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混合粒子 三相流動層內의 相滯留量 特性에 關한 硏究

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Phase Holdup Characteristics of Three Phase Fluidized Beds of Mixed Particles

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개 요

두개의 다른 크기의 입자를 혼합한 삼상 유동층에서의 각 상의 체유량을 측정하였다.
삼상유동층에서 적은 균일입자를 액체로 유동화 시킨 후 기체를 주입하였을 때 층 높이 감소 현상이 여러 경우의 혼합입자 층에서는 관찰되지 않았다. 혼합입자의 무게비 변화에 따라서 층기공율 및 액상 체유량은 최저값을 보여 주었다.
혼합입자 유동층에서의 최저 유동화 속도는 균일입자의 경우보다 상대적으로 낮은 것으로 나타났다. 실험 결과는 무차원군인 유체의 Reynolds 및 Froude numbers로써 harmonic 평균입자 크기를 근거로하여 상관식을 얻었으며 이 실험식은 삼상 유동층내의 균일입자 및 혼합입자 경우의 층기공율 및 액상 체유량등을 산출하는데 유용할 것이다.

ABSTRACT

Individual phase holdups were measured in three phase fluidized beds of mixed particles having binary size distributions.
The bed contraction phenomena, which have been observed in the beds of small monosized particles, could not be found for some mixtures of solid particles at the same experimental

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conditions. The variation of bed porosity and liquid phase holdups showed miniumm values depending upon the variation of weight fraction of the component particles.
The minimum fluidizing velocity of the mixed particle systems was comparatively lower than that of the large particle component only.
Results were summarized with dimensionless correlations, in terms of fluid Reynolds and Froude numbers based on harmonic mean particle diameter, which can be applicable to both monosized and mixed particle systems.

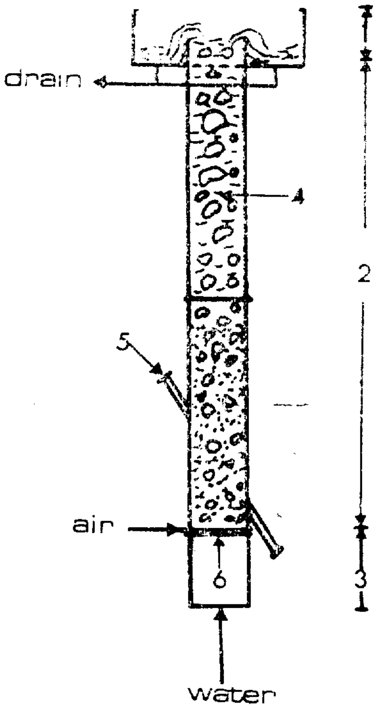
I. INTRODUCTION

Three phase fluidization is generally described as a fluidization of solid particles by cocurrent upward flow of two fluids, namely gas and liquid phases. It has been known to be an adequate method for contacting of multiphase flow systems and has an advantage of superior heat transfer characteristics.

The industrial applications of three phase fluidized beds are H-Oil[1] and Hy-C[2] processes in petroleum industry as the catalytic hydrogenation, hydrocracking and desulfurization of feed stocks. Recently the studies on microbial fermenter[3] by means of three phase fluidization have resulted in considerable interest in this mode of operation.

Relatively many studies have been emphasized on the phase holdup characteristics of three phase fluidized beds[4-8] since the size of reactors and the residence time distributions of fluids depends mainly on phase holdups. However, all the studies have been carried out with solids of uniform size, though wide size distribution of solids are being used in real processes.

In the present study, the phase holdup data are reported for the beds of solids having binary size distributions, and correlated empirically by the equations involving fluid Reynolds and Froude numbers based on harmonic mean particle diameter.



1. outlet weir
2. test section
3. distributor box
4. pressure tap
5. loading, port
6. distributors

Fig. 1. The Column

Ⅱ. EXPERIMENTAL

Experiments were carried out in a relatively large plexiglass column of 250 cm high and 15 cm in diameter as shown in *Figure 1*.

Throughout this study, water was used as the liquid phase, air as the gas phase and either 1.63mm, 2.92mm or 7.85mm glass beads with density of 2.5 g/cm³ as the solid phase.

The superficial velocities of water and air ranged from 0 to 14 cm/sec and from 0 to 12 cm/sec, respectively.

The solid particles were supported on a perforated plate grid which contained 237 evenly spaced holes with diameter of 3 mm and served as the liquid distributor.

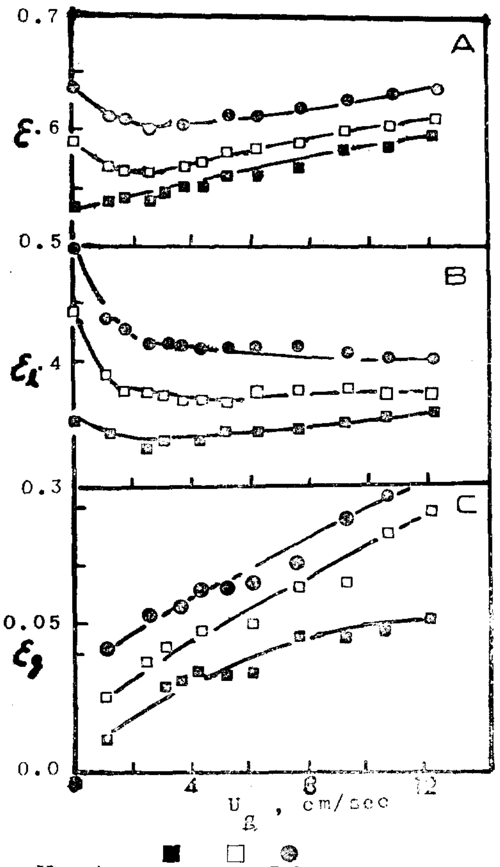
Oil free compressed air (40 psi) was fed to the column through a filter, pressure regulator and a calibrated rotameter. It was admitted to the bed through four 0.25 in. perforated-pipe distributor[6] which were evenly spaced across the width of the column.

An approximately constant dynamic liquid level was maintained in the column by means of an outlet liquid weir situated top of the column. A brass screen was attached across the weir to prevent the entrainment loss of particles.

The static pressure of the bed was measured by means of ten pressure taps which were mounted on the column in 15 cm height intervals and connected to the water manometers.

The bed height, H, was taken as the point at which a change in the slope of the plot of bed pressure versus bed height.[13]

The bed porosity and phase holdups were calculated from the relations;



U,cm/sec 4.57 6.10 7.62
wp, kg.: 7.6

Fig. 2. Effects of gas velocity on Phase holdups in the beds of 1.63mm glass beads.

$$\varepsilon = 1 - \varepsilon_s = 1 - \frac{1}{AH}\left(\frac{W_1}{\rho_{s_1}} + \frac{W_2}{\rho_{s_2}}\right) \quad (1)$$

$$P_b = H(\varepsilon_l \rho_l + \varepsilon_g \rho_g + \varepsilon_s \rho_s)\frac{g}{g_c} \quad (2)$$

$$\varepsilon_l + \varepsilon_g + \varepsilon_s = 1.0 \quad (3)$$

in which ε, ε_s, ε_l and ε_g can be calculated by solving the equations simultaneously.

In the gas-liquid systems, ε_s is zero and H is the height of the column test section. For the beds of monosized particles, the second term in the parentheses of the equation (1) will be zero.

In the three phase systems, phase holdups were measured in the beds of no particle segregation between two different size of glass beads.

Experiments were carried out by the following procedures;

1) completely fluidize the bed of solids with the maximum liquid and gas velocities,
2) set the liquid and gas flow rates at the desired levels,
3) pressure profiles were measured by the water manometers with decreasing the air flow rate at given intervals.

(1) Beds of Monosized Particles

The bed porosity as a function of gas and liquid velocities in the beds of 1.63 mm particles are shown in *Figure 2. A.*

As may be seen in the figure that bed porosity or expanded bed height decreased initially and then increased slowly with increasing gas velocity. This initial decrease of bed porosity with gas velocity at constant liquid velocity is termed as the bubble coalescing bed.[7] The contraction of three phase beds containing small particles has been attributed to predominantly liquid wakes which are dragged through the bed behind the fast moving gas bubbles. This result in a reduction in the contineous liquid phase velocity and a consequent bed contraction since liquid phase is the main fluidizing medium.

For a given liquid velocity the minimum value of bed porosity is displaced toward the high gas flow rates as the liquid velocity is increased. Similar observations were made by previous studies.[7-9]

The liquid phase holdups at the same experimental conditions are shown in *Figure 2. B.* Liquid phase holdups decreased with increasing gas velocity and with decreasing liquid velocity. However, at higher gas velocities, liquid phase holdup was nearly independent

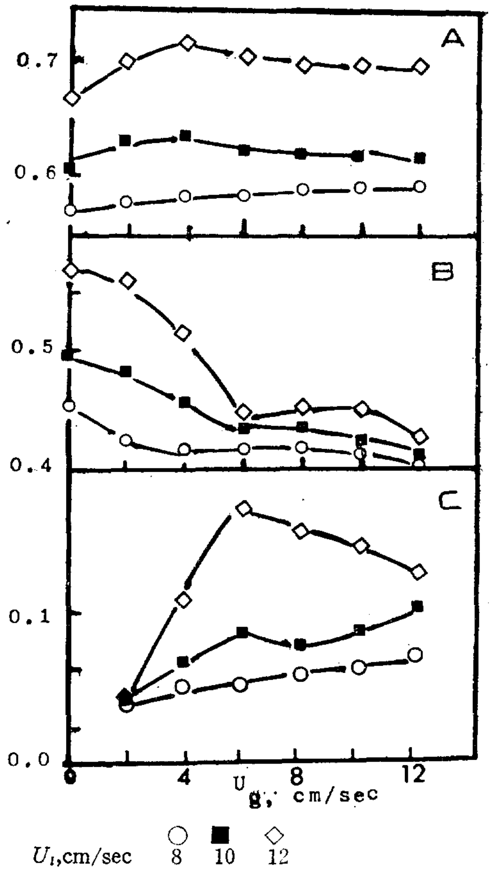


Fig. 3. Effects of gas velocity on phase holdups in the beds of 2.92 mm glass beads.

of gas velocities. It may be due to the bubbly flow regimes progressed to intermediate or slug flow regimes with higher gas flow rates.

Figure 2. C. illustrates the effects of gas and liquid flow rates on gas phase holdups. Gas phase holdup increased with increasing gas velocity, however, the effects of liquid velocity on gas holdups were somewhat anomalous as found in the previous studies.[4-7]

In *Figure 4*, the effects of gas velocity on each phase holdups in the beds of 7.85 mm glass beads were illustrated.

The bed porosity and gas phase holdups

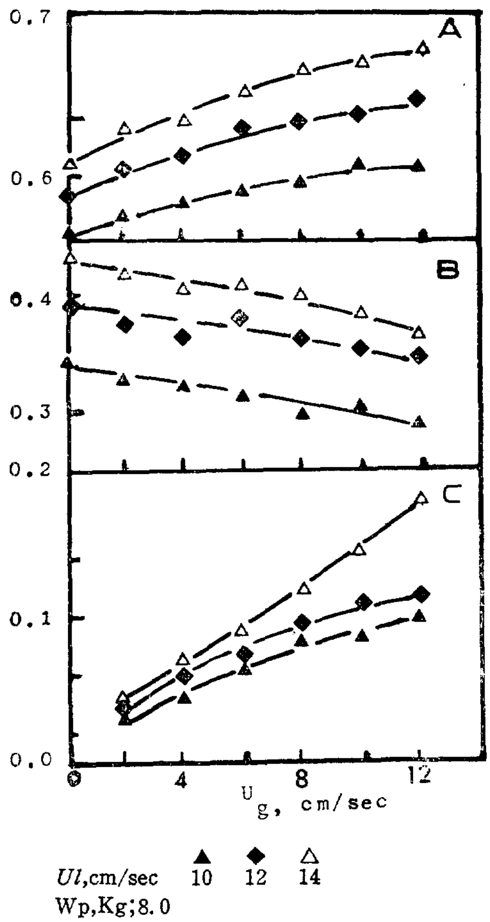


Fig. 4. Effects of gas velocity on Phase Holdups in the beds of 7.85mm glass beads.

increased with gas as well as liquid velocities. However, as may be expected, liquid phase holdups decreased with gas flow rates whereas it increased with liquid velocity. This type of bed expansion characteristics has been termed bubble disintegrating bed.[4]

Figure 3. shows erratic phenomena, namely bed porosity increased initially with gas flow rates and then slightly decreased with further increase of gas flow rates at higher liquid velocities in the beds of 2.92mm glass beads. However, at lower liquid rates, bed porosity increased with gas velocity. It may be termed as an intermediate phenomena between bed expansion and contraction characteristics Similar trend was also observed by Ostergaard and Michelsen.[12]

Systems with high liquid flow rate and low gas flow rate are characterized by breakup of bubbles, and behave like the beds of 7.85 mm particles. In consequence, the bed expand rather than contraction. At gas velocity exceed 4cm/sec, bubble coalescence may begins and the system becomes unstable. Further increase of gas velocity may produces severe bubble coalescnce. Therefore, a sudden decrease in bed porosity and gas phase holdups take place. However, liquid phase holdups did not change appreciably in these systems.

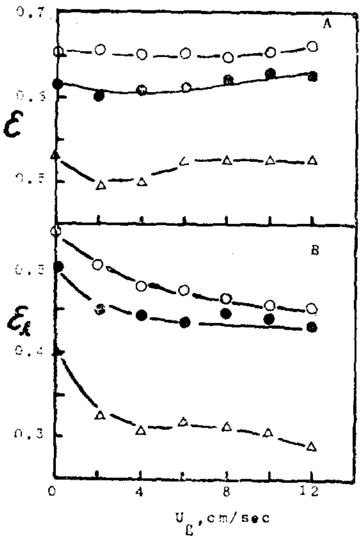
Ⅲ. BEDS OF MIXED PARTICLES

(1) Mixture of 1.63mm and 2.92mm particles

Segreation of particles was negligibly small at all liquid and gas velocities However, in the presence of gas bubbles, entrainment has been observed at liquid velocities studied. However, in the presence of gas bubbles, entrainment has been observed at the liquid velocity greater than 10 cm/sec.

The characteristics of the mixed particles bed were well illustrated in the beds of 50 weight % of large particles as shown in *Figure 5.* The bed porosity or bed height increased somewhat with liquid as well as gas velocities. However, at lower liquid flow rate, bed porosity initially decreased with gas flow rate as that of the bed of 1.63mm glass beads only.

Whereas liquid phase holdups decreased with gas rates up to 4cm/sec thereafter the rate of decrease was minimal with gas velocity.

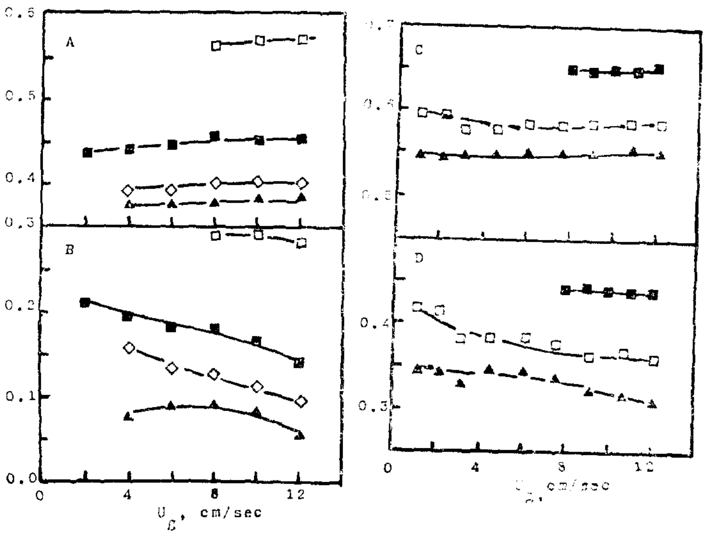


U_l, cm/sec, 6 △ 8 ● 10 ▩

Wp, Kg; 10.0

Xw, 1; 0.5

Fig. 5. Effect of gas velocity on phase Holdups in the Beds of Mixed Particles. (1.63 & 2.92mm)



U_l, 3 ▲ 4 ◇ 6 ▣ 8 □ for Fig. A.B. -Wp(Kg):8.0

U_l, 6.10 ▲ 7.62 □ 10.00 ■ for Fig. C.D. -Wp(kg):10.85

Xw, 1: 0.5 for Fig. A.B.

Xw, 1: 0.3 for Fig. D.C.

Fig. 6. Effects of gas velocity on Phase holdups in the beds of mixed particles. (1.63 & 7.85mm)

Ⅳ. BEDS OF MIXED PARTICLES

(Ⅱ) Mixture of 1.63mm and 7.85mm particles

Segreation between small and large particles was significant and the degree of segreation increased as the weight fraction of large particles incresed. In consequence, the beds of high weight % of large perticles, narrow ranges of gas and liquid velocities were satisfied for the condition of no particle segreation. As may be seen in *Figure 6A*, the bed porosity slightly increased with gas flow rate. However, the rate of increase was marginal compared with that of the bed of 7.85mm particles only. In contrast, liquid phase holdups decreased almost linearly with gas flow rates as may be seen in *Figure 6B*.

In the beds of 30% large particle component mixed with small particlees, the bed porosity did not change appreciably with gas velocity in spite of vigorous movement of large particles.

However, liquid phase holdups decreased slightly as the gas velocity increased in the same experimental conditions, and it increased with liquid velocity considerably.

It has been explained previously that the

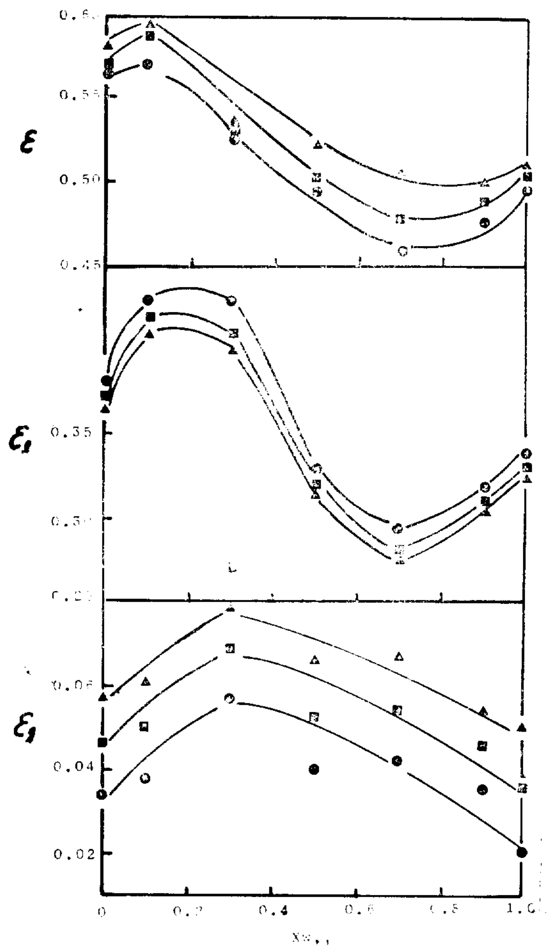


Fig. 7. Effects of particle Weight Fraction on Phase Holdups in the Beds of Mixed Particles (1.63 & 2.92mm), $U_l = 6.0$cm/sec.
U_g, cm/sec: ● 2.0 ▲ 4.0 ▲ 6.0

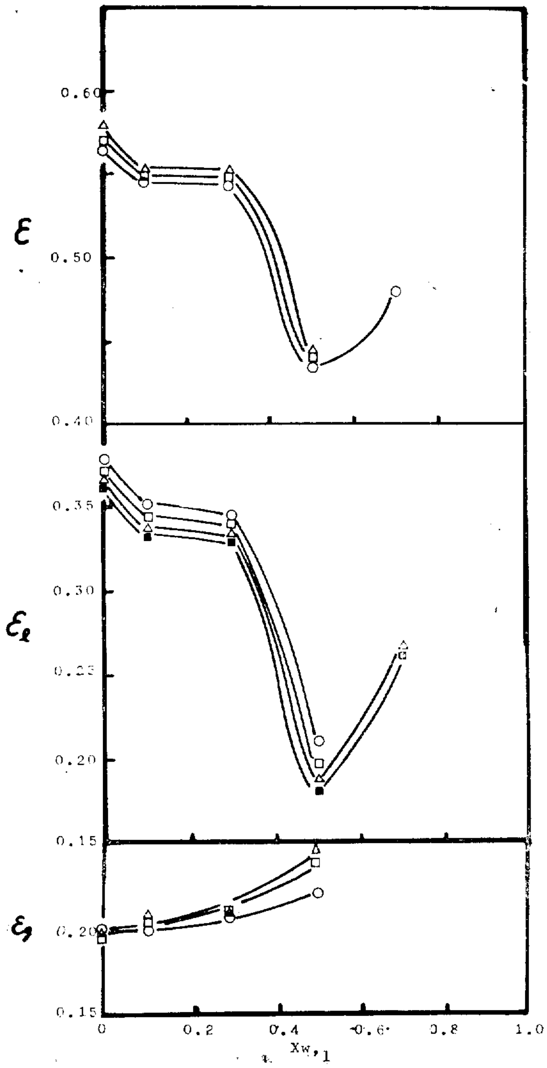


Fig. 8. Effects of Particle Weight Fraction on Phase Holdups in the beds of Mixed Particles. (1.63 &7.85mm)
U_g(cm/sec); ○ 2.0 □ 4.0 △ 6.0 ■ 8.0
$U_l = 6.0$ cm/sec.

bed contraction phenomena may be attributed by the velocity difference between bubble and contineous liquid phases as well as the volume of wakes. *Figure 6A and 6C* demonstrate that the bed of 50% large particles did not prevailed the bed contraction characteristics however, reverse was true in the bed of 30% large particle. It may imply that the bed of comparatively large % of large particle components act as a bubble breaker[13] so that the bubble size was relatively smaller than that of the bed of small % of large particle components. It may be also expected that the large population of large particles may disturb the formation of wakes behind bubbles.

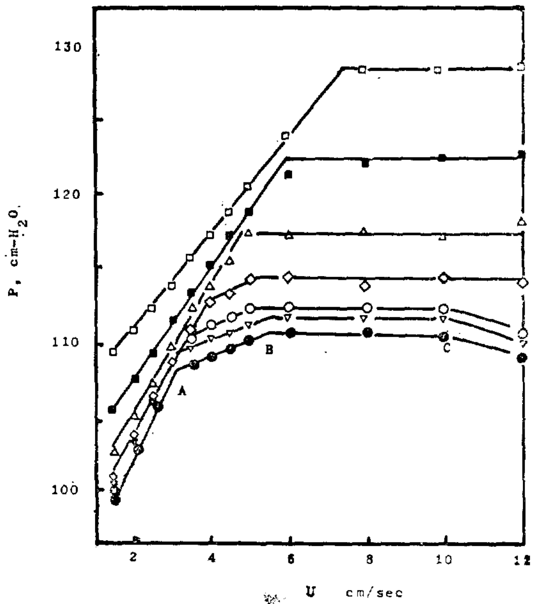
V. EFFECT OF PARTICLE WEIGHT FRACTTON IN THE BEDS OF MIXED PARTICLES

The overall trend of bed porosity and gas phase holdups increased with gas flow rates whereas liquid phase holdups decreased with increasing gas velocity as can be seen in *Figures 7 and 8*. At the given fluid velocities, the addition of large particles in the bed of small particles, bed porosity has to be decreased due to the weight increase of solids in the bed. However, there were minimum values of bed porosity and liquid phase holdups in the beds of 1.63mm and 2.92mm glass beads (*Figure 7*). When small particles were added to the beds of large particles only, the bed porosity or expanded bed height decreased rather than increased as opposed to the overall trend.

This characteristic was more pronounced when the diameter ratio of two component particles was large and was less remarkable at the higher liquid velocities.

The detail mechanism of this phenomena is not certain at present. However, this mechanism may be attributed to the bed fluidity i.e. the addition of fines in coarse particles improves the quality of fluidization since the fines act as a lubricant between the coarse paritcles.

Therefore, expanded bed height decreased with the addition of small particles to the bed of large particles of 2.92mm in diameter until the fine weight fraction reaches 0.3. In this case, the slip velocity of liquid may be increased due to the lubrication effect of fines so that liquid phase holdups may be increased.



□ ▲ △ ○ ▽ ●
U_g, cm/see: 0 2 4 6 8 10 12

Fig. 9. Bed Pressure Drop as a function of Liquid Velocity in the beds of 7.85mm glass beads

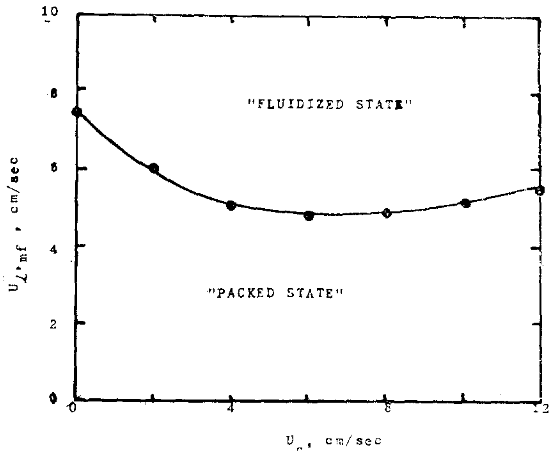


Fig. 10. Liquid Velocity as a function of Gas velocity at Minimum Fluidizing Conditions

In contract, the weight fraction of small particles exceeding 0.3, the system may have a closed packed state and having large total surface area of solids. In consequence, liquid holdups may be increased due to the increase of drag force on particles.

This effect has been persists until the fraction of fines reaches 70~80%. In this system, ε_g also prevailed maximum values with the bubble breakage effect of large particle fraction[14] of 30%, However, the fraction of large particles exceeding 0.3 the specific surface area of solids may decrease and ε_g may also decrease due to the increase of bubble free path ways. In this case, the weight or volume fraction of large particles was so high that bubble breakage effect became negligible.[13]

The minimum values of bed porosity and liguid phase holdups were shifted to 50% of fine particles in the bed of 7.85mm glass beads (*Figure 8*). This may imply that the fines may act as a lubricant more effectively in the beds of more large particle components. As can be seen from the figure that ε_g increased with the weight fraction of large component. It may be due to the bubble breakage effect of large component particles as explained previously.

Ⅵ. MINIMUM FLUIDIZATION VELOCITY IN THE BEDS OE MIXED PARTICLES

The bed pressure drop was plotted against liquid superficial velocity as a function of gas velocity (*Figure 9*). In the Figure, three inflection points are present. Below point A, liquid and gas flow were channeled through the packed bed and the point B would be the fluidizing point. When the liquid flow rates were increased above the point C, the bed height boundary became fuzzy and the bed pressure drop decreased with increasing gas flow rates.

The minimum fluidizing velocity so obtained are also plotted in *Figure 10*. with the variation of gas flow rates.

The upper region of the demarcation line denotes the fluidizing state and the lower region is packed bed state.

From these results one of the important characteristics of the mixed particle systems can be defined, i.e., minimum fluidizing velocity of the beds of mixed particles was comparativelly lower than that of the beds of large particles only.

The beds of mixed particles of 50 weight % of 1.63 mm and 7.85 mm particles could be fluidized at liquid velocity of 3 and 4 cm/sec, which are under the minimum fluidizing velocity condition of 7.85 mm particle at any given gas velocities.

This may ascertains the rule of thumb used in industry, namely the addition of fines improve the quality of fluidization, and this would be the first observaton of such characteristics in three phase fluidized bed.

Ⅶ. EMPIRICAL CORRELATIONS FOR BED POROSITY AND LIOUID PHASE HOLDUP

From the method of multilinear dimensional analysis,[10] bed porosity and liquid phase holdup data were correlated successfully in terms of fluid Froude numbers and liquid phase Reynolds numbers based on harmonic mean particle diameter.

The resulting correlations can be seen as;

$$\varepsilon = 0.46(Fr_l)^{0.19}(Fr_g)^{0.01}(Re_l)^{0.026} \qquad ④$$

where multiple correlation coefficient; 0.944
standard error of estimate; 0.047

$$\varepsilon_l = 0.26(Fr_l)^{0.44}(Fr_g)^{-0.032}(Re_l)^{-0.006} \qquad (5)$$

where multiple correlation coefficient; 0.875

standard error of estimate; 0.169

In this study, bed characteristics have been studied at comparatively higher fluid velocities and wider range of mixed particle systems than have been reported previously. It is of particular importance to note that the above correlations are applicable to monosized and mixed particle systems in the industrially realistic intermediate flow regimes of three phase fluidized beds.

NOMENCLATURES

A : cross sectional area of bed, cm^2

d_p : harmonic mean particle diameter, mm $(1/X_w/d_p)$

Fr : Froude number, $(U/d_p g)$

g : accleration of gravity, cm/sec^2

g_c : conversion factor

H : bed height, cm

ΔP : pressure drop, cm-H_2O

Re : Reynolds number, $(d_p U\rho/\mu)$

U : fluid superficial velocity, cm/sec

W : weight of solid particles, gr.

X_w, : weight fraction of particles

ε : bed porosity, $\varepsilon_l + \varepsilon_g$

ρ : density, gr/cm^3

μ, : liquid viscosity, gr/cm sec

Subscripts

b : bed

g : gas phase

l : liquid phase

l : large

mf : minimum fluidizing condition

s : solid phase

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