EVALUATION OF SOLID-SOLID MIXING IN AN AIR FLUIDIZED BED

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ABSTRACT

Solid mixing in air fluidized system of a binary mixture of the same mean particle size (0.52mm) of salt & sand was investigated experimentally to study the degree of mixedness radially and axially through the bed for different air velocities, mixing time, and for different bed heights. The experimental results were statistically analyzed and compared with the theoretical calculated values.

It is concluded that the value of the degree of mixing will depend upon the system parameters measured by the experiments which are mixing time, bed height, and air velocity.

KEY WORDS: Solids mixing, air fluidized beds, mixing index.

INTRODUCTION

Mixing is the intermingling of two or more dissimilar portions of materials resulting in the attainment of a desired level of uniformity in the final product (1, 2, and 3).

A particulate material can not attain perfect mixing unlike fluid-fluid mixing. The best that can be obtained will be a degree of randomness in which two particles to be mixed may well stay side by side. No amount of mixing will lead to the formation of a uniform mosaic, but only to a condition, where there is an overall uniformity but not point uniformity (4).

Solids mixing in gas fluidized beds is generally caused by bubbles which increase in number and size as the gas velocity increases above the minimum fluidization value(5). It has been observed by Rowe et al (5,6,and 7) that no bubbles appear and, therefore, no particle mixing occurs at gas velocities up to about 1.2 U_{mf} ,and therefore, the rate of mixing depends upon the rate of bubbling. If the gas velocity is increased beyond the minimum fluidization velocity, surface boiling occurs, and as the gas velocity increases further, the surface boiling becomes vigorous. At this stage, if the operation is started with a well-mixed bed of particle, segregation i.e. demixing occurs instead of further mixing. As the gas velocity is increased more and more at about 1.2 to 1.4 U_{mf}, bubbles start appearing from the bottom of the bed which causes random reshuffling of the particles causing mixing. As the gas velocity is further increased, more and more bubbles appear and the bubble diameter also increases. The mixing operation thus may be performed by increasing the gas velocity up to the point of the onset of pneumatic conveying.

Many authors have investigated this phenomenon using conventional mixers. Most of the earlier works reported are qualitative in nature and process development type. Latter workers, in an attempt to specify the performance of their different types of mixers, tried to quantitatively define the extent of homogeneity by the term "Degree of Mixing". As mixing is a statistical phenomenon, the degree of mixing has been tried to be defined as functions of statistical properties such as sample variance, standard deviation, Chi square test, F test etc. (1,8,9,10,11,12,13,14,15,16,17, and18). In the present work, the definition of the degree of mixing given by Nelson and Smith (15) with a slight modification is adopted.

The method of conducting the experiment, sample analysis and particularly, the technique of taking out the spot samples are very simple, safe and practically unbiased.

Theoretical Basis for Evaluating Mixing

The model used here for evaluating mixing (13) is based on the assumption that a perfect mixture is one which is completely random. If further assumes that a comparison of observed and theoretical standard deviations, found by analyzing spot samples, is a satisfactory measure of the extent of blending.

For a binary mixture of particles, the unbiased estimate of the variance found from N spot samples is given by

$$S^2 = \sum_{i=1}^{N} \frac{(x_i - \bar{x})^2}{N-1} \tag{1}$$

$$\bar{x} = \sum_{i=1}^{N} \frac{x_i}{N} \tag{2}$$

For a completely random mixture the theoretical variance, assuming a binomial distribution, is

$$\sigma^2 = \frac{c(1-c)}{n} \tag{3}$$

As two layers of particles, initially separated, become more and more intermixed, the measured variance should approach the theoretical variance for a completely random mixture. Thus a completely blended mixture is one for which

$$S^2/\sigma^2 = 1.0 \tag{4}$$

This work is after Weidenbaum and Bonilla (13) and has been adopted by Nicholson and Smith (15) with slight modification.

Spot concentrations are expressed in terms of weight fractions. Theoretical variance for a binomial distribution is

$$\sigma^2 = c\,(1-c) \tag{5}$$

If particle sizes are not much different from each other, this theoretical variance expression is still acceptable. The degree of mixing defined here is as follows:

$$I_M = \frac{\sigma}{S} \tag{6}$$

$$= \frac{\sqrt{c(1-c)/n}}{\sqrt{\sum \frac{(x_i - \bar{x})^2}{N-1}}} \tag{7}$$

According to this definition, when the particles are completely separated, i.e. at zero time of mixing, S also is equal to σ, so that

$$I_M = 0 \text{ when } t = 0,\ \frac{\sigma}{S} = 1.0 \tag{8}$$

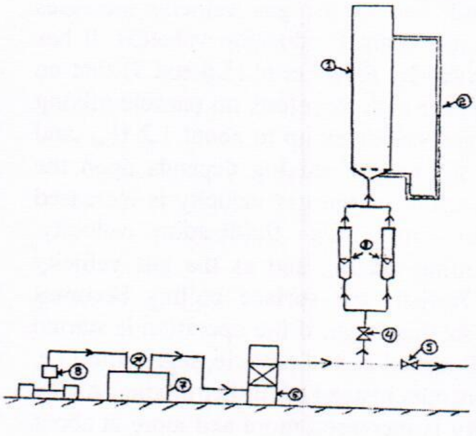
Under certain set of mixing conditions, as time of mixing increases, S decreases indefinitely. So $I_m = \sigma/s$ should increase indefinitely.

Again, mixing occurs due to random shuffling of particles when the bubbles agitate the bed at higher gas flow rates. But as there are differences in physical properties of different particles such as particle size and density along with mixing there should be segregation of particles due to pneumatic classification. Also, the extent of demixing will increase with the increase of gas flow rate. Therefore, as gas flow rate increases mixing and demixing both should increase and at certain point both the phenomena may be equal where dynamic equilibrium may be reached. The degree of mixing I_M at this equilibrium may be called the "equilibrium degree of mixing" I_{MB} and its value should be independent of the time of mixing Kang and Osberg (21).

EXPERIMENTAL WORK

The experimental set-up as shown below mainly consists of:

1- Fluidizing bed column made of standard Q.V.F. glass tube 65 mm diameter and 500 mm in height. The fluidizing bed is supported by an air distributor made of 150 mesh steel screen.
2- Manometer to measure the bed pressure drop.
3- Two air flow calibrated rotameters to measure the input air velocity.
4- Air inlet valve.
5- Solid valve (ON/OFF).
6- Silica gel column to control the inlet air humidity that enters the bed.
7- Air accumulator.
8- Air compressor.



The air is metered and allowed to vent off initially through the bye-pass line fitted with solid valve. When the bye-pass line is open, a definite amount of sand is poured into the fluidizing column from the top. By partially closing and opening the bye-pass line, the sand bed is vibrated till the upper surface of the bed becomes horizontal and reaches maximum compaction. Next the required amount of salt is poured from the top, and the uppermost surface of salt bed is roughly leveled with the help of a long spatula from the top. As before the salt surface is leveled. During this vibration or throbbing of the bed, the bed moves like a piston, and as there is no relative motion of particles, no mixing can take place during this operation. The physical properties of the materials used and experimental conditions are listed in Table 1.

Table 1 Physical properties and experimental conditions

Material	B.S.S. British standards	d_p mm	ρ_s gm/ cm^3	Amount gm.	Concentration of salt in mixture (weight fraction)
Salt	30/40	0.52	2.21	60.10	0.2297
Sand	30/40	0.52	2.72	261.66	-

To start fluidization the bye-pass line is closed and the stop watch is started simultaneously. The air fluidizes the charge inside the column. After desired period of mixing the bye-pass line is opened once again and the bed immediately settles down. By pneumatic vibration the mixed bed is brought to the compaction before mixing.

During fluidization care is taken to prevent channeling or slugging. The fluidization characteristics of the mixture are given in Table 2 and Figure.1. The air distributor is properly designed so as to ensure smooth and uniform fluidization. The humidity of air has been maintained at 20-30% to prevent the effects of static electricity.

Table 2 Fluidization characteristics of the mixture

U, m/hr	ΔP, Kg/m^2
242	90
293	133
326	167
460	281
513	300
563	290
587	280
650	277
800	277
1000	277
1067	277
1300	277

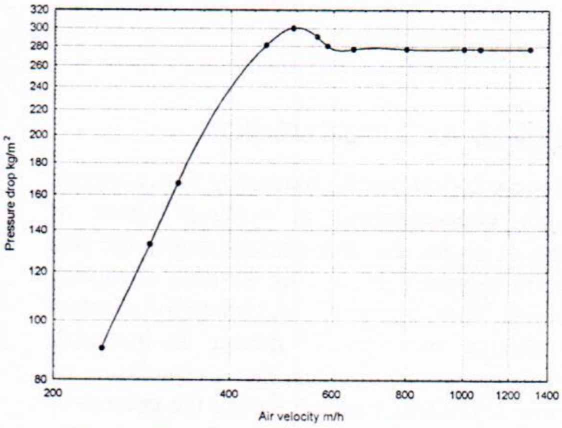


Fig. 1 Experimental pressure drop versus air velocity for the fluidized bed

Sampling Technique

Five spot samples are collected at random from each bed level. The height of the level has been measured from the grid. The sampling probe is connected with the vacuum pump through a flexible rubber tube. At first the vacuum is shut off, the probe is inserted from the top and immersed about 1mm deep into the bed. Then the vacuum is applied and this is just sufficient to arrest the entrapped sample and suspend it. The probe with the entrapped sample is taken out and the sample is released into a small index beaker which has been previously numbered and weighted. After collecting five samples in a level, the cleaning tube is attached to the vacuum line. More suction is applied by adjusting the bye-pass line of the vacuum pump. The cleaning tube is inserted from the top and the tip of the tube is moved over the bed surface like a vacuum cleaner. The cleaning is done very carefully and slowly such that the surface of the bed at any instant is always horizontal. When the specified lower level is reached, samples are taken for the next set in a manner similar to that described earlier.

The samples collected in the index beakers are immediately weighed. The soluble part is repeatedly washed out with hot distilled water. The beakers with the washed materials are kept inside an oven at 105 °C for about two hours. After drying, the beakers are kept in a desiccator for about 3 hours. The second weight is taken to find the weight of insoluble material.

The feed for this set of experiments has been cleaned sand and table salt which are always kept in desiccators.

RESULTS AND DISCUSSION

Figures 2 -7 show the frequency of occurrence of spot concentrations at different times of mixing. It is seen that at the initial stages, the area of the histogram decreases as the time of mixing increases. Then it remains substantially constant even though the time of mixing is increased indefinitely. This indicates that a condition on dynamic equilibrium sets in during the process of mixing.

Plots of bed height vs. longitudinal concentration at different times of mixing are given in Figs. 8-13. It is evident that the average spot sample concentrations of six equidistant levels show a tendency of approaching bulk concentration as the time of mixing increases.

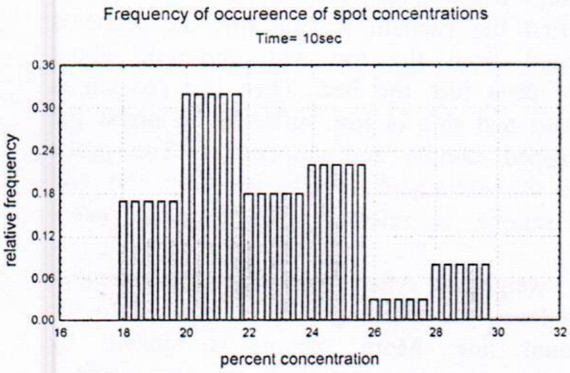


Fig.2 Frequency of occurrence of spot concentrations, t=10 sec.

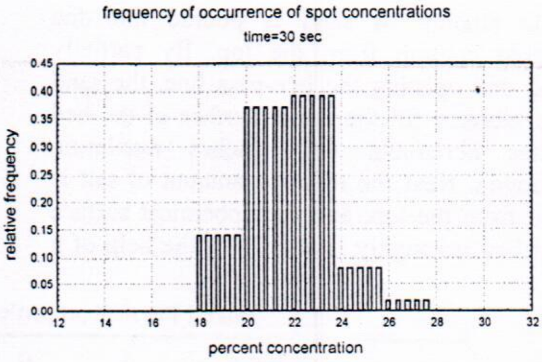


Fig. 3 Frequency of occurrence of concentrations, t=30 sec.

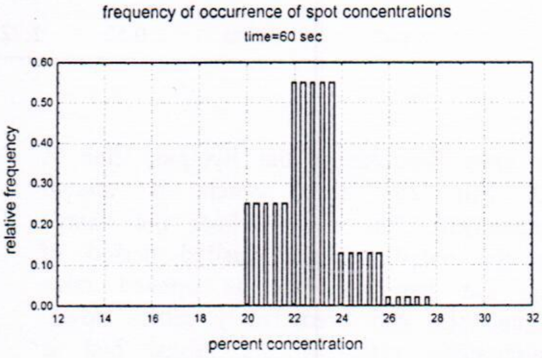


Fig. 4 Frequency of occurrence of spot concentrations, t=60 sec.

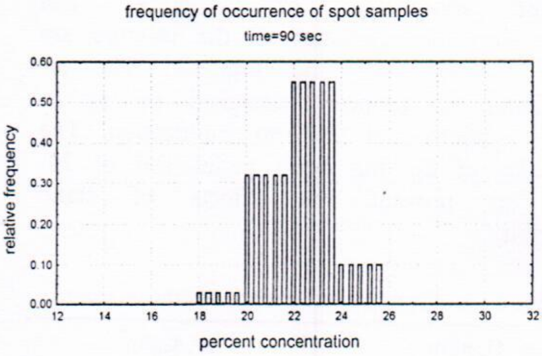


Fig. 5 Frequency of occurrence of spot samples, t=90 sec.

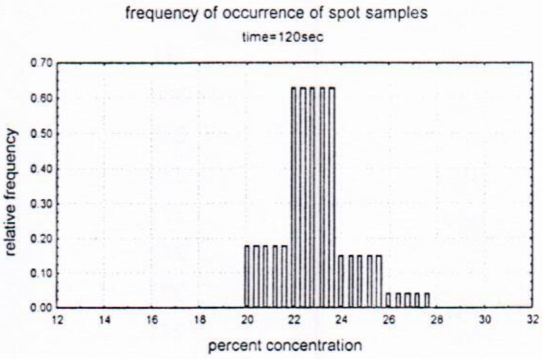


Fig. 6 Frequency of occurrence of spot samples, t= 120sec.

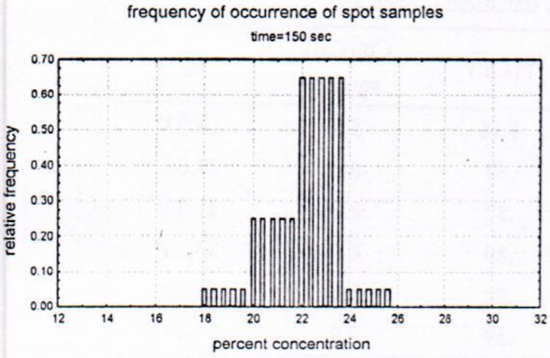


Fig. 7 Frequency of occurrence of spot samples, t= 150 sec.

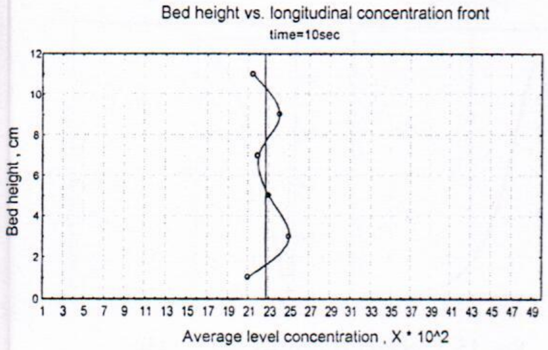


Fig. 8 Bed height vs. longitudinal concentration front, t=10 sec.

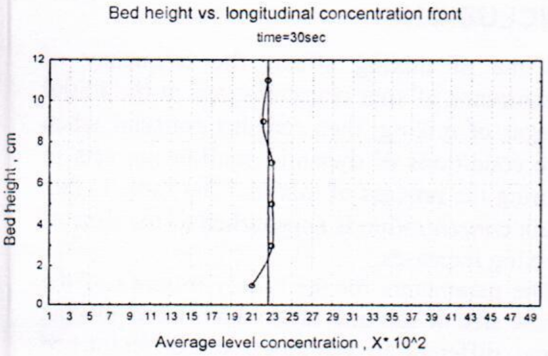


Fig. 9 Bed height vs. longitudinal concentration front, t=30 sec.

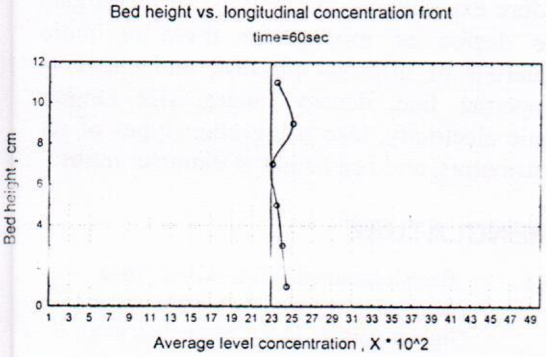


Fig. 10 Bed height vs. longitudinal concentration front, t=60 sec.

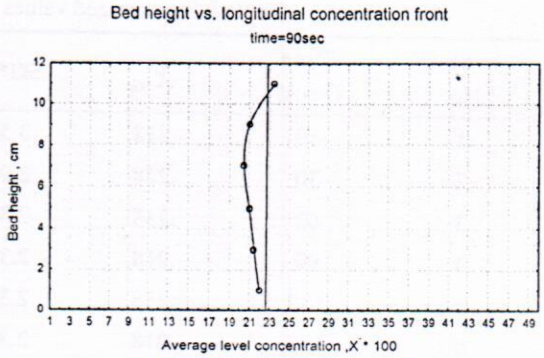


Fig. 11 Bed height vs. longitudinal concentration front, t=90 sec.

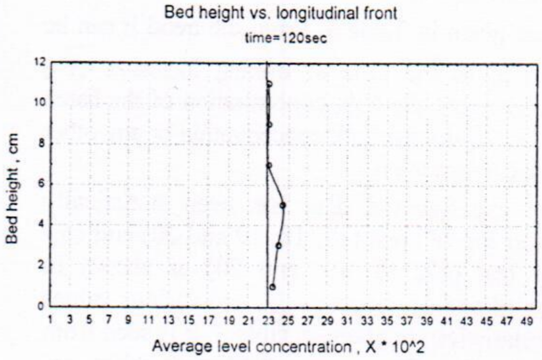


Fig. 12 Bed height vs. longitudinal concentration front, t=120 sec.

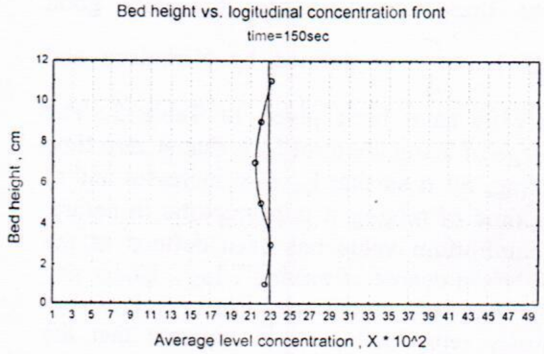


Fig. 13 Bed height vs. longitudinal concentration front,t=150 sec.

The ideal case would be when all the points fall on the bulk concentration line, i.e., the average sample concentration at all levels is the same as the bulk concentration. The variation of standard deviation spot concentration SG is [illegible] operation had been unidirectional i.e., if the demixing phenomenon has not existed, the values [illegible] mixing increased. It is seen from Table 3 that SG variation is less or equal as the time of mixing increases, supporting the hypothesis that dynamic equilibrium is set up between the phenomena of mixing and demixing.

Table 3 Summarized values of various statistical properties

SI No.	Time (Secs)	$\overline{X}_G$	SG*10^2	F(Cal)	Chi(Cal) square	I_M
1	10	.238	3.521	1.16	5.0	14.53
2	30	.228	2.944	.67	6.0	24.00
3	60	.238	2.366	.57	8.0	31.70
4	90	.218	2.366	.89	8.0	33.20
5	120	.238	2.366	.92	8.0	34.92
6	150	.218	2.366	.59	5.0	35.49

The average concentrations of all the 30 samples $\overline{X}_G$ are given in Table 3. From the trend it can be stated that as the time of mixing increases $\overline{X}_G$ fluctuates about the bulk concentration of the batch and never equals the bulk concentration or any other definite concentration.

The experimental data has been statistically analyzed for "F" test (17, 18, 19 and 20) and chi-square test (17, 18, 19, and 20) as shown in figures 14 and 15 respectively, and various values of the statistics are given in table 3. It is seen from the table, that $F_{0.95(5,\ 24)}$ = 2.62 and chi-square values are less than Chi-sq. $_{0.95}$ = 11.07.

Both these tests indicate that very good mixing, $I_M = \frac{\sigma}{S}$ as defined by Nicholson and Smith (10) have been given in Table 3. The advantage of using the term I_M is that at zero time of mixing, S= σ so that I_M also increases and at higher time of mixing it is asymptotic in nature. This equilibrium value has been defined as the "Equilibrium degree of mixing", I_{ME}. Under any definite set of conditions, I_{ME} values are practically reproducible. It is apparent that the value of I_{ME} will depend upon the system parameters measured by the experiments.

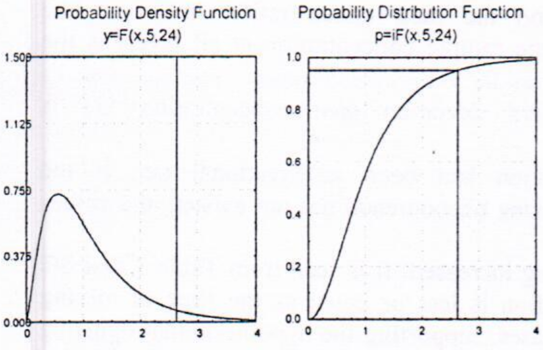


Fig. 14 Probability density function for "F" test.

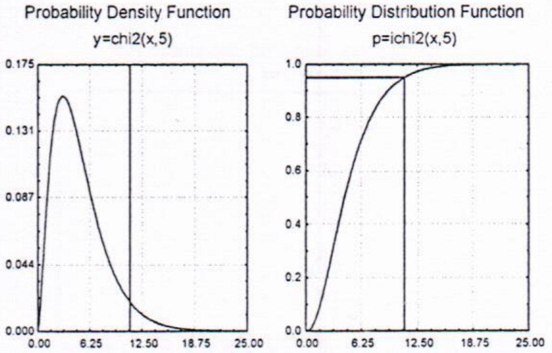


Fig. 15 Probability density function for "chi-square" test.

CONCLUSIONS

1- Time of mixing affects the frequency of occurrence of spot concentrations at the initial stages of mixing, then remains constant when the conditions of dynamic equilibrium sets in during the process of mixing. The same is that bulk concentration is approached as the time of mixing increases.

2- The parameters for the binary mixture of the same size of salt and sand which were, mixing time, different air velocities, and different bed heights had their influence on the value of the degree of mixing.

3- More experiments can be done to investigate the degree of mixing for three or more materials of different physical and chemical properties like, density ranges, size ranges, static electricity, also using other types of air distributors, and bed height to diameter ratios.

NOMENCLATURE

B.S.S.	British standard,B.S.S. 410: (1962)
c	Bulk concentration by weight of the lighter particle in the whole batch of mixture
d_p	Mean particle size diameter, mm
I_M	Degree of mixing

I_{ME}	Equilibrium degree of mixing
N	Total number of spot samples collected through out the bed
n	Number of particles per spot samples
S	Observed standard deviation at any instant
t	Time
U	Air velocity, m/hr
σ	Theoretical standard deviation according to binomial distribution
X	Observed spot sample concentration, by weight, of the lighter particle
$\overline{X}$	Average spot sample concentration by weight
Z	Height of the level measured from the grid,cm.
θ	Time of mixing, sec.
i	Indicates level position
ρ_s	Solid density gm/ cm^3
ΔP	Pressure drop through the fluidized bed, Kg/ m^2

Legend used in Figs. 1-15

G	Fluidization velocity /minimum fluidization velocity 2.8261
H	Height of static bed/column diameter, 2.0
D	Column diameter/average particle diameter,125.0
d	Diameter of heavier particles/diameter of lighter particles,1.0
R	Density of heavier particles/density of lighter particles, 1.2308
C	Bulk concentration (weight fraction of salt), .2297

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