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Experimental Segregation of Binary Particles Using Gas-Solid Fluidized Bed

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***Abstract*—This study investigates the segregation of dissimilar particles using fluidized bed. A continuous gas-solid fluidized bed with 11 cm inner diameter and 50 cm height is used. Binary particles are Al_2O_3 powder with two different mean diameters of 150, 470 micron. Effect of inlet airflow rate, initial bed height and volumetric ratio of particles are investigated. Homogeneous mixtures of two dissimilar particles start to segregate by increasing the air inlet velocity. Efficiency is reported based on the volumetric ratio of segregated small particles in top section of the bed (flotsam) to the whole. The segregation efficiency increases with increase of inlet airflow for different mixtures and bed heights. It is observed the efficiency is in direct relationship with volume fraction of small particles. Hence, better segregation occurs in flotsam-rich mixtures. Results indicate the initial bed height has negligible effect on the segregation phenomenon.**

***Index Terms*—binary mixture, fluidized bed, gas-solid, particle segregation**

I. Introduction

GAS-solid fluidized beds are widely used in many cases such as chemical, oil, pharmaceutical, biochemical and powder industries. They have become prevalent owing to their many advantages including suitable mixing characteristics and high surface contacting between the two phases [1]. Using monodisperse particles as bed medium is scarce in industry and the bed is usually a mixture of particles differing in size, density and shape. Thus, within a certain range of superficial gas velocity, the particles undergo an imbalance in forces like gravity and drag and tend to segregate [2]. The smaller and lighter particles accumulate at the top and those having a tendency to remain at the bottom section of the bed are called flotsam and jetsam, respectively.

This phenomenon could be either undesirable or beneficial depending on the situation. In cases such as fluidized bed reactors where a chemical reaction takes place and the bed is needed to remain adequately mixed, segregation could be an important issue. On the other hand, this inherent feature can be exploited to design devices like fluidized bed classifiers where particles differing in size and/or density could be separated from each other. In most cases, the complete segregation is unattainable and at least one of the layers (jetsam or flotsam) remains impure during the process. Therefore, this is of great importance to identify the optimum operating condition according to the layer, which is needed to be pure.

Many efforts have been made to understand the segregation mechanism by which occurs and to characterize behavior of different mixtures under a wide range of conditions. Hoffmann and Romp [3] experimentally investigated the segregation phenomenon in a gas-fluidized bed of sand of continuous size distribution at various fluidization velocities. They have indicated that at velocities significantly higher than minimum fluidization velocity of particles, the bed exhibits severe axial non-uniformity in its composition and at lower velocities, the segregation occurs in 'two-layer structure' similar to that found in binary and ideal mixtures. Huilin et al. [4] studied the fluidization behavior of binary mixture differing in size in a gas bubbling fluidized bed experimentally and theoretically. They indicated that the particle size, mass fraction of small particles and gas velocity have considerable impact on the segregation of binary mixture systems. Bosma and Hoffmann [5] investigated the effect of sieve-like baffles on segregation of a binary mixture in a continuous gas-solid fluidized bed. They found out that baffles promote the segregation. They also showed that the baffles increase the purity of the flotsam fraction by reducing the circulation in bed and the purity of the jetsam layer increases by increasing the gas velocity. Palappan and Sai [6] experimentally investigated the effect of density on segregation of binary mixture of solids in a continuous fast-fluidized bed. They also considered the effect of solids feed rate, feed composition and particle size on equilibrium distribution of the flotsam and jetsam. Norouzi et al. [7] investigated numerically the size segregation of binary mixtures in the presence of fines. Their results revealed that addition of fines to the binary mixture leads to the enhancement of segregation due to reduction of inter-particle forces.

This study focuses on finding the effect of parameters on the segregation in gas-solid fluidized bed. For this purpose, a thorough experimental investigation was preformed in a continuous gas-solid fluidized bed of a certain binary mixture to examine the effect of bed composition, initial bed height and gas velocity on the amount of segregation. All the experiments were carried out in conditions where the

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flotsam layer was almost pure so that efficiency could be defined based on the thickness of the segregated flotsam layer.

II. Experimental Setup and Procedure

A. Apparatus

An apparatus of the experimental setup used in this study is drawn in Fig. 1. Experiments were carried out in a Plexiglas fluidized bed column of 11 cm inner diameter and 50 cm height. A cylindrical chamber of 11 cm inner diameter and 15 cm height, made of the same Plexiglas, was attached to the main column to regulate the airflow before entering a distributer. A perforated plate, as a distributer, was mounted between the main column and the chamber in order to feed the air uniformly into the fluidized bed. An air filter was installed at the top of the column to capture outgoing fine particles. Airflow rate was controlled by a valve and measured using a digital flow meter (TESTO-6441 Compressed Air Counter) with an accuracy of 3% of measured value. These flow meters give volume flow rate of air in L/min according to standard conditions (101.3 kPa, 15^{o}C) and the flow rate must be multiplied by a correction factor depending on ambient temperature and pressure of air. A filter was placed on the entering airflow in order to collect dust, moisture and probable oil droplets. Fluidizing gas was provided by a compressed air supply including a compressor and a storage tank.

B. Materials

Table I shows the properties of the solid particles used in this study. All the experiments were performed using Alumina powders (Al_2O_3) as bed mixture and both types belong to Geldart B group. Two types of particles were selected with different colors in order to facilitate the measurements and observation of the segregation phenomenon. Type 1 with diameter of 150 and type 2 with diameter of 470 micron.

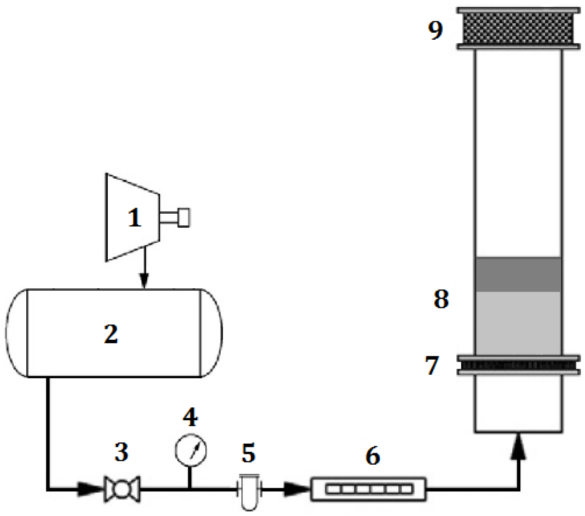

Fig. 1. Schematic diagram of experimental apparatus:
1) Compressor, 2) Tank, 3) Ball valve, 4) Pressure gauge, 5) Filter, 6) Flow meter, 7) Distributer, 8) Plexiglas cylinder, 9) Filter

TABLE I
Properties of Particles

	Type 1 (Flotsam)	Type 2 (Jetsam)
Average Diameter (µm)	150	470
Particle Density (kg/m^3)	3930	3930
Geldart Group	B	B
Color	Brown	White

TABLE II
Details of Parameters in Experiments

Exp. Series No.	Initial Bed Height (cm)	Mixture Composition				Air Velocity Range (m/s)
		Initial Thickness (cm)		Initial Thickness (% vol.)		
		Flotsam	Jetsam	Flotsam	Jetsam	
I	4	2.8	1.2	70	30	0.041~0.122
II		2	2	50	50	0.053~0.173
III		1.2	2.8	30	70	0.071~0.223
IV	6	4.2	1.8	70	30	0.038~0.121
V		3	3	50	50	0.055~0.152
VI		1.8	4.2	30	70	0.073~0.222
VII	9	6.3	2.7	70	30	0.040~0.121
VIII		4.5	4.5	50	50	0.061~0.152
IX		2.7	6.3	30	70	0.077~0.202

C. Experimental procedure

Table II briefly illustrates all the performed test series with parameter details. Experiments are conducted for three different initial bed heights of 4, 6, 9 cm. Three bed compositions flotsam-rich, equally mixed and jetsam-rich for each bed height were used. Air velocity increases from a minimum value in regular intervals to a maximum value in each test series so that the growing trend of segregation intensity can be observed with respect to the gas velocity.

First, the binary particles are uniformly premixed and introduced into the column. The airflow rate is set to the desired value prior of being fed into the column via the distributer. Then the whole mixture is suddenly exposed to the airflow and allowed to attain the steady state condition. It is worthy to mention that in steady state condition, the jetsam particles form a bulk, defluidized layer and thereafter, the segregation profile does not change significantly. In that state, the air supply cut off at once in order to freeze the particles so that the thickness of the pure flotsam layer can be measured. Since it is difficult thoroughly premix the binary mixture, attaining a uniform distribution of particles at the start of each test is almost impossible. As a result, the volume fraction of flotsam particles and therefore segregation rate is not exactly the same across the bed. Thus, the perimeter of the column is divided into 18 equal sections so that the thickness of the segregated layer can be measured every 20^o. The average value of these 18 numbers then is reported as the thickness of the segregated layer in each test series and each air velocity. Dividing this thickness by the initial thickness of

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the smaller particles leads to an approximate efficiency that is a good criterion for measuring the segregation.

Each experiment was carried out several times to ensure the repeatability of tests and improve the accuracy. The maximum deviation is in order of 5%. Table III shows the efficiency and its deviation for the bed height of 6 cm and flotsam-rich composition repeated at least three times.

TABLE III
THE EFFICIENCIES AND DEVIATION
FOR THE BED HEIGHT OF 6 CM AND FLOTSAM-RICH COMPOSITION

U (m/s)	Efficiency #1	Efficiency #2	Efficiency #3	Efficiency (avg.)	Deviation	
0.038	0.00	0.00	0.00	0.00	-0.00	+0.00
0.050	9.64	9.90	12.38	10.64	-1.00	+1.74
0.060	15.00	15.90	18.90	16.60	-1.60	+2.30
0.071	21.31	22.31	22.81	22.14	-0.83	+0.67
0.081	36.19	36.83	37.71	36.91	-0.72	+0.80
0.091	43.81	44.36	48.10	45.42	-1.61	+2.67
0.101	50.12	54.14	57.26	53.84	-3.72	+3.42
0.111	57.38	61.02	62.14	60.18	-2.80	+1.97
0.121	57.14	64.29	65.17	62.20	-5.06	+2.97

III. RESULTS AND DISCUSSION

A. *Effect of air velocity*

Fig. 2 shows three snapshots of the fluidized bed used in this study in three different steps of the segregation process.

Fig. 3 depicts all the results for each test series. Similar trend exists for segregation efficiency in all conditions. Increasing the air velocity exerts bigger upward drag force on particles and improves the segregation efficiency because of higher tendency of flotsam particles to elevate. No change in bed is observed below a certain air velocity, which could be regarded as the minimum segregation velocity for the mixtures. In addition, a maximum value exists for air velocity in which the maximum efficiency occurs. Above this limit, the segregation process begins to be interrupted by mixing effects and the flotsam layer is no longer pure. In this state, the first signs of mixing start to appear just around the border of the flotsam and jetsam layers causing this margin to be unsteady. Increasing the air velocity beyond this value promotes the segregation in lower parts of bed, where jetsam particles accumulate by helping more flotsam particles reach to the top of the bed, but it also increases the mixing in upper parts, causing the flotsam layer to be impure.

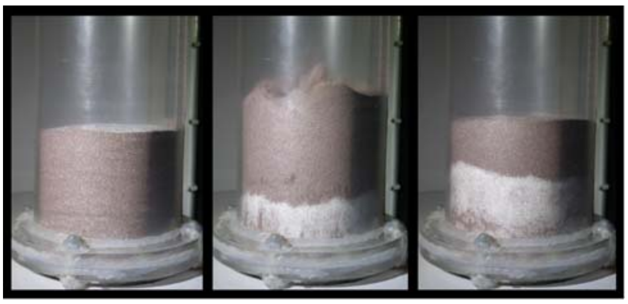
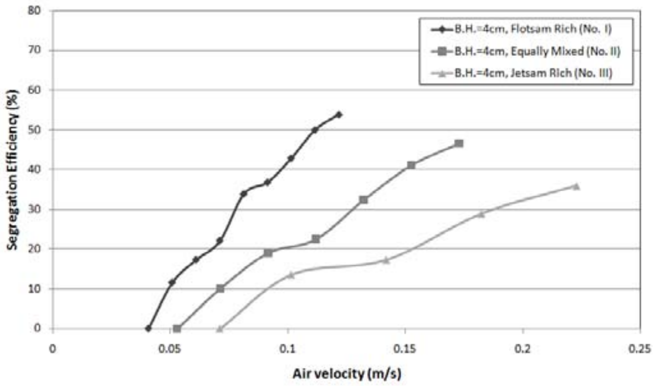


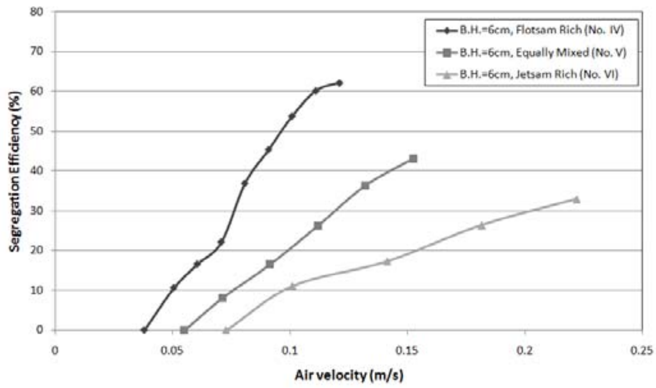
Fig. 2. Snapshots of fluidized bed in before, during and after the segregation process for bed height of 9 cm, flotsam-rich composition and inlet air velocity of 0.10 m/s

B. *Effect of bed composition*

Results indicate the segregation behavior of binary mixtures strongly depends on the bed composition. From the Fig. 3, it could be clearly inferred that the more the volume fraction of flotsam particles, the better the segregation. The interaction between jetsam and flotsam particles can account for this result. In jetsam-rich mixtures, the flotsam particles fill the small voids of air between larger particles. Therefore, they need to overcome the inter-particle forces and pass through a porous media to reach the top of the bed, as the bed is not easily fluidized. On the other hand, in flotsam-rich mixtures, the jetsam particles are in the majority and the whole bed freely starts to fluidize which easily allows larger particles to sink and therefore make the jetsam layer.



(a)



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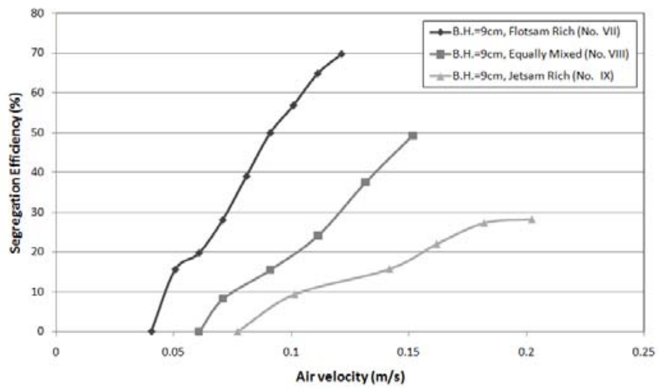

(c)

Fig. 3. Segregation efficiency versus inlet air velocity in different mixture compositions for bed height of a) 4cm, b) 6cm, c) 9cm

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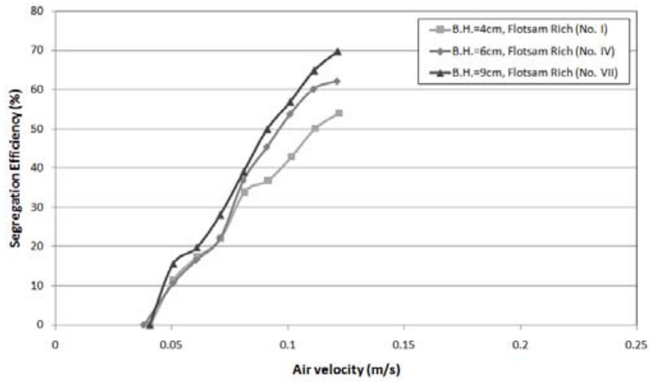
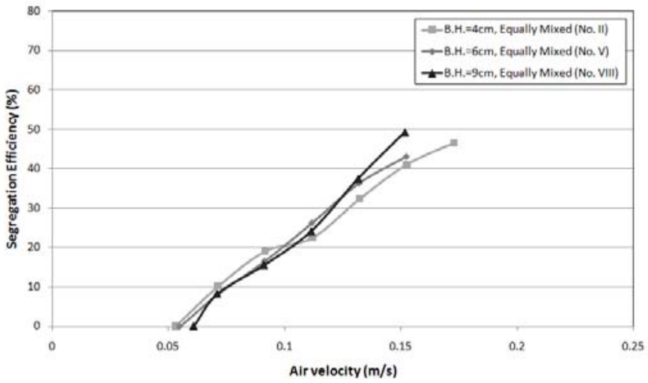
C. *Effect of bed height*

The segregation efficiency for a single composition and three different bed heights is shown in Fig. 4. Results show that unlike the composition, the bed height does not noticeably affect the segregation, especially when jetsam-rich mixtures are fluidized.



(a)



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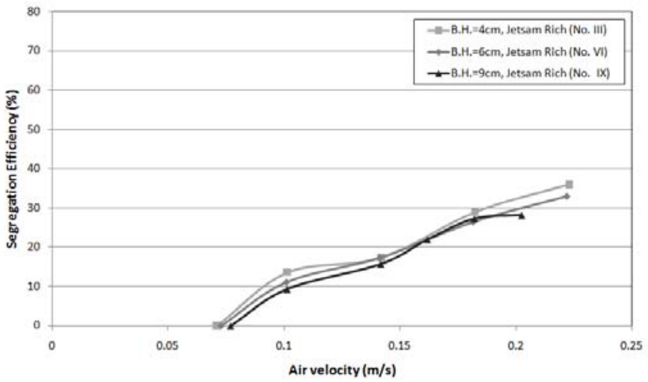

(c)

Fig. 4. Segregation efficiency versus inlet air velocity in different bed heights for mixture compositions of a) Flotsam-rich, b) Equally mixed, c) Jetsam-rich

IV. Conclusion

The segregation behavior was investigated for binary particles of the same density, but differing in size. Effect of air velocity, mixture composition and initial bed height was examined. Continuous increasing in segregation efficiency was observed with increase of the inlet air velocity. A minimum segregation velocity exists for a certain bed height and mixture composition, which only seems to depend on volume fraction of flotsam phase.

Segregation efficiency strongly depends on the composition of mixture. The more the volume fraction of flotsam particles, the easier the segregation takes place. Experimental results indicated the effect of bed height could be neglected, especially for jetsam-rich mixtures. Complete separation of particles did not happen during the tests and the segregation efficiency barely exceeded 60%, although the diameter ratio of particles was about 3. Therefore, an auxiliary method such as shaking seems helpful in order to enhance the segregation process.

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