# Effect of particle size distribution on mixing and segregation in a gas-solid fluidized bed with binary system

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***Abstract*****—***The mixing and segregation characteristics were investigated in gas-solid fluidized beds with binary solid mixture. Bed materials were constituted with binary solids, having different size and density. To investigate the effect of particle size distribution on the mixing characteristics, two other binary solid mixtures were used, which have similar mean particle size and particle density, but their particle size distribution was different to each other. Bed column has ID=0.14 m and H=2.14m. Bed aspect ratio was 3.0. Bed materials were two sets: one of bed materials was the mixture of ilmenite ($d_p$=153 $\mu$m, $\rho_s$=3,860 kg/m$^3$) and coke ($d_p$ =582 $\mu$m, $\rho_s$ =1,762 kg/m$^3$), which has wide size distribution. The other bed materials was the mixture of ceramic beads ($d_p$ =122 $\mu$m, $\rho_s$ =3,800 kg/m$^3$) and plastic beads ($d_p$ =813 $\mu$m, $\rho_s$ =1,500 kg/m$^3$), which has narrow size distribution. Bed composition of ilmenite-coke mixture was determined to 0.7:0.3 by mass ratio. And, bed composition of ceramic beads-plastic beads was 0.75:0.25 by mass ratio. Axial bed pressure drop was measured according to gas velocity. Bed composition was measured according to axial bed height by sampling. Bed pressure drop of ilmenite-coke mixture was maximized above $U_o$=0.15 m/s, and fully fluidization was occurred. However, criterion of mixing to segregation was not found in the axial bed composition according to gas velocity. In the case of ceramicbeads-plastic beads mixture, bed pressure drop was maximized at $U_o$=0.05 m/s, and the criterion of mixing to segregation was found at the same gas velocity.*

***Keywords—gas-solid fluidized bed, segregation, mixing index, takeover velocity.***

## I. INTRODUCTION

The contents of each section may be provided to understand easily about the paper. Particle mixing and segregation characteristics are important in industrial fluidized beds, where particles of wide size distribution or particles of different density are usually handled. Therefore, to analyze gas-solid fluidized beds with binary solids, the degree of these properties should be evaluated. Past studies on particles in a gas fluidized bed have concentrated primarily on the mixing aspect of the phenomenon, notably those by Rowe and Nienow [1] using two separate layers of flotsam and jetsam as a starting mixture. The flotsam is the lighter or smaller particles; which tend to float at the top of the bed, while the jetsam is those heavier or larger particles, which tend to settle to the bottom part of the fluidized bed. These words were coined originally by Rowe et al. [2] and now have become widely accepted terminology. There are two primary objectives for investigating the particle segregation characteristic in gas fluidized beds. In one respect, the fluidized beds are studied to determine the operating conditions required to promote bed mixing and minimize particle segregation. The other objective is to study the optimum conditions under which clean separation can be accomplished between different materials in the bed [3].Takeover velocity is the superficial gas velocity which the gas-solid fluidized bed with binary solids is transformed from segregated to a solid mixing region. Therefore, mixing or segregation in binary solid beds is classified if takeover velocity could be estimated. However, in case of binary solids mixture dealing with wide size distribution has different range that certain or every particle can be fluidized. The mixing phenomena are beneficial for the process which perfect mixing has to be required. In contrast, it could be harsh to separate each particle for separation process. In this study, fluidized beds with binary solids mixture which are different size and density were investigated. Mixing and segregation characteristics were investigated from experimental results, and takeover velocity was estimated. Also, alternative types of binary particles which its size distribution is narrow compared to ilmenite/coke set were chosen and analyzed.

## II. THEORY

There is the empirical correlation for the takeover velocity in gas-solid fluidized beds with binary system [4]:

$$\frac{U_{TO}}{U_{mfS}} = \left(\frac{U_{mfB}}{U_{mfS}}\right)^{1.2} + 0.9\left(\frac{\rho_H}{\rho_L} - 1\right)^{1.1}\left(\frac{d_H}{d_L}\right)^{0.7} - 2.2\sqrt{\bar{x}}\left(1 - e^{-\frac{H}{D}}\right)^{1.4} \quad (1)$$

where $U_{mfB}$ and $U_{mfS}$ are the bigger and smaller minimum fluidization velocities, respectively; $\rho_H$ and $\rho_L$ are the particle densities of the denser and less dense particle, respectively; $d_H$ and $d_L$ are the particle size of the denser and less dense particle, respectively; $\bar{x}$ is the mass fraction of the denser particles in the whole bed; H and D are the height and diameter of the bed; $U_{TO}$ is the takeover velocity at which mixing takes over from segregation. In general, $U_{TO} > U_{cf}$. Mixing index with calculated $U_{TO}$ suggested by Rowe and Nienow [5] is as follows:

$$M_I = \frac{x}{\bar{x}} = (1 + e^{-Z})^{-1} \quad (2)$$

Where,

$$Z = \frac{U - U_{TO}}{U - U_{mf,S}} e^{U/U_{TO}} \quad (3)$$

mixing index is maximum at $U_{TO}$, and MI=0.5. Brereton and Grace [6] defined the solid mixing index as the following Eqs. (4)-(8): segregation index:

$$\gamma = \frac{\sigma}{\sigma_{fs}} \quad (4)$$

where,

$$\sigma = \sqrt{\frac{1}{N}\sum x_i - \bar{x}} \quad (5)$$

$$\bar{x} = \frac{1}{N}\sum x_i \quad (6)$$

$$\sigma_{fs}\sqrt{\bar{x}(1 - \bar{x})} \quad (7)$$

$$M_I = 1 - \gamma \quad (8)$$

## III. EXPERIMENTAL

Fig.1 shows schematic diagram of experimental setup. The dimension of column was 0.14 m of inner diameter and 2.4 m of height with cylindrical acrylic column. The distributor to make uniform gas distribution was used bubble cap distributor. The orifice diameter is 1.4 mm with 76 holes. Pressure taps were installed horizontally at 0.05 m intervals to a height of 0.55 m, and then at 0.1 m intervals to 2.35 m, starting at 0.05 m above the gas distributor. The pressure drop across the bed was measured by a differential pressure transducer, connected to pressure taps, located axially. Transmitter signals were processed by a personal computer at a sampling time of 10 ms for 5000 data. To verify the entire composition of the bed, sampling ports were installed 0.1 m intervals to 0.45 m from 0.05 m above the gas distributor. Each sampling tube is 8 mm of inner diameter and 0.25 m long. All experiments were treated at steady state.

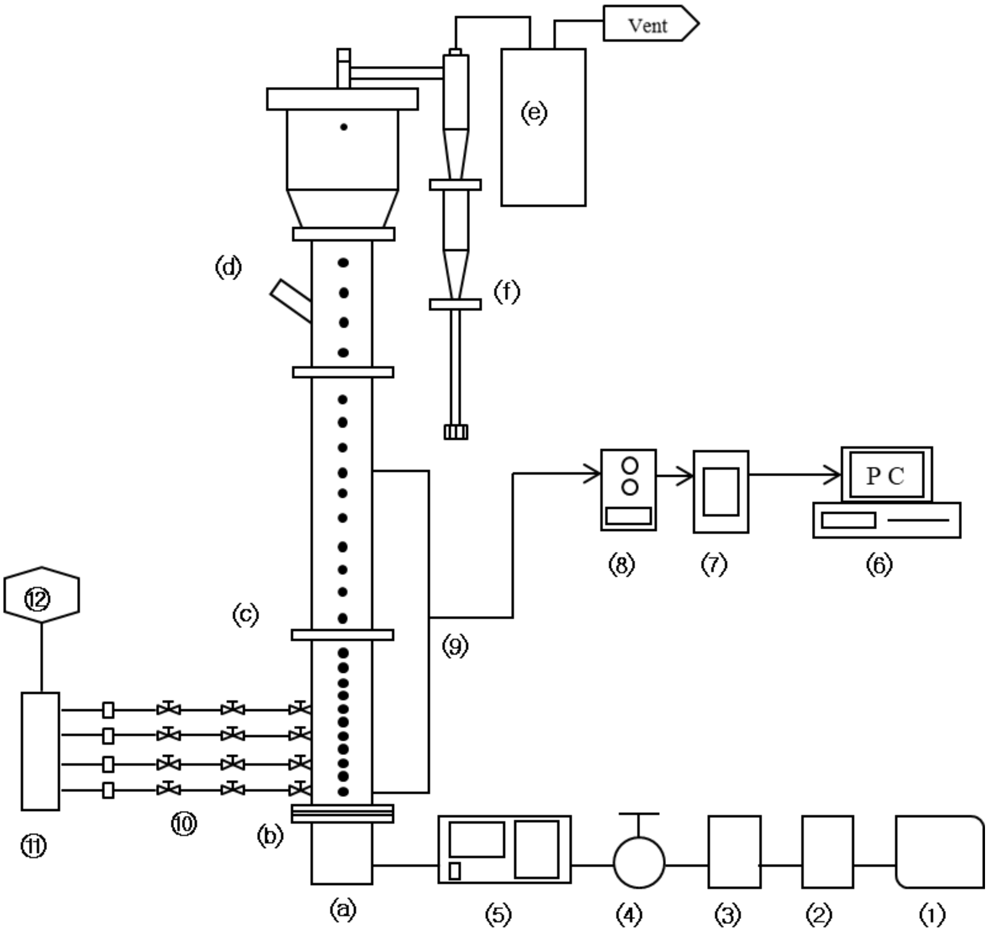


**FIG. 1. Schematic diagram of experimental apparatus: (1) Compressor; (2) Air dryer; (3) Air filter; (4) Regulator; (5) MFC; (6) Computer; (7) A/D converter; (8) Pressure transducer; (9) Pressure line; (10) Sampling line; (11) Vacuum chamber; (12) Vacuum pump; (a) Plenum chamber; (b) Distributor; (c) Main column; (d) Particle inlet; (e) Bag filter; (f) Cyclone.**

Fig. 2 shows particle size distributions of two binary mixtures used in experiments. The bed materials in this study are Ilmenite/coke and Ceramic beads/ Plastic beads with volumetric ratio of 0.5:0.5. All bed components are Geldart B particles. Physical properties ofthese solids were indicated in table 1. The Ilmenite/Coke set has wide size distribution and the set of Ceramic beads/Plastic beads has relative narrow size distribution.

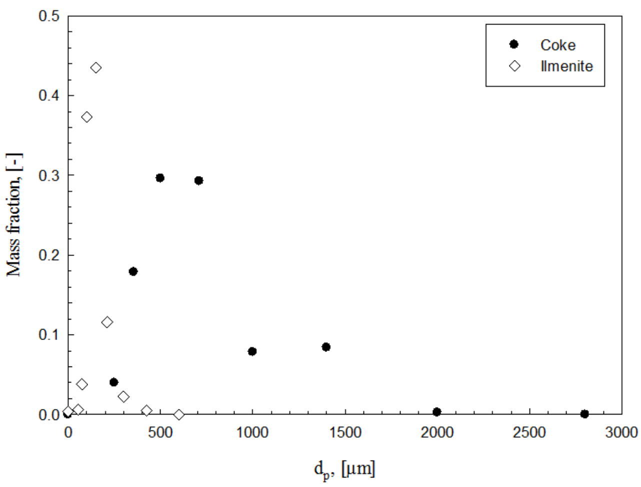


**FIG.2(a). Particle size distribution of ilmenite-coke mixture**

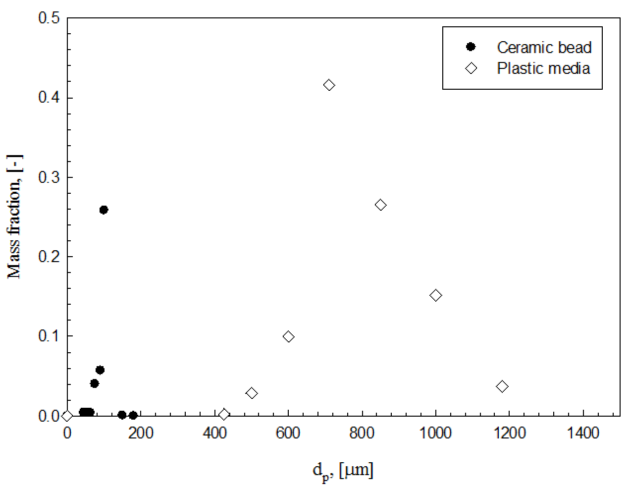


**FIG. 2(b). Particle size distribution of ceramic beads-plastic beads mixture**

**TABLE 1**
**MATERIAL PROPERTIES OF PARTICLES USED IN EXPERIMENTS.**

| | Ilmenite | Coke | Ceramic bead | Plastic beads |
|---|---|---|---|---|
| $d_p$ (μm) | 153 | 582 | 122 | 813 |
| $\rho_s$ (kg/m$^3$) | 3,860 | 1,762 | 3,800 | 1,500 |
| $U_{mf}$ (m/s) | 0.026 | 0.3 | 0.019 | 0.28 |

Analysis of axial bed composition is essential to investigate mixing or segregation characteristics in the beds. First, particle mixture in the beds was sampled from sampling port installed on the side of columns. Second, coke in the mixture was combusted. Finally, weight differential was measured, and composition of binary mixture was determined. Fig. 3 shows the result of thermogravimetric analysis of binary mixtures. The weight of ilmenite was rarely changed according to temperature. Coke was perfectly combusted at 760oC. Therefore, binary mixture of ilmenite and coke was combusted at 800° C, and total operating time was 2 hours.

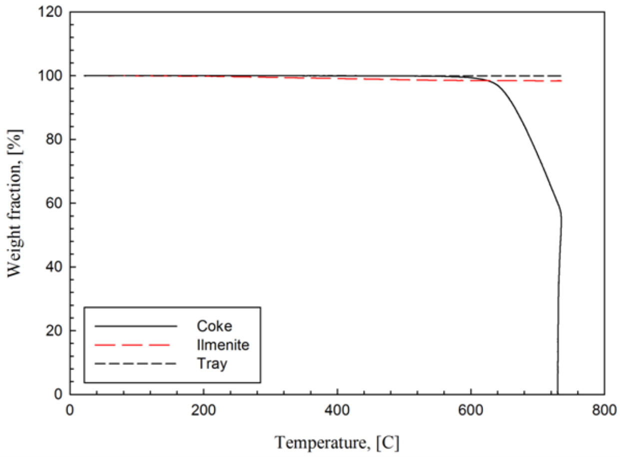


**FIG.3. THERMOGRAVIMETRIC ANALYSIS OF ILMENITE-COKE MIXTURE**

## IV. RESULTS AND DISCUSSION

Fig. 4 shows the axial pressure drop of binary mixture of ilmenite and coke (mass ratio 7:3) in each operating superficial gas velocities. The gradient of bed pressure drop in the bottom of beds below h=0.2 m was rarely differed according to superficial gas velocity. However, in the top of beds above h=0.2 m, the gradient of pressure drop was decreased according to superficial gas velocity, because the height of bed surface was increased with increasing of superficial gas velocity.

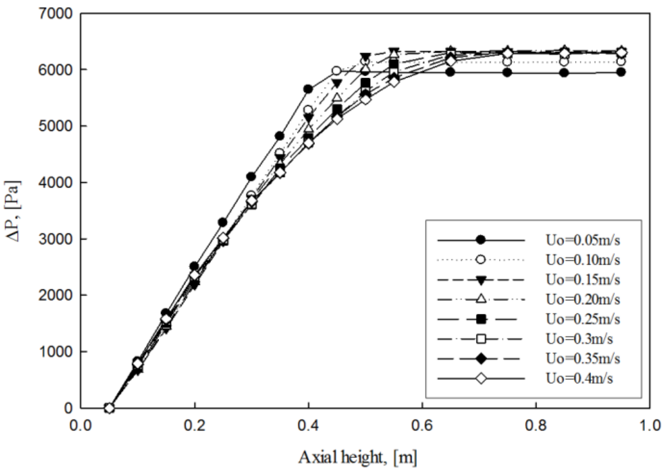


**FIG.4. AXIAL PRESSURE DROPS OF ILMENITE-COKE MIXTURE**

Fig. 5 shows the total bed pressure drop according to superficial gas velocity. In the figure, axial pressure drop was increased steadily according to superficial gas velocity up to Uo=0.05 m/s. Actually, fixed bed condition was maintained below Uo=0.05 m/s. When superficial gas velocity was in the range of Uo=0.05m/s to Uo=0.15 m/s, axial bed pressure drop was decreased slightly, and increased again. This is the region of partial fluidized beds, some particles were partially fluidized and other particles were remained in fixed bed. More increasing of superficial gas velocity above Uo=0.15 m/s, axial pressure drop was maximized, and no more increased according to gas velocity. From this result, complete fluidizing velocity of binary solid mixture of ilmenite and coke was found, that was Uo=0.15 m/s.

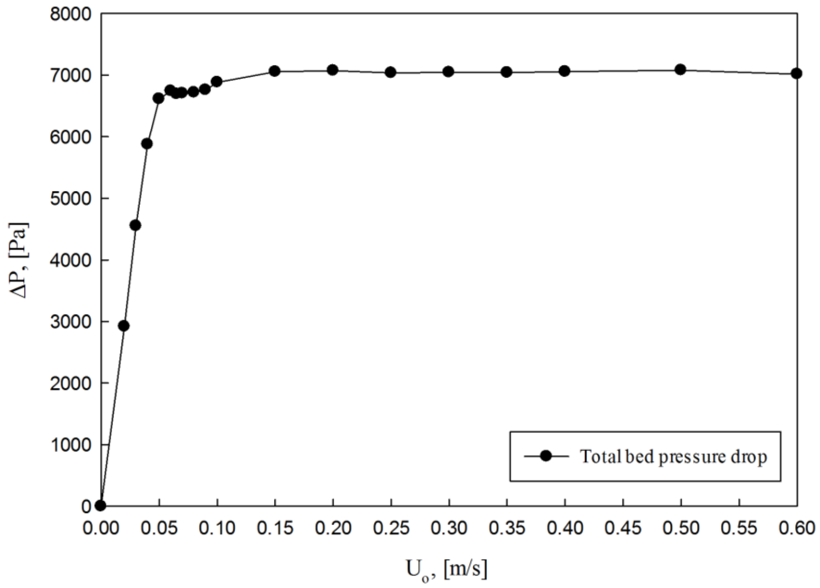


**FIG.5. TOTAL BED PRESSURE DROP OF ILMENITE-COKE MIXTURE ACCORDING TO SUPERFICIAL GAS VELOCITY**

Fig. 6 shows the mass fraction of ilmenite in each superficial gas velocity according to axial bed height. Axial mass fraction of ilmenite was measured in the range from Uo=0.05 m/s, minimum fluidizing velocity of binary mixture or ilmenite and coke, to Uo=0.33 m/s, takeover velocity, which was takeover velocity calculated by Eq. (1). All of the result was not significantly differed to 0.7 of mass ratio, which is the average mass fraction of ilmenite in the beds.

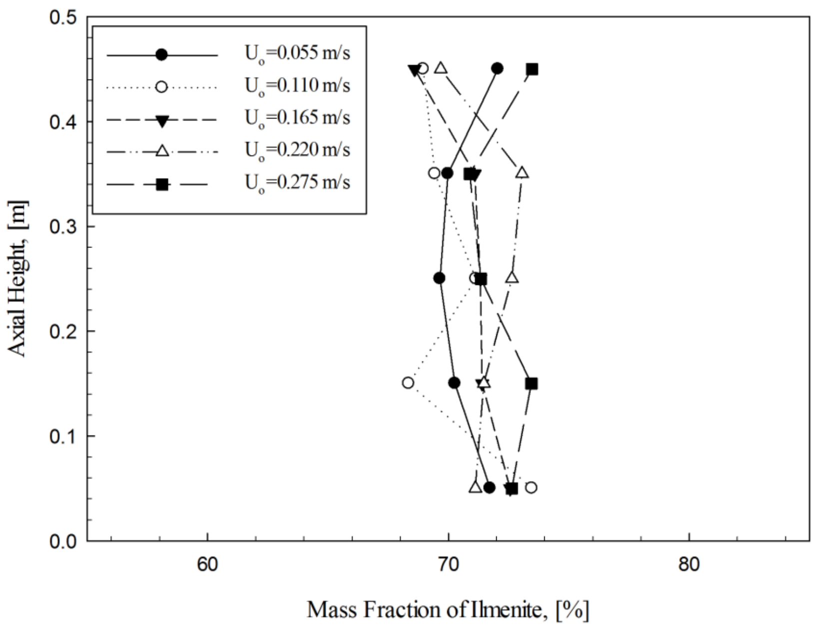


**FIG.3. AXIAL MASS FRACTION OF ILMENITE**

Fig. 7 shows mixing index calculated from axial mass fraction of ilmenite according to superficial gas velocity using Eq. (8). There were no significant tendency according to superficial gas velocity, and shown mixing index near to perfect mixing in entire gas velocity range. This result caused by very wide size distribution of two particles. Therefore, ilmenite and coke were partially fluidized at same superficial gas velocity, and they were not separated into jetsam and clearly.

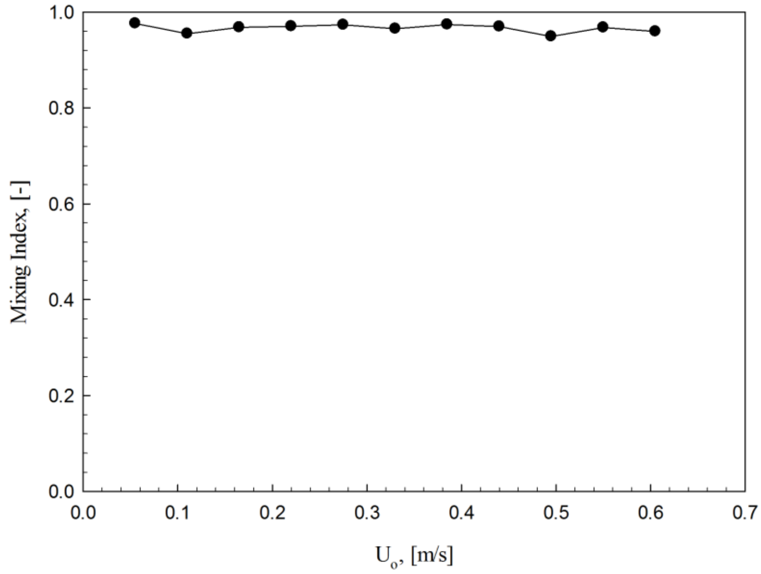


**FIG.7. VARIATION OF MIXING INDEX OF ILMENITE-COKE MIXTURE BED WITH GAS VELOCITY**

Fig. 8 shows axial pressure drop of alternated particle mixtures containing ceramic beads and plastic beads with narrow size distributions, which have similar particle density and average particle size of ilmenite and coke, respectively, according to axial bed height in each superficial gas velocities. Unlikely to ilmenite-coke mixture, in low gas velocity above Uo=0.02 m/s, gradient of pressure in the bottom of the bed was lower than in the top of the bed. Increasing gas velocity above Uo=0.02 m/s, gradient of pressure drop in the top of beds was decreased according to superficial gas velocity. Above Uo=0.05 m/s, gradient of pressure drop was uniform in entire beds.

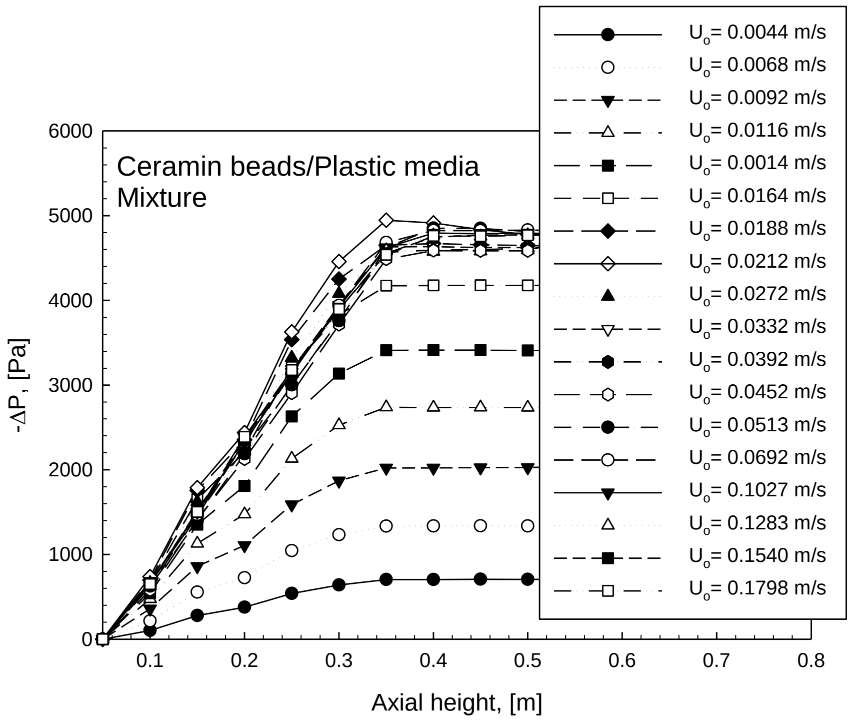


**FIG.8. AXIAL PRESSURE DROPS OF CERAMIC BEADS-PLASTIC BEADS MIXTURE**

Fig. 9 shows total bed pressure drop of ceramic beads-plastic plastic beads mixture. Comparing to total bed pressure drop in Fig. 9, gradient of pressure drop in the top of bed was decreased from Uo=0.02 m/s, which was minimum fluidizing velocity of ceramic beads-plastic beads mixture. Above Uo=0.05 m/s, in the complete fluidizing area, gradient was same in entire beds. From these results, flow regime in the bed could be classified to fixed, partial fluidized, and complete fluidized bed.

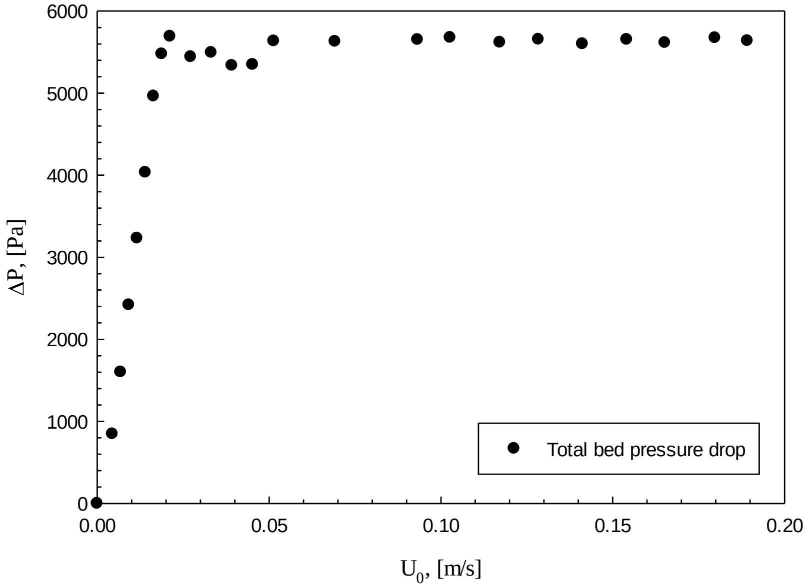


**FIG.9. TOTAL BED PRESSURE DROP OF CERAMIC BEADS-PLASTIC BEADS MIXTURE**

Fig. 10 shows the result of axial sampling experiments to ceramic beads-plastic media mixture. As different from ilmenite-coke mixture shown in Fig. 6, there was significant difference in the axial bed composition. Under Uo=0.057 m/s, mass fraction of ceramic beads in the bottom of bed was lower than that of the top of bed. Above Uo=0.057 m/s, mass fraction of ceramic beads was uniform in entire bed.

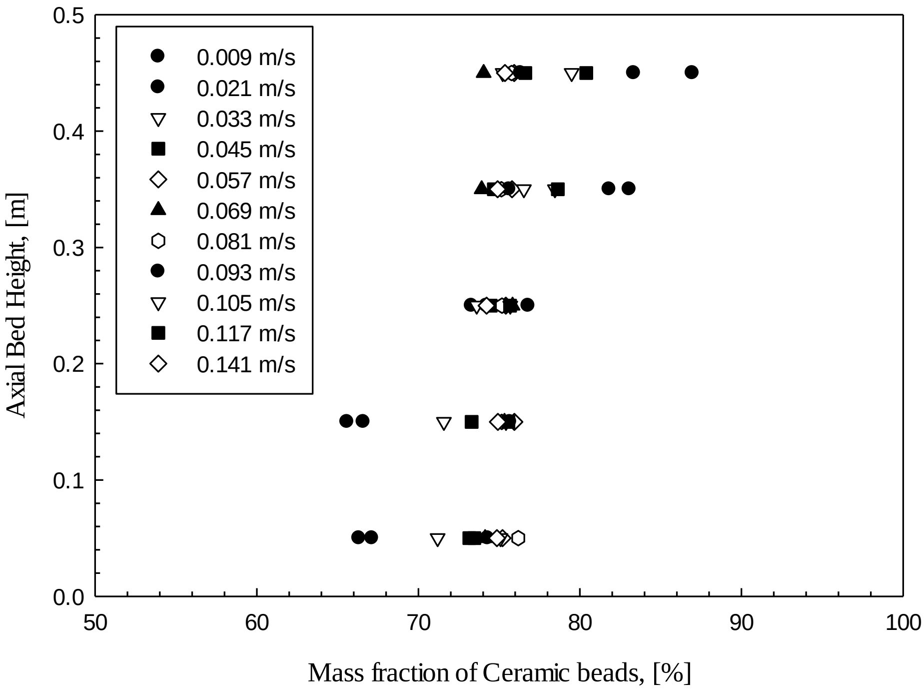


**FIG.10. AXIAL MASS FRACTION OF CERAMIC BEADS**

Fig. 11 shows mixing index calculated from the results in Fig. 10 according to superficial gas velocity. Mixing index was increased according to superficial gas velocity under Uo=0.057 m/s, and maximized at Uo=0.057 m/s. Thesis results indicate that there were the takeover velocity in the ceramic beads-plastic beads mixture, unlike to ilmenite-coke mixture.

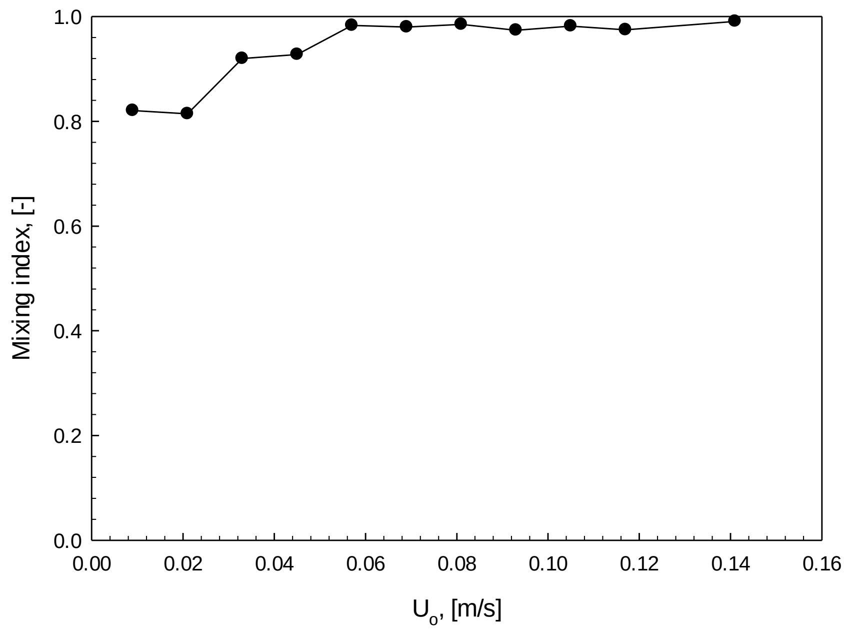


**FIG.11. MIXING INDEX OF CERAMIC BEADS-PLASTIC BEADS MIXTURE**

## V. CONCLUSION

In the ilmenite-coke binary solid mixture, takeover velocity was not found significantly, because of their wide particle size distribution. However, in the ceramic beads-plastic beads mixture which has narrow size distribution, takeover velocity was found unlike to ilmenite-coke mixture. From these results, we figured out that particle size distribution of binary mixture strongly affect to mixing characteristics of beds.

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