Hydrodynamics and Particle Mixing Characteristics of a Ternary Mixture in a Gas-Solid Fluidized Bed

Jaya Bharathi. J., K. Saravanan

Abstract: ***Gas-Solid Fluidized Beds are widely used in current industrial practices for their high efficiency in producing products of very high standards. The study of bed dynamics has become an important concern for the design of fluidized beds. Various parameters like pressure, temperature, gas velocity, mean residence time and solids composition affect the bed behavior. In this view, an experimental study was carried out to determine the influence of gas flow rate, mixing time, solids composition and bed height on mixing/segregation behaviour of the bed of particles. Since fluidized beds involving more than two solids are more frequently encountered in current industrial practices, the experiments were conducted using three solid sand particles of average sizes 231 µm, 335 µm, and 510 µm. Various mixing patterns were observed for different mixing times (10, 20 and 30 minutes), different gas flow rates (7.5, 12.5, 17.5, 22.5 and 27.5 LPM), and different solids ratio. Good mixing occurred at an optimum mixing time of 30 minutes and gas flow rates of 17.5 LPM and 22.5 LPM at all solids ratio. The components exhibited relatively better mixing at intermediate bed heights.***

Keywords: ***Fluidized bed, particle mixing, mixing time, gas flow rate, bed height, solids ratio.***

I. INTRODUCTION

Particulate system consisting of mono-sized particles of equal density seldom occurs in practical fluidized bed applications where as simultaneous treatment of dissimilar materials is normally encountered in a fairly large number of industrial applications. Both in the case of chemical conversions and of physical operations, the presence of two or more solids, differing in one or more of their constitutive properties is often demanded by some specific characteristic of the process; in other situations, the fluidized particles though uniform in size in the beginning, may change due to attrition, coalescence and chemical reaction, thereby affecting the quality of fluidization by high elutriation loss, de fluidization , segregation in size and inhomogeneous residence time in the bed, leading to non uniform products for wide particle size distribution. Therefore, proper characterization of the bed dynamics for the binary and the multi-component mixtures in gas solid systems is an important prerequisite for their effective utilization.

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Mixing in fluidized beds is an important and essential phenomenon which involves the treatment of two or more components in such a way that the individual particle of the different components in the mixture are evenly distributed and lies adjacent to each other within the highest possible probability.

Mixing in gas-solid fluidized bed depends on various factors like pressure, temperature, solids diffusivity, internal and gross circulations, aspect ratio (H/D) of the bed, type of distributor, mixing time, solids concentration and inlet gas velocity, etc. Material properties and the quality of the final products are highly dependent on equipment mixing performance. The quality of mixing is described using quantitative means like Mixing Indices [1].

Many studies have been made in the past in order to understand the underlying mechanism and to predict influence of various parameters on mixing. Navid Mostoufi and Jamal Chaouki [2] showed that solids diffusivities, both axial and radial, increased with superficial gas velocity. Norouzia et al. [3] suggested that increasing the superficial gas velocity caused rigorous internal and gross circulations, which in return, improved solids mixing and decreased deviations from well mixed state. Formisani and R. Girimonte [4] found that the binary fluidization of a mixture occured within a characteristic velocity range whose boundaries coincide with the “initial” and the “final fluidization velocity” of the particle mixture. Jinsen Gao et al. [5] found that segregation efficiency increases with increasing gas velocity and mean residence time of the binary particles, but decreases with increase in small particle concentration. Abbas H. Sulaymon et al. [6] showed that mixing index (denotes mixing quality) increases with increasing air velocity and mixing time until it reaches an optimum value, then decreases to an equilibrium value and also stated that mixing index depends on the particle size of the tracer.

II. MATERIALS AND METHODS

II. A. Materials

Majority of gas-solid reactions, metallurgical operations and others involve particles of size 40 µm to 500 µm having density $1.4 < \rho_s < 0.4$ g/cm^3. Sand particles of average sizes 231 µm, 335 µm and 510 µm were considered for the study. The choice of using the materials was strongly based on the available and easy analyzable materials. Air is used as the fluidizing medium having density of 1.1761 Kg/m^3 and viscosity of 1.983 x 10^{-5} Kg/ms.

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Table: I Physical Properties of Solids

S. No	Size µm	Density Kg/m^3	Porosity (ε)	Sphericity (Φ)	Voidage (ε_{mf})
1	231	2800	0.5	0.86	0.43
2	335	2500	0.5	0.86	0.42
3	510	2220	0.47	0.86	0.4

II. B. Experimental

The experimental work was done to determine the influence of mixing time, ratio of three differently sized sand particles and gas flow rate on solids mixing. Experiments were carried out for different solids ratio of 1:1:1, 0.5:1:1, 1.5:1:1, 1:0.5:1, 1:1.5:1, 1:1:0.5 and 1:1:1.5 (231 µm : 335 µm : 510 µm) at different mixing times 10, 20 and 30 minutes, and different gas flow rates of 7.5, 12.5, 17.5, 22.5 and 27.5 LPM. Different mixing patterns were obtained at different heights by varying each parameter (with the other two held constant).

II. B. 1. Experimental setup

The experimental setup shown in the Fig.1. consists of a fluidization column, air distributor, and measuring devices for air flow rate (rotameter), and pressure (U-tube manometer).

Fluidization column: The experiments were conducted in an acrylic column of 40 mm

internal diameter, 600 mm height and open at the top to the atmosphere. The flanges of 15 mm each were used according to the height required.

Air distributor: A conical section below the column filled with glass beads forms the air distributor. It provides uniform air distribution to the fluidization system and is covered with wire screen to prevent particles leakage.

Air flow rate measurement: Air supplied by means of a compressor was used as a fluidizing gas. The air was metered by means of calibrated feeding rotameter located before entering the fluidizing bed system.

Pressure Measurement: The pressure drop across the bed was measured by using a U-tube manometer filled with water.

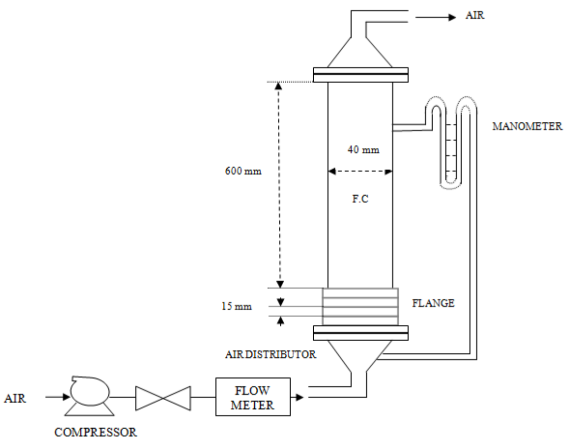


Fig. 1. Schematic Diagram of the Experimental Setup.

II. B. 2. Procedure

The sand particles of sizes 231 µm, 335 µm, and 510 µm were taken in the ratio of 1:1:1 (120 g) respectively and placed in the column fitted with flanges, in the order of decreasing particle size from the bottom of the column. The solid particles were allowed to fluidize at different gas flow rates of 7.5, 12.5, 17.5, 22.5 and 27.5 LPM, for a period of 10 minutes each. After 10 minutes, the air supply was cut off and the samples were collected from each flange and weighed. The samples collected from each flange were then sieved to separate out the particles based on their sizes. The weight fraction of each particle size in each sample was calculated. The above procedure was repeated for mixing times of 20 and 30 minutes. The entire procedure was then repeated by varying the solids ratio. The data obtained from the experiments were then used for the analysis of mixing patterns at different gas flow rates, mixing times for each solids ratio.

III. RESULTS AND DISCUSSION

III. A. Minimum Fluidization Velocity

In general, minimum fluidization velocity (U_{mf}) is a function of particle properties/geometry, fluid properties and bed geometry. U_{mf} can be found experimentally through pressure drop measurements and also using theoretical equations like Ergun equation and Wen and Yu equation.

In this study of ternary components mixing, Wen and Yu equation was used to determine the minimum fluidization velocity of the individual sand particles. Wen and Yu equation can also be used in the Reynolds number range 0.001 to 4000, giving predictions of U_{mf} having a 34% standard deviation [1].

$$Ar = \frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2}$$

[1]

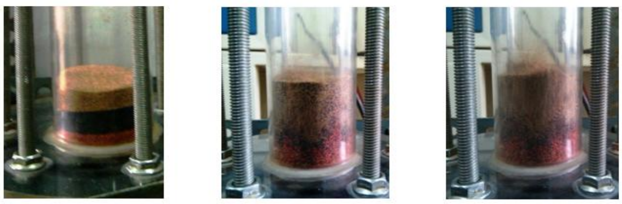
Table II: Minimum Fluidization Velocities of Three Solids

$$\mathrm{Re}_{p,mf} = [(28.7)^2 + 0.0494\, Ar]^{\frac{1}{2}} - 33.7$$

S.No	Particle Size (µm)	Wen and Yu Equation	
		U_{mf} (m/s)	U_{mf} (LPM)
1	231	0.044	4.013
2	335	0.082	7.480
3	510	0.162	14.770

III. B. Prediction of optimum mixing conditions

The observed mixing pattern of solids with increasing mixing time is shown in the Fig. 2 and Fig. 3. The figure shows how the mixing was initiated and progressed with increase in time.



(a) (b) (c)

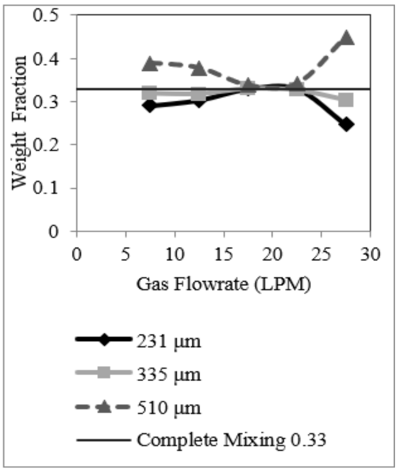
Fig. 2. Observed Mixing Pattern of Solids in the Initial Stages of Mixing.(a) Stage 1 (Before start of mixing), (b)Stage 2, (c) Stage 3.

(d) (e) (f)

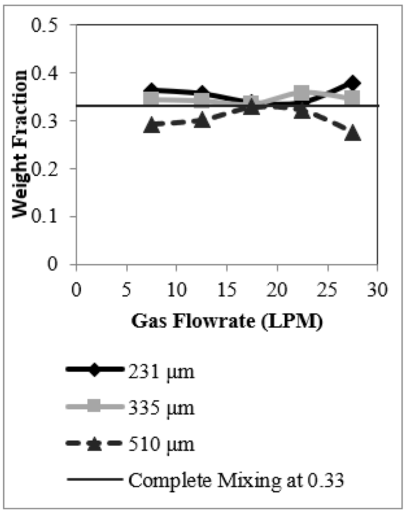
Fig. 3. Observed Mixing Pattern of Solids in the Final Stages of Mixing.
(d) Stage 4, (e) Stage 5, (f) Stage 6 (end of mixing).

III. B. 1. Influence of gas flow rate on mixing

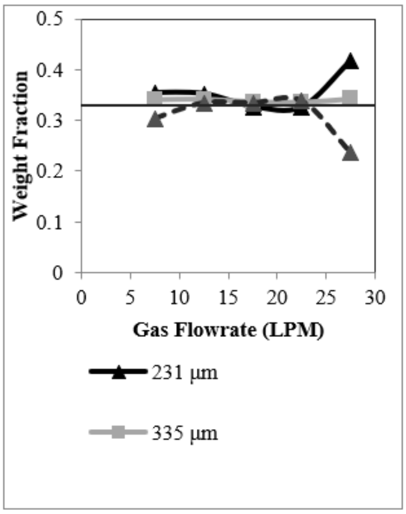
It was observed from the experiments that the solids flow pattern and the solids mixing were dependent on the superficial gas velocity. The circulation movement caused good mixing of the solids in the bed. At low superficial gas velocity, particles obtain energy from gas passing through the emulsion phase (that is just enough to keep particles suspended), in contrast to the bubbling regime in which particles obtain energy from the rising bubbles. In this condition, the particles move randomly in different directions inside the emulsion. This confirms that bubbles in bubbling fluidized beds are the main cause of solids circulation and solid mixing mechanisms change considerably in the absence of bubbles. In this study, the solids circulation velocity and the solids mixing were found to increase with the superficial gas velocity and at higher superficial gas velocity complete mixdeness was also approached faster. Fig. 4 shows the effect of air velocity on mixing, for equal solids concentration.



(a) Bed Height = 1.5 cm



(b) Bed Height = 3.0 cm



(c) Bed Height = 4.5 cm

Fig.4 Weight Fraction of Particles at Different Gas Flow Rates (Solids Ratio = 1:1:1, Mixing Time = 30 min)

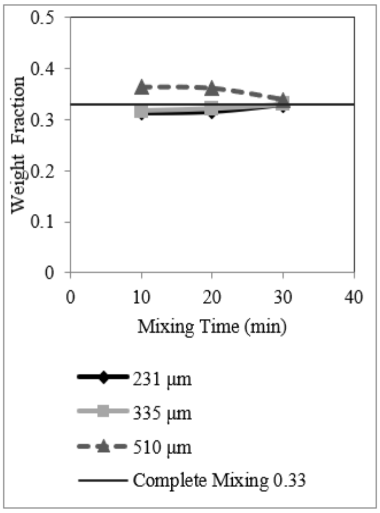
The study on the effect of air velocity shows that mixing of components increase with increasing air velocity until the air velocity reaches an optimum value at which complete mixing can be observed. After this value however the air velocity is increased, the components start to segregate. Mixing is found to depend on the rate of bubbling but this does not necessarily increase with increasing gas flow-rate, so any further increase in air velocity may decrease mixing.

Similar plots were also obtained for solid mixtures having variation in concentrations (for different solids ratio). From the set of experimental data obtained, it can be inferred that at the range of optimum flow rate from 17.5 and 22.5 LPM, most of the solid mixtures can be completely mixed when fluidized with the air.

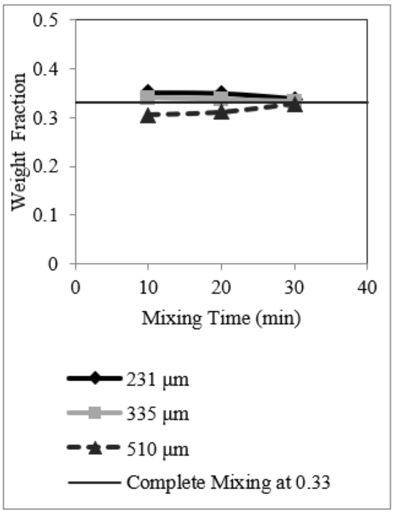
It was also observed that the time required for complete mixing decreases with increasing velocity, i.e. increase in gas velocity results in better mixing even at lower mixing times. From the experiments it was also observed that mixing/slight de mixing occur simultaneously. The overall trend observed was increase in mixing with increasing gas flow rate even at lower mixing times due to the fact that at gas velocities much higher than the U_{mf} of the big particles, better mixing is normally achieved.

III. B. 2. Influence of mixing time on mixing

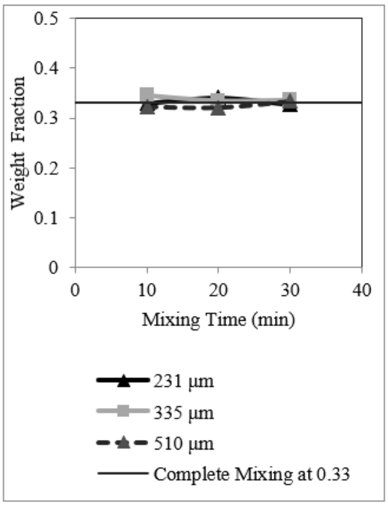
It has been found that mixing time also affects the mixing pattern of solids. It was inferred that mixing efficiency increases with increasing residence time to an optimum time beyond which the particles start segregating.



(a) Bed Height = 1.5 cm



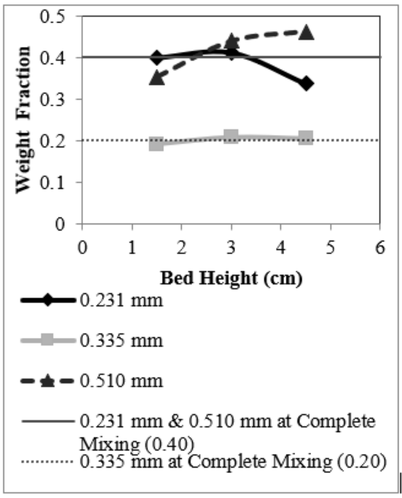
(b) Bed Height = 3.0 cm



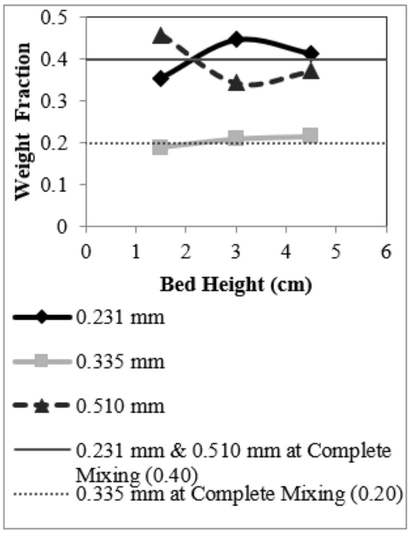
(c) Bed Height = 4.5 cm

Fig.5. Weight Fraction of Particles at Different Mixing Times (Solids Ratio = 1:1:1, Gas Flow Rate = 17.5 LPM

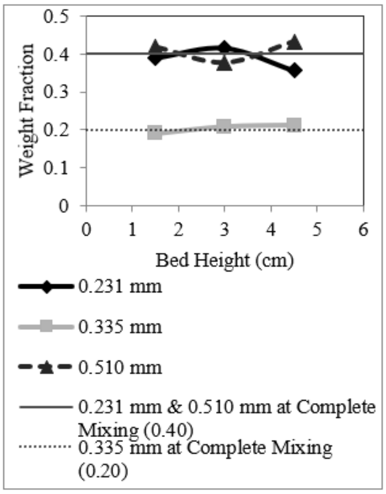
Increase in mixing time beyond the optimum value resulted in partial segregation of particles, which also changed with further increase in time. Hence for the particles chosen and experimental conditions considered, mixing time of 30 minutes give proper mixing for all solids proportions. Increase in mixing time improved mixing even at low gas flow rates, this is shown in the Fig.6.



(a) 10 minutes



(b) 20 minutes

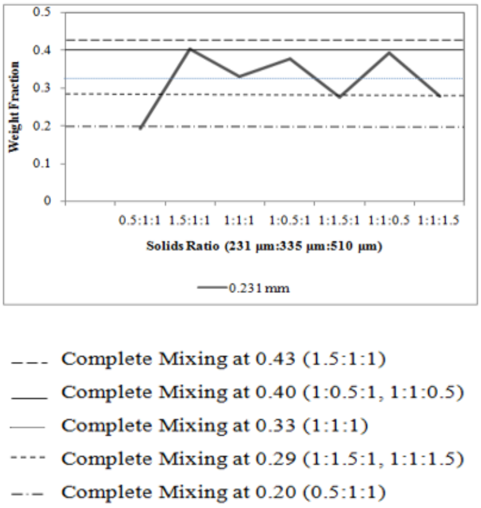


(c) 30 minutes

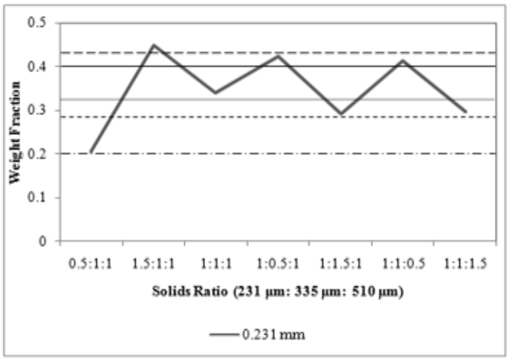
Fig.6 Weight Fraction of Particles at Different Mixing Times (Solids Ratio = 1:0.5:1, Gas Flow Rate = 7.5 LPM, Mixing Time = 30 min)

III.B.3 Influence of solids ratio on mixing

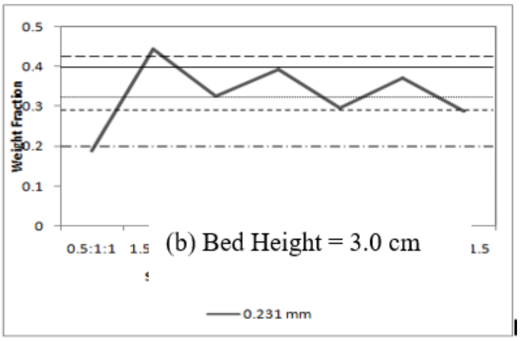
In order to determine the influence of each particle concentration on the mixing dynamics of the fluidized bed, experiments were carried out at different solids ratio for a fixed gas flow rate and mixing time.



(a) Bed Height = 1.5 cm



(b) Bed Height = 3.0 cm



(c) Bed Height = 4.5 cm

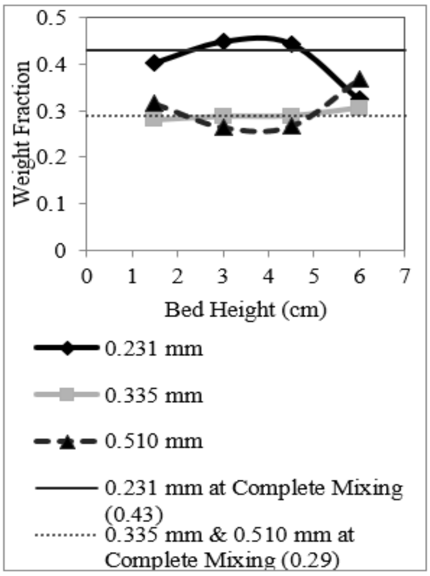
Fig.7. Weight Fraction of 231 µm Particle at Different Solids Ratio (Gas Flow Rate = 22.5 LPM, Mixing Time = 30 min)

The Fig.7 shows the closeness of 231µm particles to the complete mixedness state (shown as straight lines for respective solids ratio) at different solids ratio for an optimum gas flow rate of 22.5 LPM and mixing time of 30 minutes. In the system containing differently sized particles, it was shown that under suitable conditions the particles in a fluidized bed could be made mixable or non-mixable depending on the ratios of particle sizes and densities. Better mixing of the particles was found in the system containing particles with less different densities and closer sizes.

Effectively better mixing was achieved using different solid concentrations than that predicted when the particles are in equal proportion. Mixing improved with increasing concentration of one of the components because of the increase in distribution of particles of that component between the other component (231 µm/335 µm/510 µm) particles. In general, the mixing of the particles is due to bulk solids circulation and this circulation decreases (resulting in segregation) with increasing density for any mixture. Adding more (or less) of any one of the components did not significantly change the mixture average diameter and density, hence the bed behavior predicted with changes in composition did not result in abrupt segregation of components as that would happen in many other systems having wide density or size differences. However it was also found that increase or decrease in concentration of any one of the components resulted in better mixing than that would be obtained for equal solids concentration for the same gas flow rate and mixing time considered.

III. B. 4. Influence of bed height on mixing

The components as they fluidize exhibited different concentration profiles along the height of the bed, for different gas flow rates, mixing time and solids concentration. It was widely observed that comparatively better mixing was achieved at intermediate bed heights. Initial bed height can be changed by either increasing or decreasing the mass of the bed particles. It was observed that change in weight of solid particles did not significantly affect the mixing behavior of the bed. More of a dilute phase of particles was observed at the upper portion of the bed and a dense solid phase was observed at the bottom of the bed.



(a) Solids Ratio = 1.5:1:1

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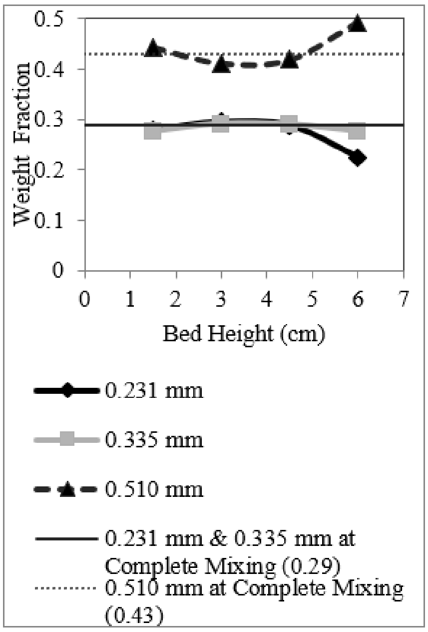
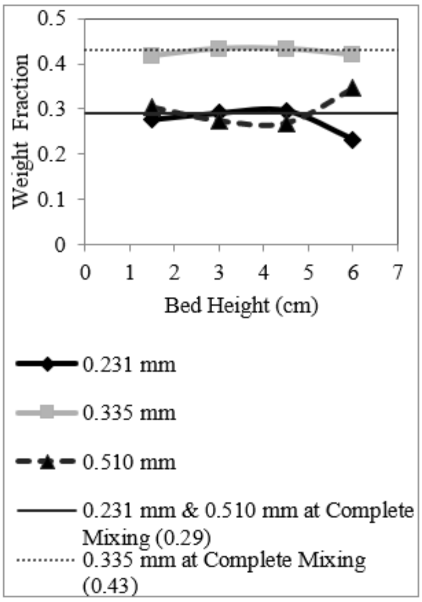


(b) Solids Ratio = 1:1:1.5



(c) Solids Ratio = 1.1.5:1

Fig. 8. Weight Fraction of Particles at Different Bed Heights (Gas Flow Rate = 22.5 LPM, Mixing Time = 30 min)

For all solids concentration better mixing was achieved at intermediate bed heights for the optimum gas flow rate and mixing time. Fig. 8. shows the mixing pattern of particles at different bed heights. It was observed that at the intermediate bed heights from 3 cm to 4.5 cm good mixing was achieved and segregation was observed above and below this range.

IV. CONCLUSION

The mixing pattern of gas fluidized ternary solids was examined at different mixing times and gas flow rates for different solids ratio. Experiments were carried out with ternary mixture of sand particles (of average sizes 231 µm, 335µm and 510µm) fluidized by air and influence of gas flow rates, mixing times, solids ratio and bed height on the mixing pattern were also studied. It was observed that mixing and segregation of components occur simultaneously and better mixing of particles occur at an optimum gas flow rate, mixing time. For the material and experimental conditions considered, good mixing was achieved at all solids ratio and at intermediate bed heights. The results thus obtained could be used for developing a suitable model for the mixing of ternary components in gas-solid fluidized beds.

NOMENCLATURE

Ar	Archimedes number
d_p	Diameter of solid particle
g	Acceleration due to gravity
LPM	Litres Per Minute
$Re_{p,mf}$	Reynolds number of particle at minimum fluidizing condition
U_{mf}	Minimum Fluidization Velocity
ρ_s	Density of solid
ρ_g	Density of gas
φ_s	Shericity of sand
ε	Porosity
ε_{mf}	Voidage at minimum fluidization velocity
M	Viscosity of gas

References

1. Kunii D. and Levenspiel.O, 1991, *'Fluidization Engineering'*, Elsevier, London, ISBN 0-409-90233-0.
2. Navid Mostoufi and Jamal Chaouki, 2001 , 'Local solid mixing in gas–solid fluidized beds', Powder Technology, vol. 114, pp. 23–31.
3. H.R. Norouzia, N. Mostoufia, Z. Mansourpoura, R. Sotudeh-Gharebagha and J.Chaoukib, 2011, *'Characterization of solids mixing patterns in bubbling fluidized Beds'*, Chemical Engineering Research and Design, vol. 89, pp.817–826.
4. B. Formisani and R. Girimonte , 2003, *'Experimental analysis of the fluidization process of binary mixtures of solids'*, Kona No. 21.
5. Jinsen Gao, Jian Chang, Chunxi Lu, and Chunming Xu, 2008, *'Experimental and computational studies on flow behavior of gas–solid fluidized bed with disparately sized binary particles'*, Particuology, vol. 6, pp. 59–71.
6. Abbas H. Sulaymon, Ammar S. Abbas, and Rasha H. Salman, 2010, *'Prediction of equilibrium mixing index and optimum mixing time for three solid materials in fluidized column'*, Al-Khwarizmi Engineering Journal, vol. 6, no. 4, pp. 21 - 30.
7. A. Sahoo and G. K. Roy, 2008, *'Mixing characteristics of irregular binaries in a promoted gas-solid fluidized bed: a mathematical model'*, Canadian Journal of Chemical Engineering, vol. 86, no. 1, pp. 53-61.
8. K. Savolainen and R. Karvinen, 2008, *'Particle mixing in gas-solid bubbling bed'*, Department of Energy and Process Engineering, Tampere University of Technology, Finland.
9. Abbas H. Sulaymon and Rasha Habeb Salman, 2008, *' A quantitative analysis of the mixing of three solids different in density by an air fluidized bed'*, Iraqi Journal of Chemical and Petroleum Engineering, vol.9, no.1, pp. 1-8.

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