

A Quantitative Analysis of the Mixing of Three Solids Different in Density by an Air Fluidized Bed

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Abstract

Three cohesionless free flowing materials of different density were mixed in an air fluidized bed to study the mixing process by calculating performance of mixing index according to Rose equation (1959) and to study the effect of four variables (air velocity, mixing time, particle size of trace component and concentration of trace component) on the mixing index and as well as on mixing performance.

It was found that mixing index increases with increasing the air velocity, mixing time and concentration of trace component until the optimum value. Mixing index depends on the magnitude of difference in particle size

The first set of experiments (salt then sand then cast iron) give higher mixing index and better performance of mixing than the second set of experiments (sand then salt then cast iron).

Box-Willson method was used to minimize number of experiments and to represent the relationship between the variables.

Keywords: Quantitative analysis, fluidized bed, mixing, solid

Introduction

Mixing is the treatment of two or more components in such away that the individual particles of the different components in the mixture are evenly distributed and lie adjacent to each other within the highest possible probability [1].

Mixing is important and essential component in many operations. Material properties and the quality of the final products are highly dependent on equipment mixing performance [2].

Particles will change their relative positions only when subjected to movement. Once movement begins, the particles may randomize or segregate depending on both

the type of movement imposed on the system and on the physical characteristics of the constituent [3].

There are many different types of mixers are used in the mixing of solids materials and in the present study an air fluidized bed was used.

Gas fluidized beds are successfully applied to different physical and chemical processes, for example solids mixing, solids drying, catalytic oil cracking and coal combustion. It is important for the modeling of processes occurring in fluidized beds to have knowledge about the nature of the fluidized particles, how they move, how, if at all, they make contacting and how segregation of a typical particles takes place [4].

In fluidized beds, particles of different size and / or density are moving to reach other; equilibrium is set up between the competitive

mechanisms of mixing and segregation. This leads to a variation in solid composition over the height of the bed, the flotsam tending to rise and the jetsam tending to sink. The comprehensive study of single and binary component systems has shown that particle movement is caused solely by the bubbles [5].

Some of the previous studies had shown that solid materials could be classified according to Burak classification about role of division of powder. It had been suggested by Burak that particles below 100 μm are nearly always cohesive, particles above 400 μm are generally free-flowing and particles with sizes between 100 and 400 μm may be free-flowing or cohesive [6].

It was found that material pairs could be grouped as “easy” or “difficult” mixtures depending upon the absence of segregation tendency.

“Non-easy” mixtures were produced whenever differences in specific gravity and/or particles size occurred between the two mixture components [7].

Statistical analysis has been a major tool of solids mixing investigations because of the random nature of mixing process. The statistical degrees of mixing are essentially different forms of the mean deviation, standard deviation or variance [8].

Rose [9] proposed an expression to evaluate the degree of mixing:

$$M=1-(\delta/\delta_o) \tag{1}$$

Where:

$$\delta_o = \sqrt{x(x-1)} \tag{2}$$

$$\delta = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} \tag{3}$$

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_n \tag{4}$$

Which, it is the most appropriate to determine the final state of a mixture, this was approved by Yano and Sano when they set up nine expressions for the degree of mixing and they compared the particular definitions using the experimental data.

The mixing degree defined by Rose (Eq. 1) can be applied only when the mixing value scale has been specified. A scale thus specified is proposed and presented in Table 1 [10].

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 [11].

Table 1 proposed scale of mixture quality [10]

Quality of mixture	Boundary value of M
Bad	0.7
Un-satisfactory	0.7 – 0.8
Fairly good	0.8 – 0.9
Good	0.9 – 0.94
Very good	0.94 – 0.96
excellent	> 0.96

Mixing process is usually followed by sampling in order to assess the process. Unlike liquid mixing, which can always produces a homogenous mixture; solids mixing always produce an inhomogeneous mixture.

Therefore, the most important and desirable step is to get samples represent the whole mixture. However, there is always difference between the sample and the mixture.

The aim of this research is to achieve efficient mixing.

Experimental Work

Application of Box-Willson design method

To design the experiments, the operating ranges of variables are:

- Air velocity range from 0.408 to 0.566 m/s and designated as X₁.
- Mixing time range from 1 to 5 minutes, and designated as X₂.
- Particle size of trace component range from 0.4 to 1.09 mm and designated as X₃.
- Concentration of trace component range from 5 to 25% by weight and designated as X₄.

Materials

Sand with particle size of 0.74 mm was used, salt with the same size was used and if it was used as a trace component it’s particle size was 0.4, 0.57, 0.74, 0.915 and 1.09 mm and cast iron which was used always as a trace component in all sets and it’s particle size 0.4, 0.57, 0.74, 0.915 and 1.09 mm.

Each component was close-sieved to give a narrow size distribution. The physical properties of the material are tabulated in Table 2.

Table 2 Physical properties of the materials [12]

Physical properties	Sand	Salt	Cast iron
	Real density, kg/m ³	2530	2100
Shape factor	0.6-0.861	0.63	0.578
Surface properties	Non-cohesive free flowing	Same	Same besides magnetic

Equipment

Equipment consisting mainly of the following parts:

A. Fluidization system:

1. Fluidization column: Experiments were conducted in a 150 mm ID Q.V.F glass column, 900 mm in height and open at the top to the atmosphere.

2. Air distributor Plate: it is covered with wire screen to prevent particles leakage. The distributor was placed firmly between the cylindrical section and the conical section using two flanges equipped with gaskets.

3. Air flow rate measurement: Air is supplied by means of a compressor (type LMF) which is used as a fluidizing gas. Air is fed to a copper coil then to a damping tank to minimize plus fluctuations in flow rate. The air was metered by means of three calibrated rot meters before entering the fluidizing bed system, which were regulated by means of a glob valve for each rot meter. The rot meters were calibrated using wet gas meter device.

4. The pressure drop across the material was measured by using a U-tube manometer filled with water

Drawing samples from the fluidized bed by means of a pipe made from tafflon which is connected to the vacuum. Fig 1 shows the schematic diagram of the experimental setup.

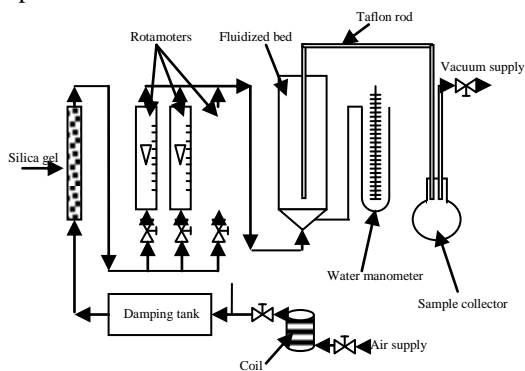


Fig. 1 Schematic diagram of experimental setup

B. Spinning riffler sampler type (Q-Retsch) consisting of the following parts:

1. Receiver (Conical hopper) of dimensions 190 mm upper diameter, 300 mm height diameter, 27 mm outlet diameter and 40 mm outlet channel length.

2. Vibratory feeder which is a rectangular channel of 200 mm length and 50 mm width (with side wedges of 20 mm height). Variable vibration (range of vibration 0 to 100) was used to control flow rate of sample from the hopper.

3. Spinning riffler divider: which is dividing and reducing dry granular material by golden rule method, consisting of small receiving hopper (cylindrical shape of 180cm³ capacity), leading to a dividing channel to eight sample jars. Constant speed of rotation of 100 rpm was used.

- Glass beakers and funnels were used for dissolving the salt and filtering the sand.
- Drying oven (Funditor Ltd. , London and Wembley).
- Sieves.
- Test sieve shaker, (type Endecott) with timer.
- Balance meter with maximum weight 1500 g (type Satorius), accuracy 2 orders.

Procedure

The choice of using the materials was strongly based on the utilized of available and easy analyzable materials. A mixture of sand and salt could be separated by dissolving out the salt and drying sand .For a mixture of cast iron, salt and sand, a magnetic bar was utilized to easy separation of the components both for analysis of the samples and for removing all trace material from the bed.

The total weight of the charged was 2500 g. The procedure in all experiments was basically the same.

- Weighted quantities of the particulate components (according to Box-Wilson design of experiments) were poured into the column carefully to obtain a horizontal interface between the components.
- Air at chosen flow rate was set for a desired time to ensure that mixing was achieved.

After the desired time, the source of air flow rate was shut down and when the bed settled ten samples were taken from ten different positions axially and radially, which are position 1cm above the air distributor and spaced 2 cm axially between them and 1.5 cm radially.

- Each sample was loaded to the spinning riffler sampler where it subdivided into eight jars.
- Each jar was weighted.
- For a mixture of sand and salt: the salt was dissolved using water, the sand was filtered and dried. For a mixture of cast iron with sand and salt the cast iron in each jar was separated magnetically and the remaining components were re-weighted and the weight of cast iron was obtained by subtracted the weight of other components from the total weight.

Results and Discussion

The minimum fluidized velocity of each component was found by preliminary tests which were carried out to find the amount of air which are sufficient to fluidize the considered materials and it was found that:

$$U_{mf \text{ cast iron}} (0.408 \text{ m/s}) > U_{mf \text{ sand}} (0.29 \text{ m/s}) > U_{mf \text{ salt}} (0.283 \text{ m/s})$$

Statistical analysis

Estimation the coefficients of the proposed correlation

Using the experimental data which are fitted by nonlinear regression analysis STATISTICA software, the coefficients of the second order polynomial are estimated

and the second order polynomial was predicated that reasonably correlates the mixing index in terms of controllable variables.

For set (1) the following response function is obtained which correlates the four variables with mixing index:

$$M = -1.6089 + 7.352X_1 + 0.0636X_2 + 1.0399X_3 + 1.552X_4 - 8.441X_1^2 - 0.0291X_2^2 - 0.467X_3^2 - 7.97X_4^2 + 0.4817X_1X_2 - 0.377X_1X_3 - 0.4487X_1X_4 - 0.0692X_2X_3 + 0.09X_2X_4 + 0.8422X_3X_4 \quad (5)$$

For set (2) the following response function is obtained which correlates the four variables with mixing index:

$$M = -1.6 + 7.5968X_1 + 0.04559X_2 + 0.9385X_3 + 1.0967X_4 - 8.68X_1^2 - 0.0277X_2^2 - 0.4379X_3^2 - 7.833X_4^2 + 0.447X_1X_2 - 0.411X_1X_3 + 0.391X_1X_4 - 0.0391X_2X_3 - 0.0685X_2X_4 + 0.706X_3X_4 \quad (6)$$

The optimum conditions of the four variables that correspond to the maximum mixing index for each set of experiments are found they were: air velocity=0.526 m/s, mixing time=4 min, particle size of trace component=0.74mm and concentration of trace component=10 % by weight.

Maximum values of mixing index for set (1) was 0.9554 while for set (2) was 0.9298. According to Table 1 the first set of experiments gives very good mixing and the second set of experiments gives good mixing.

Effect of studied variables on the mixing index

The effect of each variable (air velocity, mixing time, particle size of trace component and concentration of trace component) on the mixing index is found by studying each variable separately from other variables by keeping them constant at their optimum values and this is represented in Fig. 2 to 5. Each figure represents the two sets of experiments.

In Fig. 2, the effect of air velocity on the mixing index is shown, it can be noticed that mixing index is increased with increasing air velocity until the air velocity reaches an optimum value at which the maximum mixing index is reached. After this value however the air velocity is increased, the mixing index is decreased.

Previous work has shown that mixing does not occur until a gas velocity is reached at which the bed is bubbling, and the lowest possible velocity at which this happens is the lower of the two fluidization velocities (U_f). As the gas velocity increases further, so the rate of bubbling increases, and this leads to improve mixing [13].

The volume of gas passing through the system in the form of bubbles is approximately equal to the excess volumetric flow rate and as a bubble rose through the upper layer it took with it a wake composed of material from the lower layer, But it has already been mentioned that segregation is optimized by the presence of small

bubbles in the bed by the use of small excess gas velocity [3].

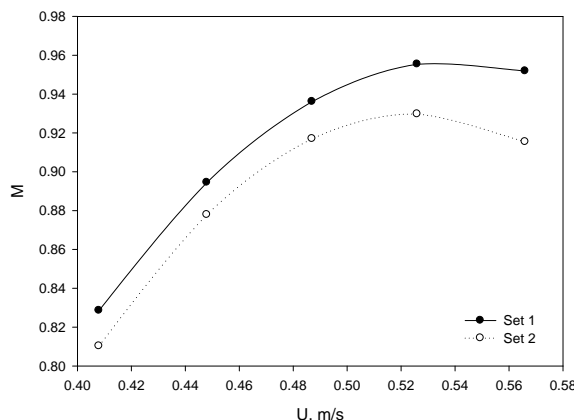


Fig. 2 Effect of air velocity on mixing index

Mixing depends on the rate of bubbling but this does not necessarily increase with increasing gas flow-rate, so any further increasing in air velocity mixing index may be decreased [14].

Fig. 3 shows the effect of mixing time on mixing index, it can be noticed that the behavior of mixing index with mixing time is the same as

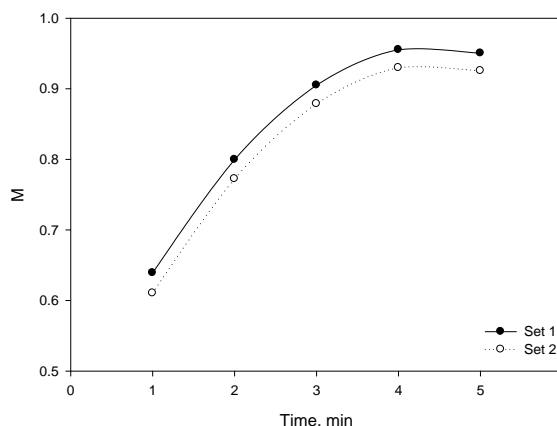


Fig. 3 Effect of mixing time on mixing index

the behavior of mixing index with air velocity and this is in agreement with Fan model (sited in [15]), which states that mixing effect increases with increasing time but as mentioned previously the mixed state represents an intermediate state so that the segregation effect will appear as the mixing time increases.

In Fig. 4 the effect of particle size on mixing index is shown. Particles size difference is by far the most important and most serious cause of segregation [3].

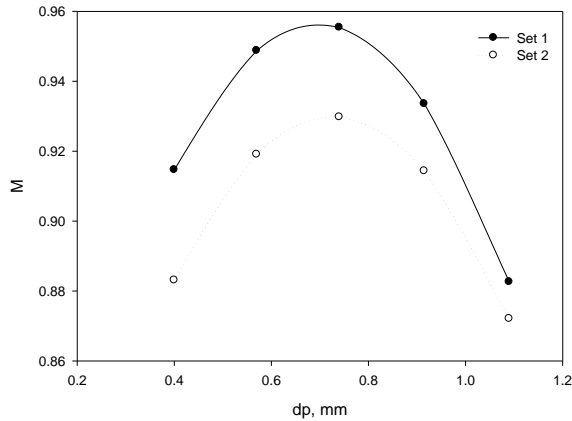


Fig. 4 Effect of particle size on mixing index

According to Ashton and Valentin [7], the easy mixture was produced whenever there is no difference in particle sizes between the two components. Therefore the segregation effect is found when there is a particle sizes difference. “Non-easy” mixtures were produced whenever differences in specific gravity or particle sizes occurred between the two mixture components. The extent of segregation occurring was related to the magnitude of difference in specific gravity or particle sizes.

Fig. 5 shows the effect of concentration of trace component on mixing index. Mixing index increases with increasing the concentration of trace component until it reaches an optimum value after it the demixing increases and mixing index decreases.

The mixing of the particles is due to bulk solids circulation this circulation decreases with increasing density for mixture [14].

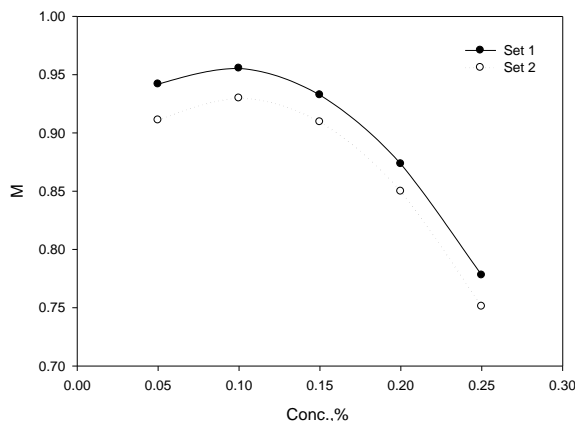


Fig. 5 Effect of concentration of trace component on mixing index

Fig. 6 shows the interaction effect between air velocity and time of mixing on mixing index while keeping the other two variables (particle size and

concentration of trace component) constant at their optimum value. As mentioned before the mixing rate increases with increasing air velocity and time of mixing until the air velocity reaches it’s optimum value, then the rate of mixing will decrease and rate of demixing increase so as for the time of mixing when it continue in increasing the rate of mixing increasing too until the time of mixing reaches it’s optimum value then the segregation rate increases however mixing time increases.

Fig. 7 shows the interaction effects between air velocity and particle size of trace component on the mixing index.

As mentioned before that according to Ashton and Valentin [7] the mixtures can be classified to easy mixtures (same particle sizes of the components) and non-easy mixtures (different particle sizes of the components). It’s now clear that when the particles are of different sizes and /or density, problems of segregation occur and according to Harwood et al. [16] the free-flowing/free-flowing powder pairs had very tendency to segregation due to the difference in particle sizes between the components which were used. According to Fan et al. [15] these differences in size and/or density on rate appears to follow the path of rising very rapidly initially, passing through a maximum, and diminishing to a point of equilibrium.

Fig. 8 shows the interaction effect of mixing time and concentration of trace component (salt or cast iron) on mixing index. This figure indicates that mixing index increases with increasing mixing time and with continuing in mixing process. It reaches an optimum value (where the maximum value of mixing index can be obtained) then the segregation effect will appear as mixing time increases and this behavior agrees with Fan’s model. The interaction effect of concentration of trace component (salt or cast iron) in consideration it can be seen that mixing index increases with increasing concentration of trace component until the concentration reaches it’s optimum value which it was equal to 10 % by weight.

Fig. 9 shows the interaction effect of concentration of trace component and particle size of trace component on mixing index.

As shown in Fig. 9 mixing index increases with increasing concentration of trace component because the increasing of distribution of particles of trace component between the other component (sand or salt or sand-salt) particles (Lacey [17]). According to Poole et al. [18] high ratio of tracer blends are more easily randomized than low ratio ones, and after this optimum value with continuation of mixing process the vibration segregation effect will appear when the larger particles tend to rise to the surface [19]. Therefore, the effect of different partied size on mixing index has a higher effect than the increasing of air velocity.

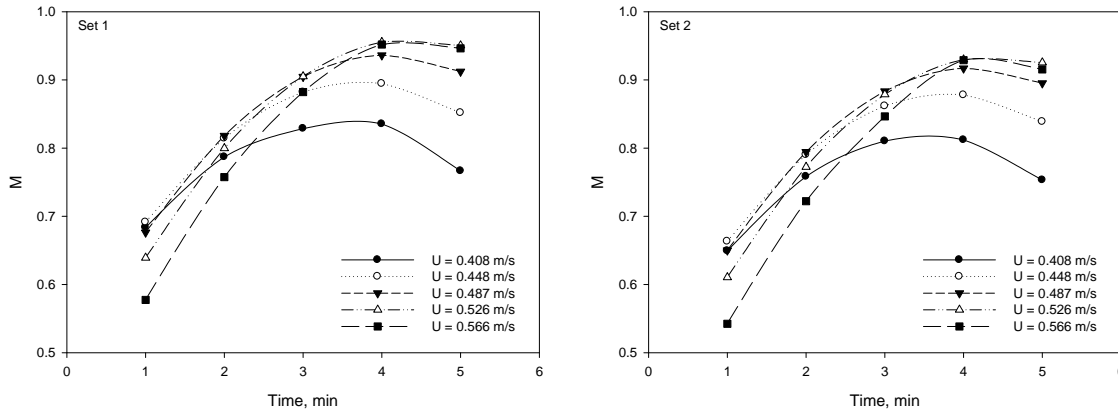


Fig. 6 Interaction effect between air velocity and mixing time on mixing index

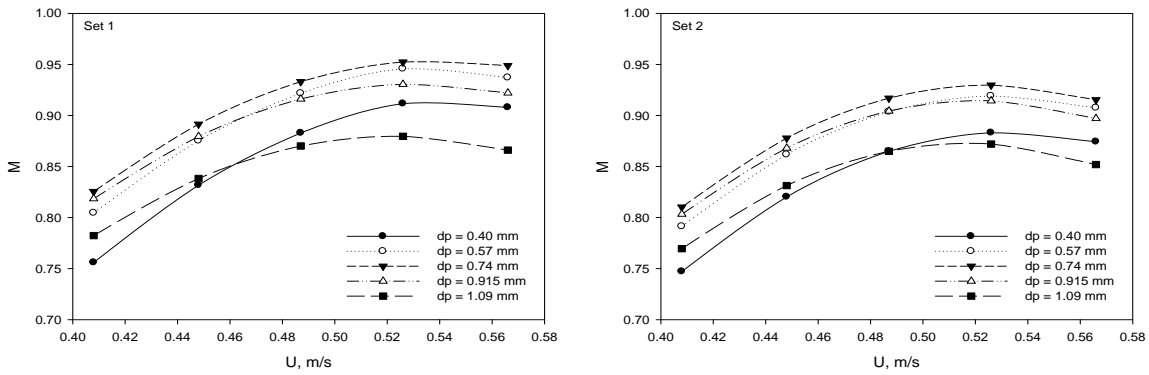


Fig. 7 Interaction effect between air velocity and particle size on mixing index

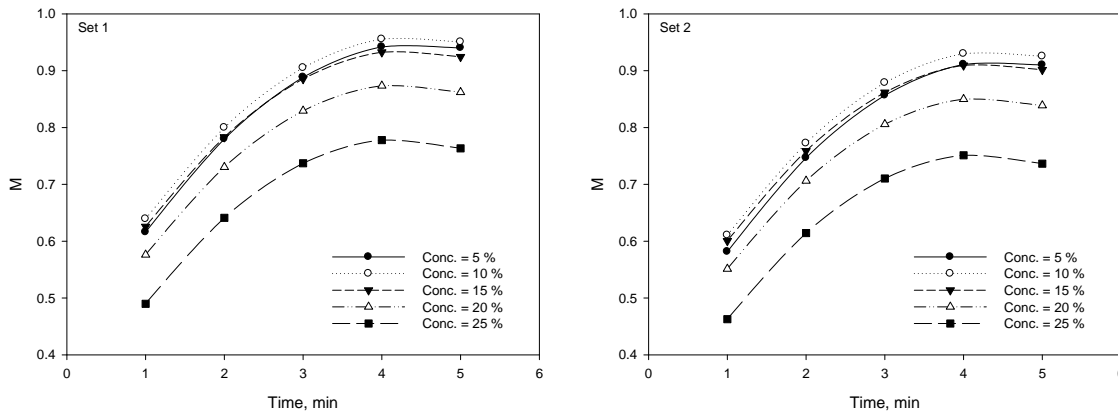


Fig. 8 Interaction effect of mixing time and concentration of trace component on mixing index

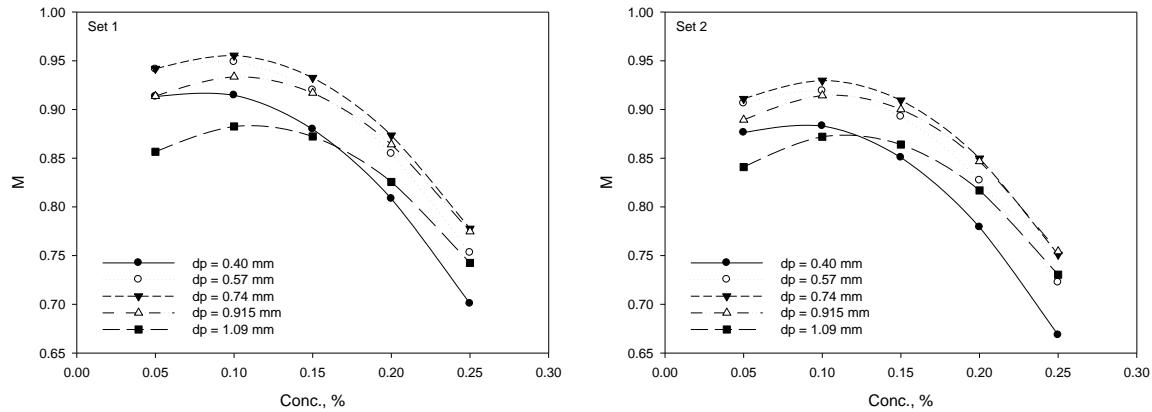


Fig. 9 Interaction effect of concentration and particles size of trace component on mixing index

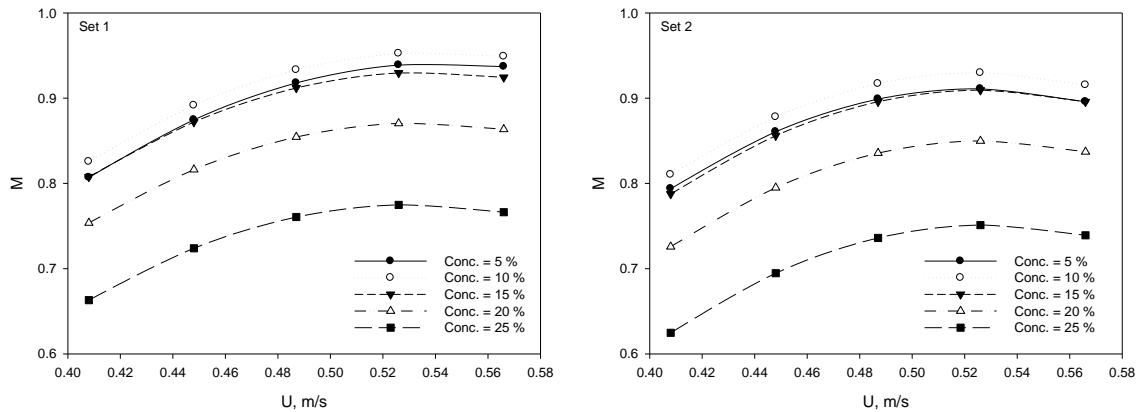


Fig. 10 Interaction effect between air velocity and concentration of trace component on mixing index

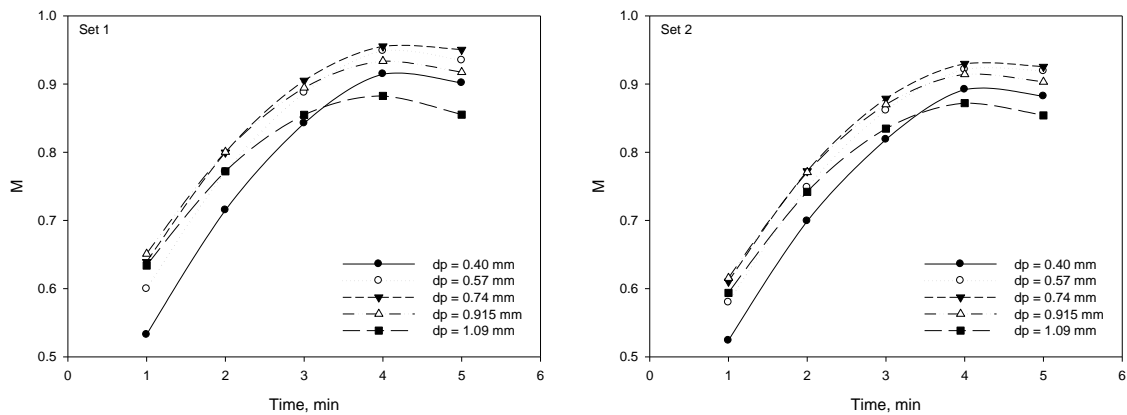


Fig. 11 Interaction effect of mixing time and particle size of trace component on mixing index

Fig. 10 shows the interaction effect of air velocity and concentration of trace component (cast iron) on the mixing index. It can be seen that mixing index increases with increasing air velocity in the same manner as that

shown in Fig. 6, and with increasing concentration of trace component until they reach their optimum values.

Fig. 11 shows the interaction effect of mixing time and particle sizes of trace component on mixing index. It can be noticed that mixing index increases with increasing

mixing time in the same manner as that shown in figure 3, and the particle sizes of trace component (salt or cast iron) which will give the maximum value of mixing index (higher performance of mixing) is equal to 0.74 mm. Examining the data it can be noticed that the presence of a modest sizes difference will tend to accelerate the rate of mixing in comparison with the case of identical particles. The effect of segregation increase and mixing index decrease, and the behavior of particle size of trace component agree with Ashton and Valentin [7].

Conclusions

1. Particle size and density differences are the main cause of segregation which has an appreciable effect in the range used.
2. Mixing index increases with increasing the air velocity, time of mixing and concentration of trace component until they reach their optimum values.
3. Mixing index depends on the magnitude of different particle size so when there is no particle size difference between the main component and the trace component, best mixing will be achieved.
4. Set (1) gives higher mixing index and better performance of mixing than set (2).

Nomenclature

- dp Particle size, mm
 M Mixing index
 n Number of samples
 t Mixing time, min
 U Superficial gas velocity (measured on an empty bed), m/s
 δ Standard deviation
 δo Standard deviation of totally segregated mixture

References

1. Vaizoglu, O., "Assessment of the degree of mix of powder characterization of dispersive and distributive mixing in a single screw extruder", *Tr. J. Physics*, **23**, 94-104 (1999).
2. Alemaskin, K., Zloczower, I. M. and Kaufman, M., "Simulation characterization of dispersive and distributive mixing in a single screw extruder", *Int. Polym. Process*, Department of Macromolecular Science, Case Western Reserve University, Cleveland, Ohio (2002).
3. Harnby, N., Edwards, M. F. and Nienow, A. W., "Mixing in the process industries", Butter Worths, London, (1985).
4. Hartholt, G. P., Hoffman, A. C. and Janssen, L. P., "Visual observation of individual particle behavior in gas and liquid fluidized beds", *Powder Technology*, **88**, 341-345 (1996).
5. Naimer, N. S., Chiba, T. and Nienow, A. W., "Parameter simulation for a solid mixing/segregation model for gas fluidized beds", *Chem. Eng. Sci.*, **37** (7), 1047-1057 (1982).
6. Liyod, P. J. and Yeung, P. C., "Mixing of powders", *Chem. Process Eng.*, **57** (1967).
7. Ashton, M. D. and Valentin, F. H. H., "The mixing of powders and particles in industrial mixers", *Trans. Inst. Chem. Engrs.*, **44**, T166-T188 (1966).
8. Fan, L. T. and Wang, R. H., "On mixing indecies", *Powder Technology*, **11**, 27-32 (1975).
9. Rose, H. E., "A suggested equation relating to the mixing of powders", *Trans. Inst. Chem. Engrs.*, **37**, 47 (1959).
10. Boss, J. and Poland, W. M., "Evaluation of the homogeneity degree of a mixture", *Bulk Solid Handling*, **6** (6), 1207 (1986).
11. Sahoo, A. and Roy, G. K., "Mixing characteristic of homogeneous binary mixture of regular particles in a gas-solid fluidized bed", *Powder Technology*, (2005).
12. Perry, J. H., "Chemical engineer's handbook", 5th edition, McGraw Hill, New York, (1984).
13. Nienow, A. W., Rowe, P., N. and Cheung, L. Y. L., "A quantitative analysis of the mixing of twp segregating powders of different density in a gas-fluidized bed", *Powder Technology*, **20**, 89-97 (1978).
14. Scarlett, B., "Mixing", *Chem. Process Eng.*, 612 (1964).
15. Fan, L. T., Gleves-Arocha, H. H., Walawender, W. P. and Lai, F. S., "A mechanistic kinetic model of the rate of mixing segregating solid particles", *Powder Technology*, **12**, 139-156 (1975).
16. Harwood, C. F., Walanski, K., Luebacke, E. and Swannstrom, C., "The performance of continuous mixes for dry powders", *Powder technology*, **11**, 289-296 (1975).
17. Lacey, P. N., "The mixing of solid particles", *Trans. Inst. Chem. Engrs.* **21**, 53 (1943).
18. Poole, K. P., Taylor, R. F. and Wall, G. P., "Mixing powders to fine scale homogeneity: studies of continuous mixing", *Trans. Inst. Chem. Engrs.*, **43**, T261 (1965).
19. Harnby, N., "A comparison of the performance of industrial solids mixers using segregation materials", *Powder Technology*, **1**, 94-102 (1967).