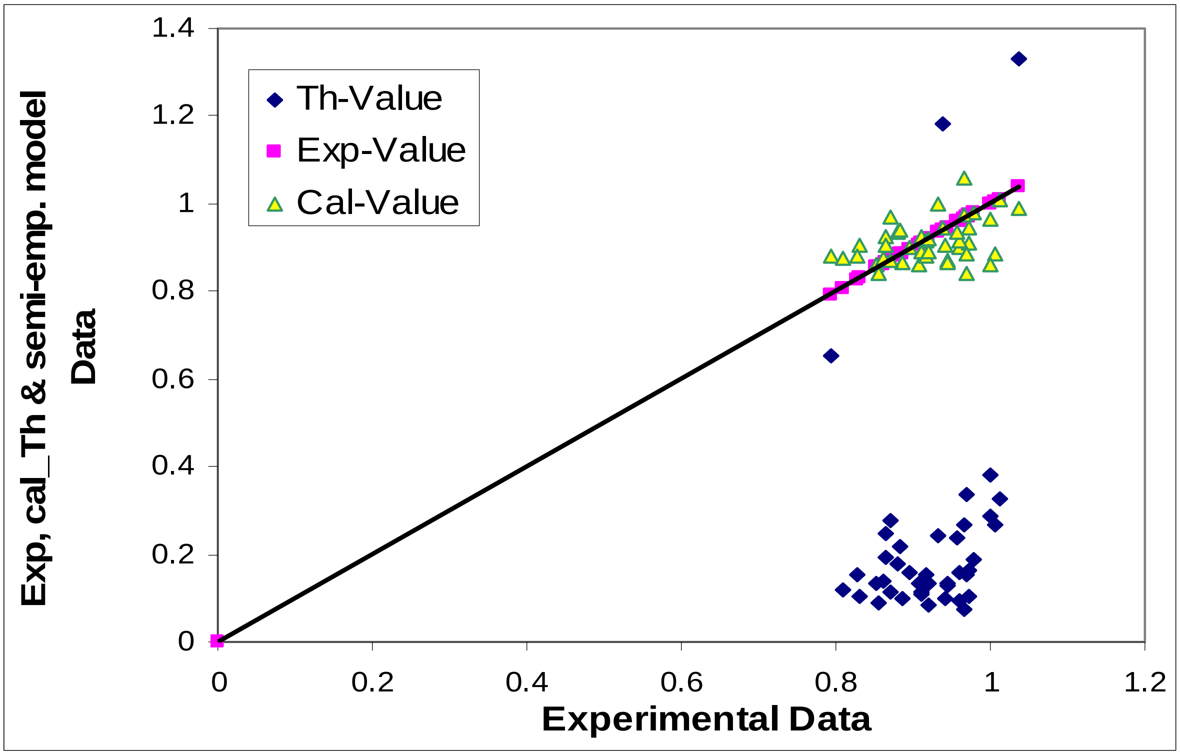

Fig.3(A) : For static bed condition

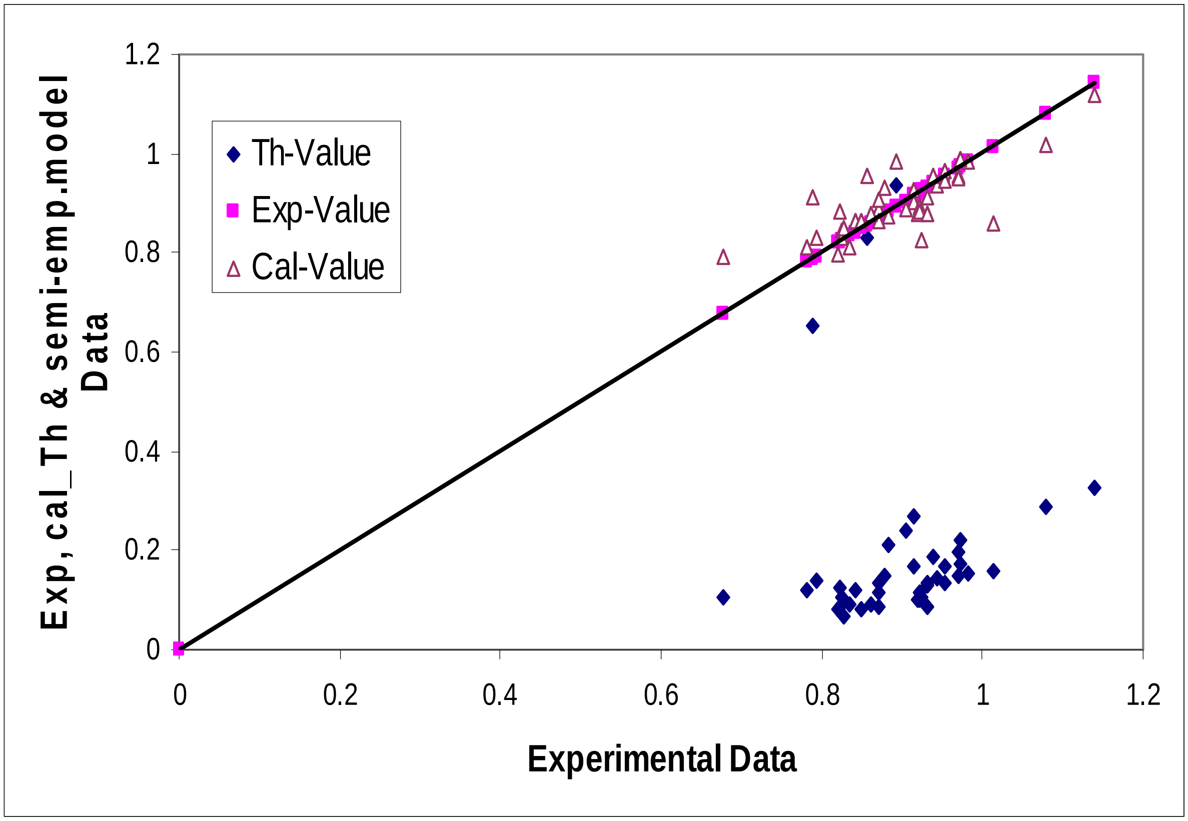

Fig.3(B): For Un-promoted fluidized bed condition

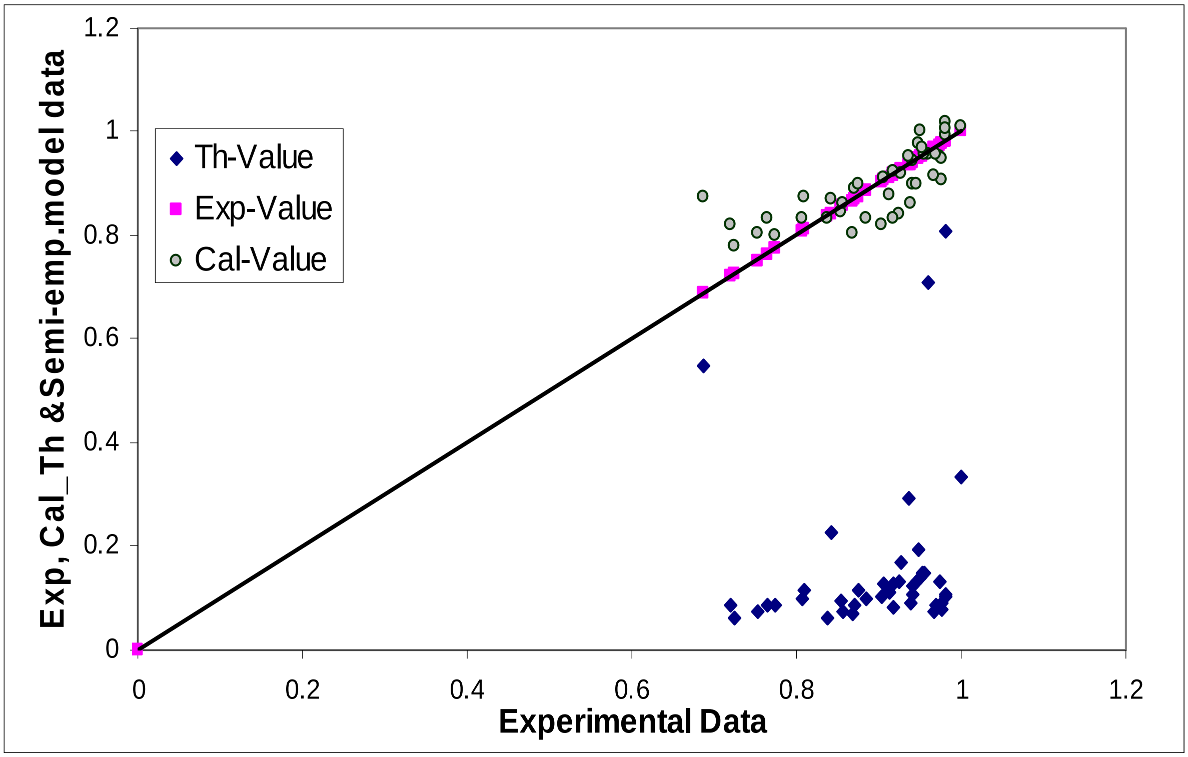

Fig.3(C): For promoted fluidized bed condition

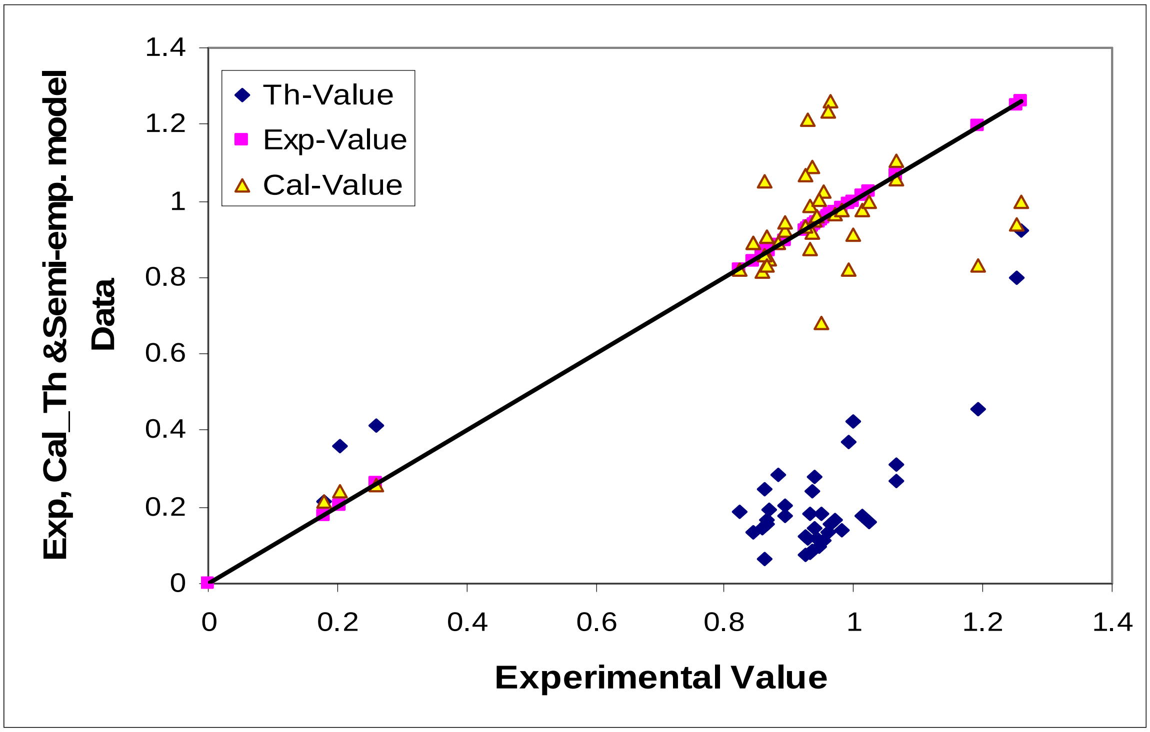

Fig.4(A): For static bed condition

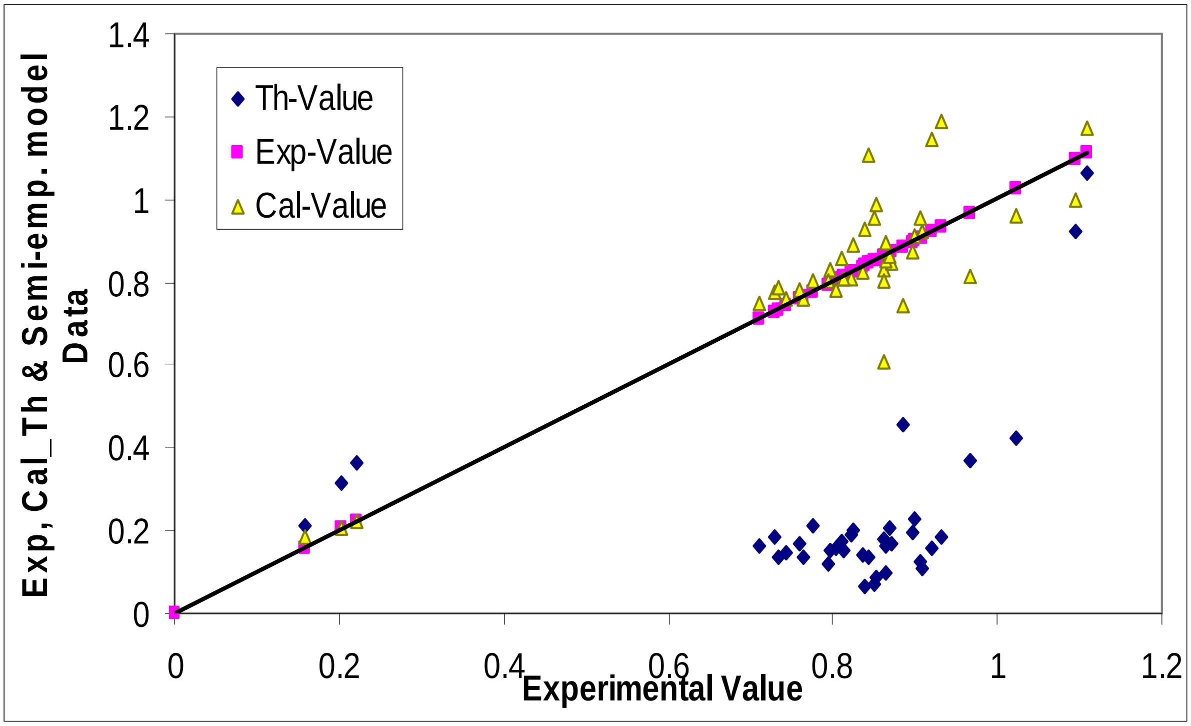

Fig.4(B): For Un-promoted fluidized bed condition

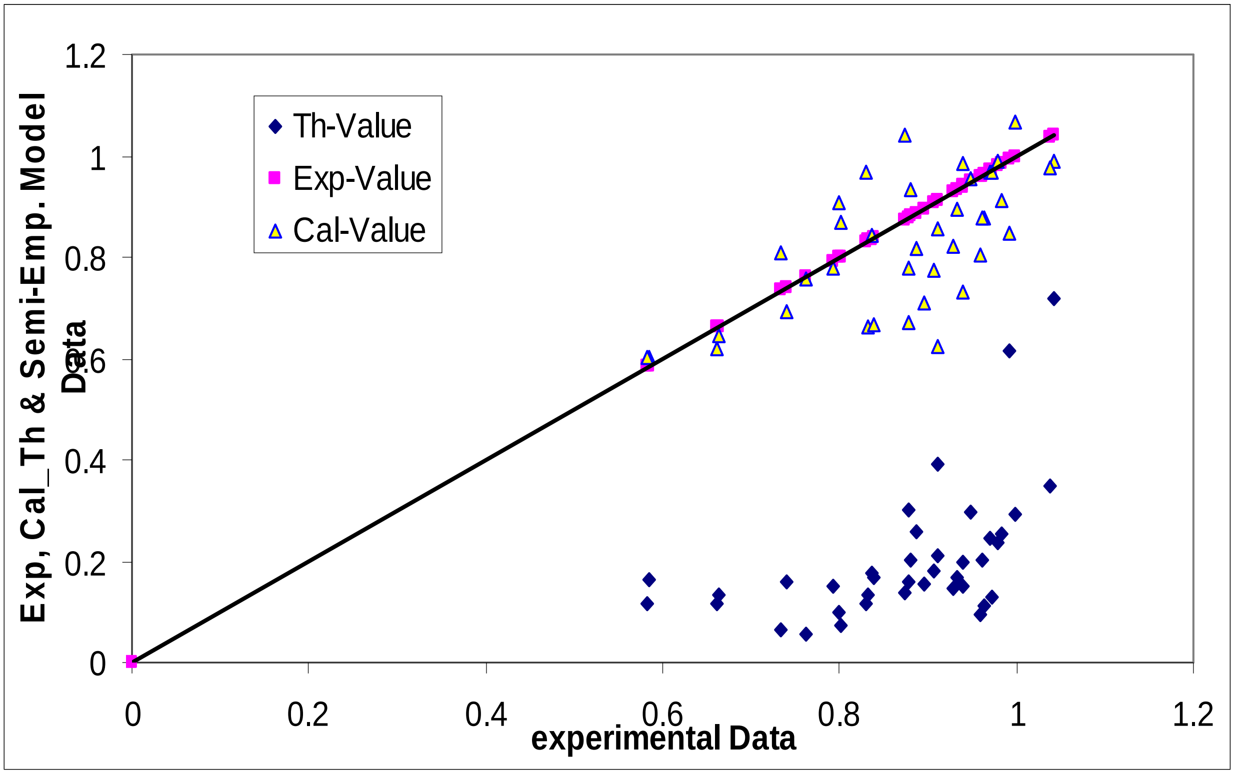

Fig.4(C): For promoted fluidized bed condition

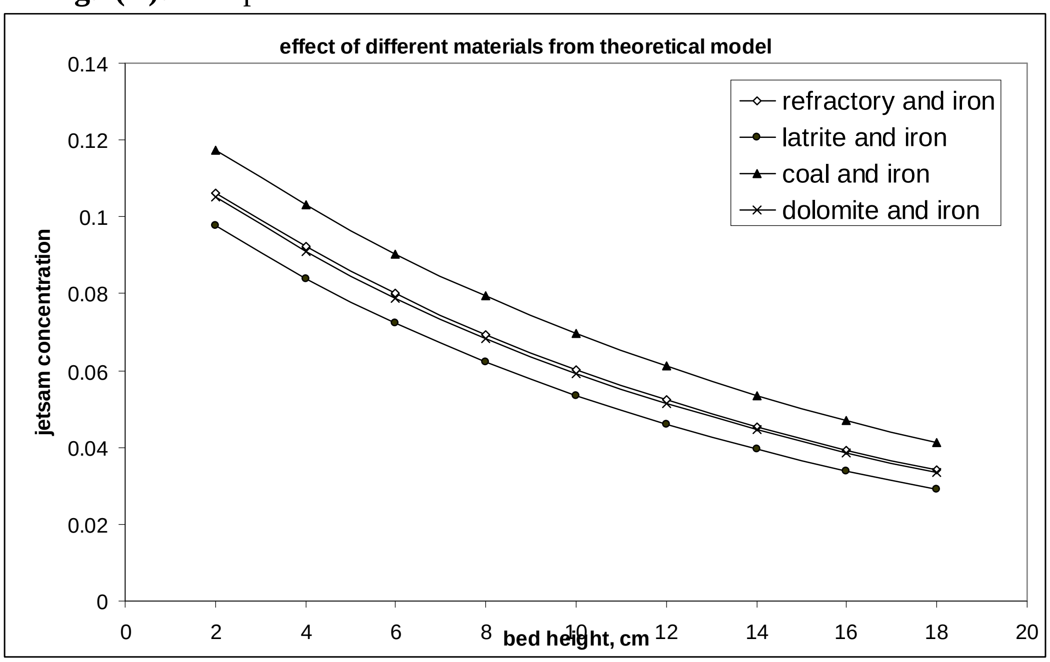

Fig-5. (A)

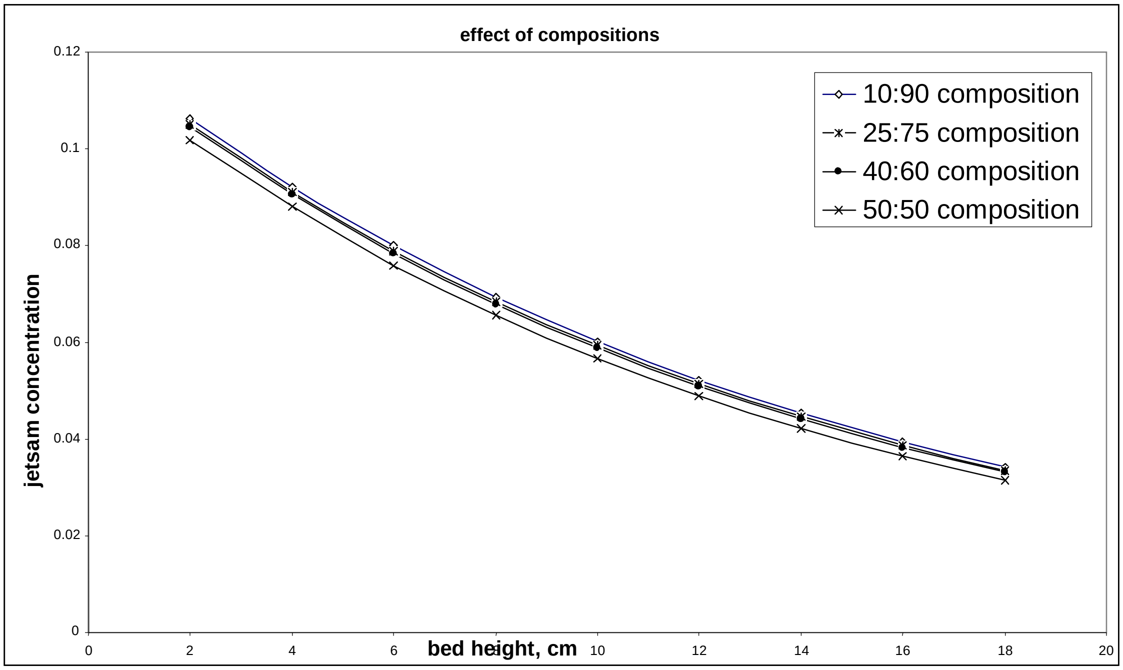
effect of compositions
jetsam concentration
bed height, cm
0
0.02
0.04
0.06
0.08
0.1
0.12
0
2
4
6
8
10
12
14
16
18
20
10:90 composition
25:75 composition
40:60 composition
50:50 composition

Fig-5. (B)

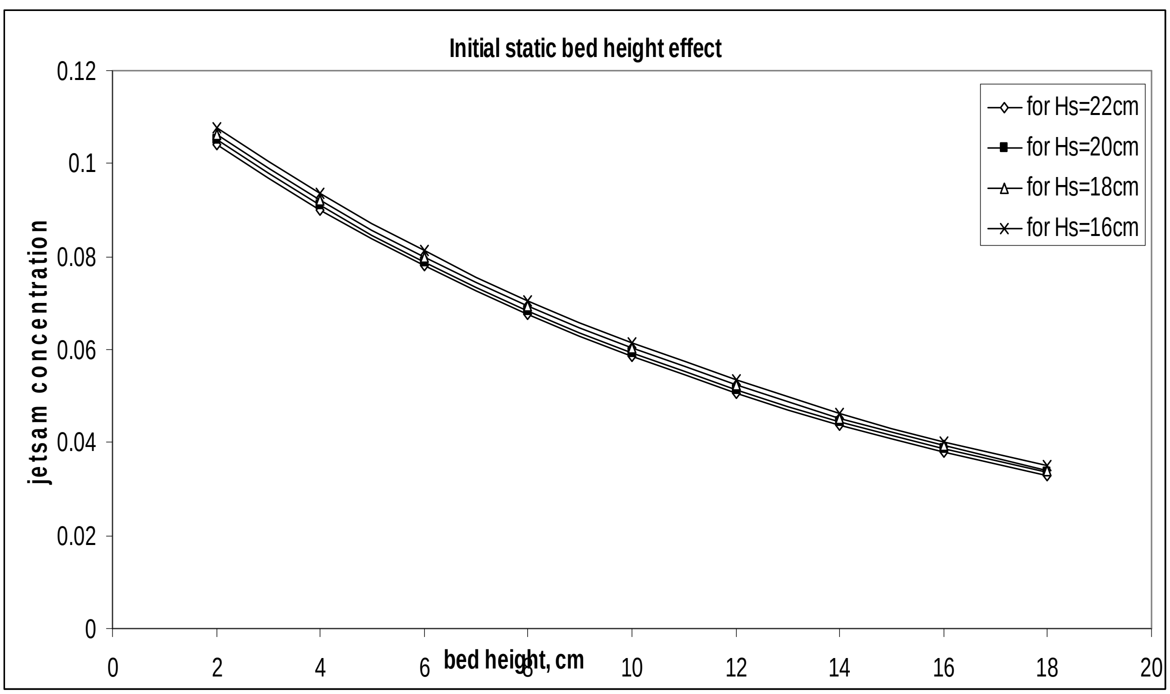
Initial static bed height effect
jetsam concentration
bed height, cm
0
0.02
0.04
0.06
0.08
0.1
0.12
0
2
4
6
8
10
12
14
16
18
20
for Hs=22cm
for Hs=20cm
for Hs=18cm
for Hs=16cm

Fig-5. (C)

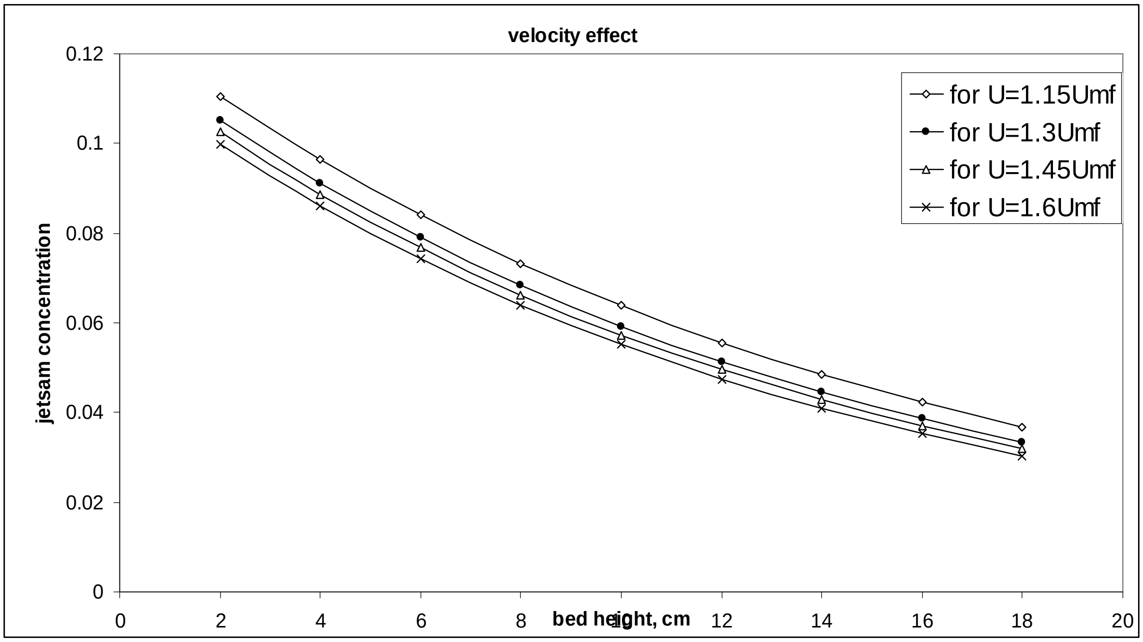

Fig-5. (D)

Table-1(A): Scope of the Experiment (for homogeneous binaries)

Sl. No.	Bed material	Size of Jetsam $dp \times 10^3$,m	Size of Flotsam $dp \times 10^3$,m	Ratio of jetsam to flotsam in the mixture	Average particle size of the mixture $dp \times 10^3$,m	Initial static bed height Hs, $\times 10^2$, m	Heights of layers for the withdrawal of samples, $H_b \times 10^2$, m
1	Dolomite	1.015	0.725	25:75	0.798	12	2,4,6,8,10,12
2	Dolomite	1.015	0.725	25:75	0.798	14	2,4,6,8,10,12,14,
3	Dolomite	1.015	0.725	25:75	0.798	16	2,4,6,8,10,12,14,16
4	Dolomite	1.015	0.725	25:75	0.798	20	2,4,6,8,10,12,14,16,18,20
5	Dolomite	1.015	0.725	10:90	0.754	20	2,4,6,8,10,12,14,16,18,20
6	Dolomite	1.015	0.725	40:60	0.841	20	2,4,6,8,10,12,14,16,18,20
7	Dolomite	1.015	0.725	50:50	0.870	20	2,4,6,8,10,12,14,16,18,20
8	Dolomite	1.29	0.725	25:75	1.008	20	2,4,6,8,10,12,14,16,18,20
9	Dolomite	1.44	0.725	25:75	1.083	20	2,4,6,8,10,12,14,16,18,20
10	Dolomite	1.7	0.725	25:75	1.213	20	2,4,6,8,10,12,14,16,18,20

Table-1(B): Bed material Properties (for homogeneous binaries)

Table-2(A): Scope of the experiment (for heterogeneous binaries)

Table-2(B): Bed Material Properties (for heterogeneous binaries)

Bed material	Component	$dp \times 10^3$,m	U_{mf}, m/s
Mixture-1	Larger material	1.015	0.585
	Smaller Material	0.725	0.376
	Ratio of above two	1.400 (unit less)	1.556 (unit less)
Mixture-2	Larger material	1.290	0.759
	Smaller Material	0.725	0.376
	Ratio of above two	1.780 (unit less)	2.016 (unit less)
Mixture-3	Larger material	1.440	0.843
	Smaller Material	0.725	0.376
	Ratio of above two	1.986 (unit less)	2.242 (unit less)
Mixture-4	Larger material	1.700	0.976
	Smaller Material	0.725	0.376
	Ratio of above two	2.345 (unit less)	2.590 (unit less)

Sl. No.	Bed material	Density of Flotsam particles $\rho_p \times 10^3$,kg/m^3	Density of Jetsam $\rho_p \times 10^3$,kg/m^3	Ratio of jetsam to flotsam in the mixture	Average particle density of the mixture $\rho_m \times 10^3$,kg/m^3	Initial static bed height Hs, $\times 10^2$, m	Heights of layers for the withdrawal of samples, $H_b \times 10^2$, m
1	Coal & Iron	1430	4760	25:75	2262.5	20	2,4,6,8,10,12,14,16,18,20
2	Refr.brick & Iron	2550	4760	25:75	3102.5	20	2,4,6,8,10,12,14,16,18,20
3	Latrite & Iron	3390	4760	25:75	3732.5	20	2,4,6,8,10,12,14,16,18,20
4	Dolomite & Iron	2940	4760	25:75	3395.0	20	2,4,6,8,10,12,14,16,18,20
5	Dolomite & Iron	2940	4760	10:90	3122.0	20	2,4,6,8,10,12,14,16,18,20
6	Dolomite & Iron	2940	4760	40:60	3668.0	20	2,4,6,8,10,12,14,16,18,20
7	Dolomite & Iron	2940	4760	50:50	3850.0	20	2,4,6,8,10,12,14,16,18,20
8	Dolomite & Iron	2940	4760	25:75	3395.0	16	2,4,6,8,10,12,14,16
9	Dolomite & Iron	2940	4760	25:75	3395.0	18	2,4,6,8,10,12,14,16,18
10	Dolomite & Iron	2940	4760	25:75	3395.0	22	2,4,6,8,10,12,14,16,18,20

Bed material	Component	$\rho_p \times 10^3$,kg/m^3	U_{mf}, m/s
Coal & Iron mixture	Heavier material	4760.0	1.055
	Lighter material	1430.0	0.469
	Ratio of above	3.329 (unit less)	2.249 (unit less)
Refractory brick & Iron mixture	Heavier material	4760.0	1.055
	Lighter material	2550.0	0.703
	Ratio of above	1.867 (unit less)	1.502 (unit less)
Dolomite & Iron mixture	Heavier material	4760.0	1.055
	Lighter material	2940.0	0.773
	Ratio of above	1.619 (unit less)	1.366 (unit less)
Latrite & Iron mixture	Heavier material	4760.0	1.055
	Lighter material	3390.0	0.849
	Ratio of above	1.404 (unit less)	1.244 (unit less)

Table-3: Averaged error values for each of the semi-empirical models presented (with reference to Eqs. No. 20-25) in comparison with the experimental values for different types of beds and bed materials.

Material Type	Homogeneous Mixture			Heterogeneous Mixture		
Bed Type	UP-St. Bed	UP-Fl. Bed	Promoted bed	UP-St. Bed	UP-Fl. Bed	Promoted bed
Ref. Eq.	Eq.no.-20	Eq.no.-21	Eq.no.-22	Eq.no.-23	Eq.no.-24	Eq.no.-25
Std. Dev	6.399	5.995	6.642	13.759	10.787	11.455
Mean Dev.	0.587	-0.624	-0.619	-1.881	-2.446	4.754