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Review

Dynamic Properties of Powder and Particle Characteristics

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The diffusion process of powder particles into the vibrating powder bed was observed and the relation between the interparticle force and the dispersion property was investigated. The diffusion process of fine powder to the coarse powder bed affected by not only the ratio of particle size, but also the particle-particle interaction force. For the interparticle force, the effect of the condensed film of water on the particle surface may be considered to be most important. In order to investigate the effects of these factors, the percolation properties through the beds of coarse powders of glass beads and of bronze spheres were examined by using surface treated fine glass beads as percolating powders. For the glass beads, it may be concluded that the phenomenon of segregation occurs with the difference of the surface property between particles.

I. INTRODUCTION

The phenomena, such as mixing, segregation and separation of powder, should be discussed under consideration that a particle in the flowing powder is naturally affected by the interaction between particles. No example, however, has been found that the interaction between particles, especially, between different species of particles, was taken into consideration, although there are some reports[1~3] that the behavior of particles was kinematically analyzed by considering the flow of powder as a diffusion process.

In the present research, the diffusion process of powder particles into the vibrating powder bed was observed and the relation between the interparticle force and the dispersion property was investigated.

II. EXPERIMENTAL

As illustrated in Fig. 1, coarse powders (the particle size is about 100 μm) are put in a small sieve (the diameter is 24 mm and the aperture size is 80 μm) and the same type of another sieve is stacked upon the sieve. These two sieves are attached to a vibrator and the vertical vibration with a constant frequency, 60 Hz., is applied. A small amount of fine powder which can pass fully through meshes of a net is put in the upper sieve, and the increase in weight of fine powder with time, which passed through the network and the packed bed of coarse powder, is measured. Moreover, the amplitude

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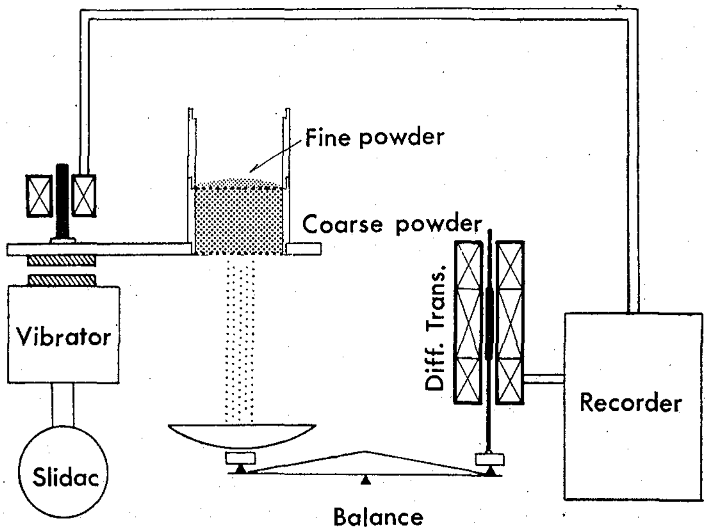

Fig. 1. Apparatus for measurement of percolation of fine powder through packed bed.

Table I. Characteristics of Sample Powder

Materials	Code	Density	Particle size (μm)	Remarks
α-Alumina	WA–800	3.91	20	
	WA–1000	〃	16	
	WA–1500	〃	12	
	WA–2500	〃	6	
Calcite	$CaCO_3$–SZ	2.70	15	
	$CaCO_3$–SZP	〃	15	Fatty acid coat.
	$CaCO_3$–5	〃	5	
	$CaCO_3$–8	〃	8	
	$CaCO_3$–20	〃	20	
	$CaCO_3$–150	〃	150	
Glass beads	GB–706	2.52	320	
	GB–705	〃	230	
	GB–703	〃	100	
	GB–703–Si	〃	100	Silicon coat.
	GB–3M	2.43	12	
	GB–ST	6.55	46	
	GB–ST–Si	〃	〃	Silicon coat.
	GB–ST–Ag	〃	〃	Ag coat.
Graphite	Gr–180	2.04	180	
	Gr–230	2.06	230	
	Gr–280	2.07	280	
Bronze sphere	Bronze	8.80	230	
Potato starch	STARCH	1.5	40	
Nylon 66	Nikolon	1.2	30	

is changed by the voltage applied to the vibrator and the effect of the amplitude on the percolation property is observed. The deflection of the amplitude is ca. 2–3% in measurement.

Characteristics of the powder samples used in this experiment, *e.g.*, density and particle size, are summerized in Table I.

III. RESULTS AND DISCUSSION

III.1. Percolation Velocity through the Packed Bed of Powder in the Vibrating State and the Particle Property

The aspect of the increase in weight of fine powder with time, which percolates through the packed bed of coarse powder in the vibrating state, is shown in Fig. 2, where the parameter is an amplitude (mm). The change of the percolation velocity of particles with the amplitude is based upon that of the kinetic energy of particles. The time at the maximum slope of the passing weight-time curve can be denoted as the average percolation time of fine powder through coarse powder, t_R. The relation between its reciprocal, $1/t_R$, *i.e.*, the average percolation velocity, and the kinetic energy of fine powder by the vibrational motion is shown in Fig. 3, and Eq. (1) can be set up as follows,

$$1/t_R = K \cdot e^{\frac{\alpha}{2} Mv^2} \tag{1}$$

where M is the mass of a fine particle, v is the average velocity of the fine particle, and K and α are constants, respectively.

In Fig. 3, the slope α of each curve relating to the change of the percolation property of fine powder through the coarse powder bed, attributed to the change of the kinetic energy of the particle. The percolation property depends upon the ratio between the particle size of a large particle and that of a small one, for example, as shown in Fig. 4 the relation is found between α of various fine powder for the bed of GB-703 and D_S/D_L, in which D_S and D_L are particle sizes of fine powder and coarse powder, respectively.

The difference between the physicochemical property of coarse powder and that of fine powder also affects the percolation property. Figure 5 shows the percolation curves of

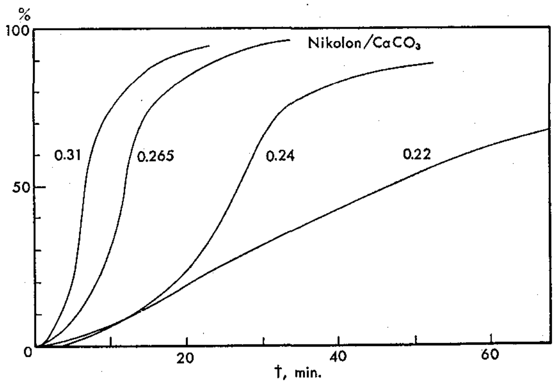

Fig. 2. Percolation curves of nylon powder through a packed bed of calcite. Numerous along the lines are amplitude (mm).

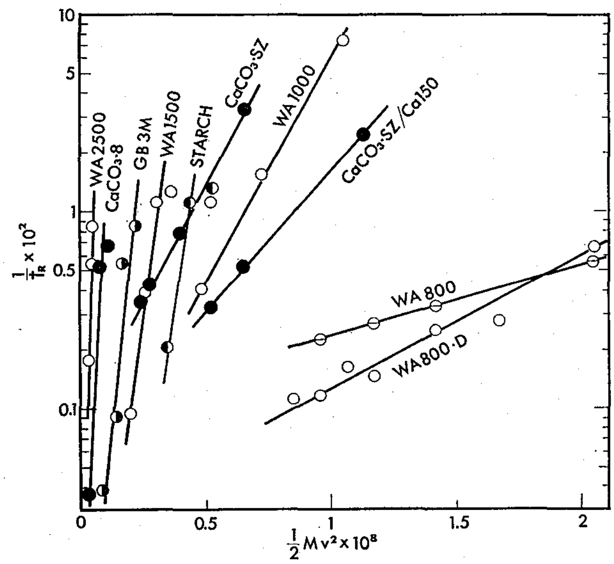

Fig. 3. Relation between 1/2 Mv^2 and percolation velocity of various powder through a packed bed of GB703.

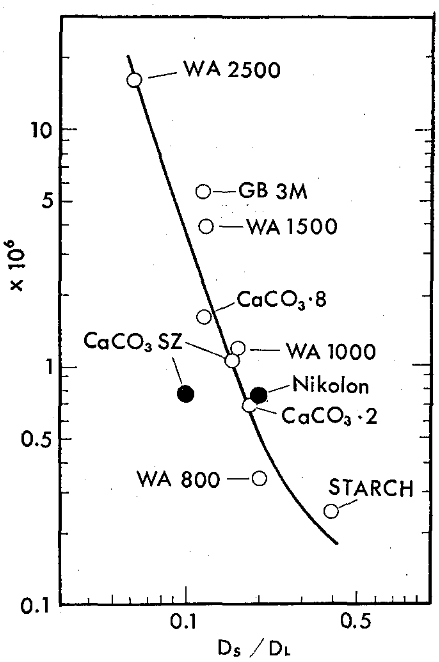

Fig. 4. Relation between D_S/D_L and α.

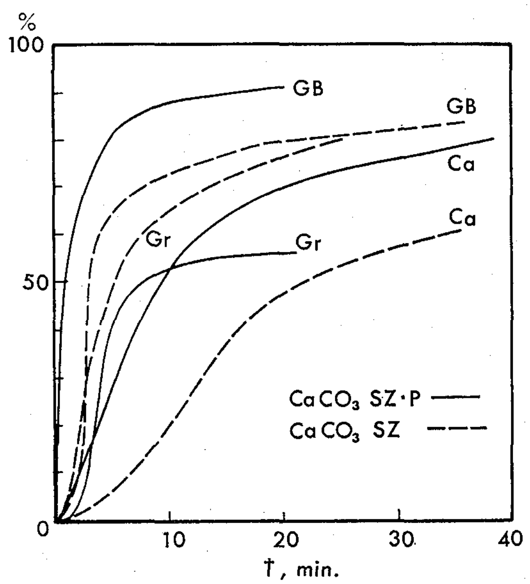

Fig. 5. Influence of surface treatment of particles for percolating property.

$CaCO_3$-SZ fine powder having the hydrophilic surface and the hydrophobic $CaCO_3$-SZP prepared by adsoption of palmitic acid to its surface through packed beds of various coarse powders. As is evident from this figure, $CaCO_3$-SZP attained by surface treatment is faster with percolation velocity than $CaCO_3$-SZ in the cases of coarse powder beds of $CaCO_3$ and glass beads having the hydrophilic surfaces, while $CaCO_3$-SZ having the hydrophilic surface can pass faster in the case of the packed beds of graphite powder having the hydrophobic surfaces. This result suggests that the diffusion process of fine powder to the coarse powder bed may be affected by the interparticle force, and that the interaction effect between particles of hydrophilic surfaces or between ones of hydrophobic surfaces may be remarkable and it may be faint between particles having surfaces of different properties each other.

The relation of Eq. (1) is set up between the percolation velocity and the amplitude in the initial part of the passing weight-time curve, and the slope α in this part is related to D_S/D_L. This fact implies that this process is mainly due to the percolation of any powder through void in the packed bed of coarse powder without interaction. But it may be understood from the result of Fig. 5 that the adhesion to the surface of coarse powder and the repetition of aggregation and dispersion between fine particles act as the apparently opposing forces against percolation.

III.2. Interaction Force between Different Species of Particles

As seen in Fig. 2, the initial part of the passing weight-time curve may be mainly due to the percolation of fine powder but it may be considered that the latter slow part in percolation velosity is based on the group of fine powder which is repeating the adhesion to and the separation from the surface of coarse particle by the vibrational motion. The quantity of fine powder in this region can be described by R as shown in Fig. 6, and the change of R on the amplitude was measured for the various samples. The relation with the amplitude between the kinetic energy and R may be as shown in Fig. 7. In all samples, there is the point at which the value of R begins to increase adruptly as the amplitude decreases. Considering that the kinetic energy of the particle becomes greater than the adhesion force to the surface of the coarse powder particle and consequently the particle separates from it in the region of the amplitude above this point, it can be assumed that

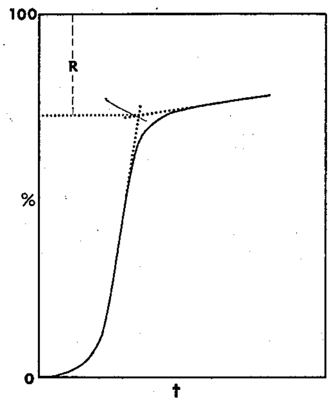

Fig. 6. Determination of residual value R.

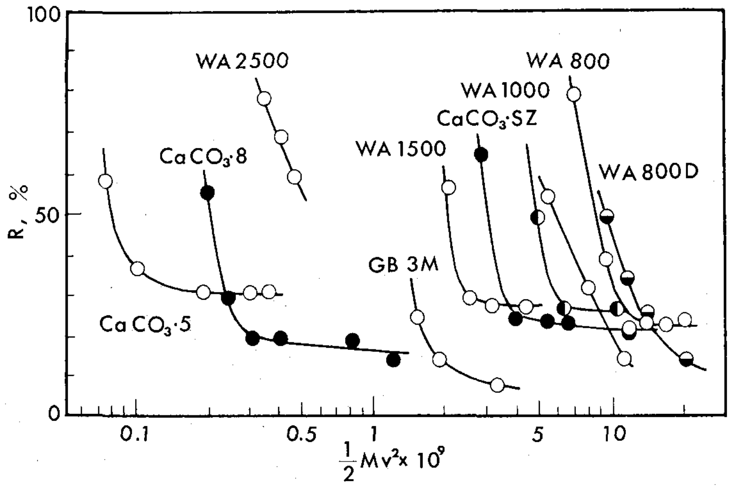

Fig. 7. Relation between $1/2\ Mv^2$ and R % of various powder through a packed bed of GB703.

Table II. Adhesion Force f of Various Powder

($g\ cm^2\ sec^{-2}$)

Fine powder	Coarse powder	
	GB 703	Ca·150
WA-800	10×10^{-9}	20×10^{-9}
WA-1000	6×10^{-9}	7.5×10^{-9}
WA-1500	2.5×10^{-9}	—
$CaCO_3$-SZ	3.5×10^{-9}	15×10^{-9}
$CaCO_2$-SZP	1.5×10^{-9}	—
$CaCO_3$-5	0.1×10^{-9}	—
$CaCO_3$-8	0.3×10^{-9}	—
$CaCO_3$-20	3.4×10^{-9}	—
GB-3M	16×10^{-9}	—
STARCH	50×10^{-9}	—

the kinetic energy at this point is equal to the adhesion force between the large particle and the small one.

The adhesion forces of fine powder to the beds of glass beads and of calcite particles, each of which can be given from the value of the amplitude corresponding to the point at which R increases abruptly, are shown in Table II. The adhesion force depends upon the particle size for the same substance. Such a change of the percolation property on the difference between characteristics of samples contributes to the segregation.

The mixed powders of not less than two kinds which are different in their particle characteristics can be separated by using this phenomenon. An example is given as follows. The adhesion force of starch to glass beads is five times that of α-Al_2O_3 WA-800. The mixture of the equal weights of these two kinds of powders is percolated through the bed of GB-703 on the vibrating stage, and then the change of the mixture ratio of percolating powder with time was measured. As these two kinds of powders are different in the shape of the particle and therefore the rounded particle of starch can be evidently distinguished from the sharpcornered one of α-Al_2O_3 as seen in Fig. 8, some percolating powder particles were taken out every appropriate time on a slide glass and each mixture ratio was measured by a microscope. The result is shown in Fig. 9, and it can be found obviously from this figure that the two kinds of powders segregate.

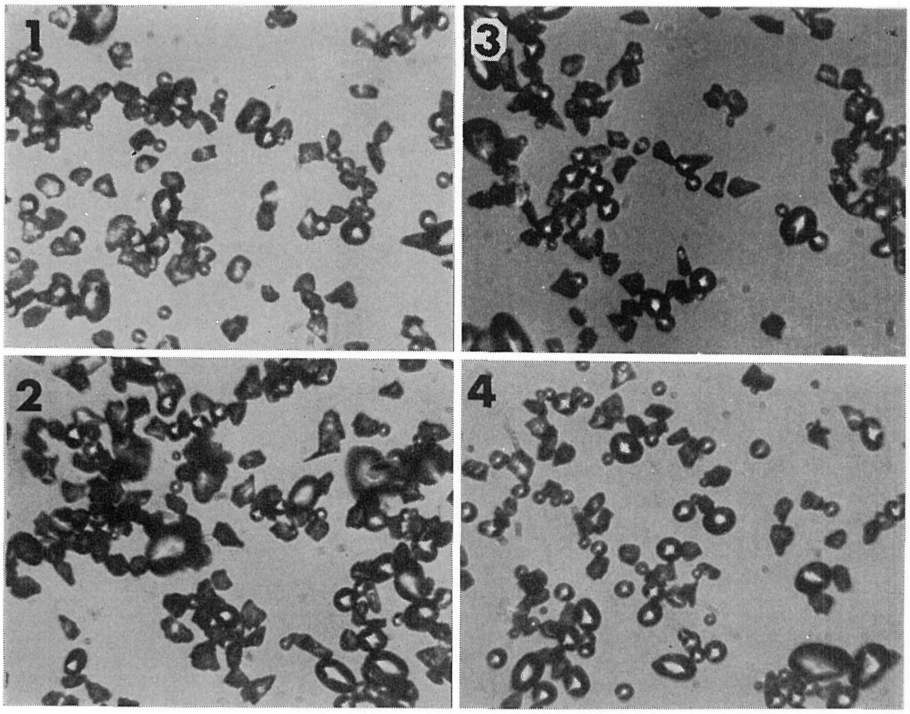

Fig. 8. Change of mixture ratio of WA 800/STARCH system with the percolation time. (blocky shape; WA 800, round shape; STARCH).
1. 100sec., 2. 180 sec., 3. 240 sec., 4. 360 sec.

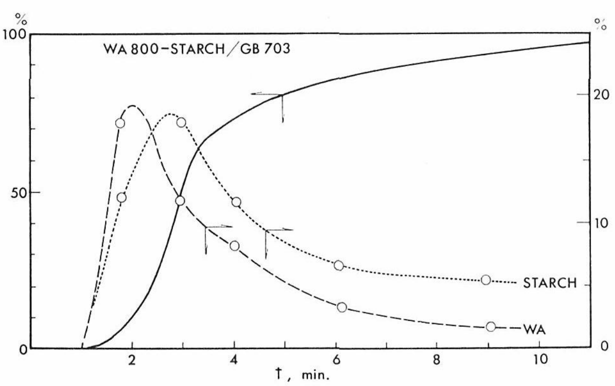

Fig. 9. Segregation of WA 800/STARCH system after the percolation through a packed bed of GB703.

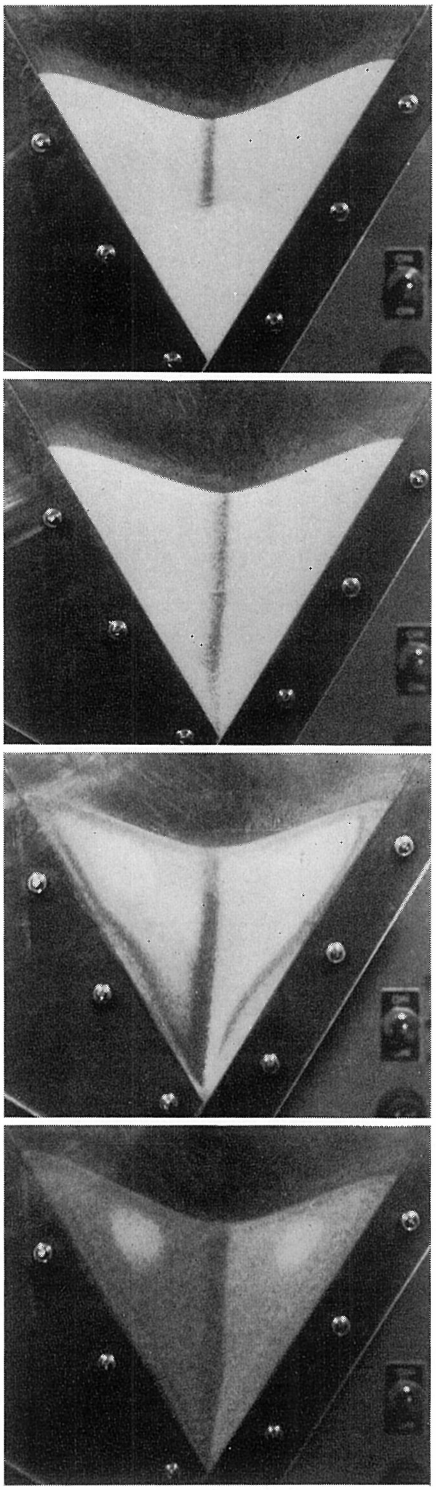

Fig. 10. Flow pattern of powder in conical container in vibrating state (two dimentional model).

In this experiment, the vibrating bed of coarse powder is 2 cm in thickness and they may be separated from each other further when some steps of beds are stacked.

III.3. Circulatory Motion of Particles and the Behavior of Fine Powder in the Vibrating Vessel

In the above-mentioned experiment, it is assumed that particles vibrate uniformly in the vibrating vessel, but actually, the motion of particles occurs various circulatory flows, depending upon the shape of the vessel.[5] When powder particles are compelled to vibrate in the two-dimensional hoppershaped vessel as illustrated in Fig. 10, the particles near the wall of the vessel begins to elevate along its slope and the middle part of the powder falls down to compensate the void. Consequently, the circulatory motion as in Fig. 10 occurs. In Fig. 10, some colored particles are added in order to inspect the situation. The larger is the amplitudes, the faster is the rate of the circulatory motion, and moreover the relation of an exponential function is found between the transfer velocity of particles, v, and the reciprocal of the amplitude, $1/A$, as seen in Fig. 11.

In order to disperse fine powder particles in the circulatory flow of coarse powder

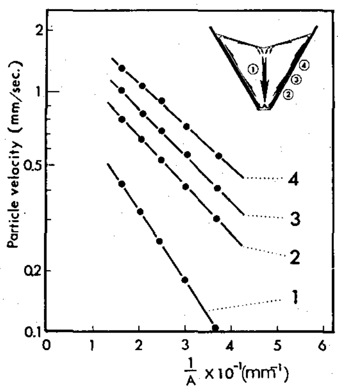

Fig. 11. Relation between amplitude A and particle velocity in the two dimentional hoppershaped vessel.

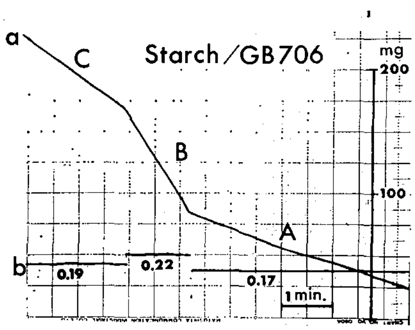

Fig. 12.

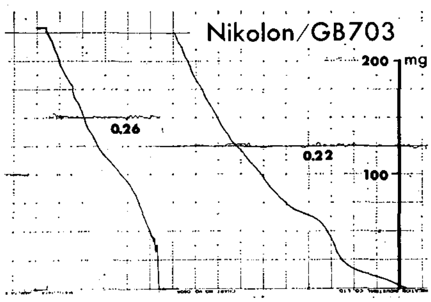

Fig. 13.

Fig. 12. Relation between amplitude and percolation velocity of STARCH through a bed of GB706.

Fig. 13. Relation between amplitude and percolation velocity of nylon through a bed of GB703.

particles and measure its percolation velocity, the hoppershaped sieve was mounted as a bivrating vessel to the apparatus as shown in Fig. 1, and then the experiment similar to that mentioned above was carried out. In the experiment of the sections, III. 1. and III. 2., a constant quantity of fine powder was placed in the upper sieve and the percolation process of its total amount was observed, on the other hand, additional amounts of fine powder were supplied successively in the upper sieve in this experiment and the relation at the stationary state between the percolation velocity and the amplitude was examined.

Figure 12 shows the change of the percolation velocity of starch through the vibrating bed of GB-705 with the amplitude, in which the line (a) is the percolating weight and the line (b) is the amplitude. The amplitude and the percolation velocity are 0.17 mm and 0.35 mg/sec, respectively, in the region of A, 0.22 mm and 1.67 mg/sec in B, and 0.19 mm and 0.75 mg/sec in C. As seen in this figure, the response to the amplitude change is extremely fast and the percolation velocity for the constant amplitude is kept constantly with a fairly good accuracy. But there are some cases in which the relation between the amplitude and the percolation velocity does not hold at all by the species of the powder. Figure 13 is one of the examples and the case of the percolation of nylon powder through the bed of glass beads. But also in the case of the percolation of nylon powder through the coarse powder bed of polystyrene, the percolation velocity becomes to correspond to the amplitude. From this result, it can be understood that the combination of powders depending on the nature of the particle surface influences the percolation property all the same. The flow pattern in the case of the percolation of $CaCO_3$ powder having the hydrophilic surface through the coarse powder bed of graphite having the hydrophobic surface is as shown in Fig. 14 by the experiment of the two-dimensional vessel and it is seen evidently that the circulatory motion of fine powder particles becomes a turbulent flow.

The relation between the logarithm of the percolation velocity of fine powder, v, and $1/A$, which was measured for the combination of powders whose flow corresponded sensitively to the amplitude change, leads to the linear curve as shown in Fig. 15. For the characteristics of the particle surface which affects the percolation velocity of fine powder through the powder bed in the vibrating state, the effect of the condensed film of water on the particle surface may be considered to be most important in the cases of ordinary powders in atmosphere. Therefore, the difference among surface characteristics of powder particles can be indicated by that of wettability to water among these particles. The wettability should be represented by the contact angle between water and a particle surface, and the ratio between the contact angles of the coarse particle, θ_L, and that of the fine one, θ_S,

$$R_\theta = \theta_S / \theta_L \qquad (2)$$

was used as a factor which displays the degree of similarity of the surface characteristics between particles. The contact angle of a particle was measured by use of the Bartell's method.[6] For $R_\theta=1$, the hydrophilic properties of the surfaces of coarse and fine particles are equal, and the larger is the value of R_θ, the more different are the surface properties and the interaction between coarse and fine particle decrease.

On the other hand, as the cohesion force between fine particles, f_p, becomes greater, it becomes more difficult for a fine powder particle to percolate. And as the particle

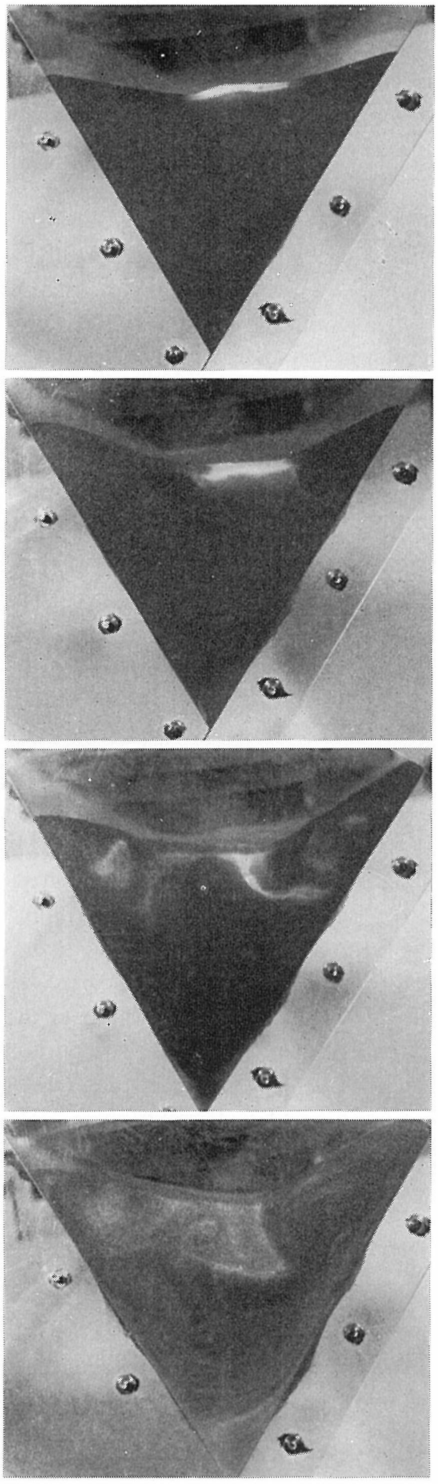

Fig. 14. Flow pattern of $CaCO_3$ fine powder in Graphite coarse powder bed in vibrating state.

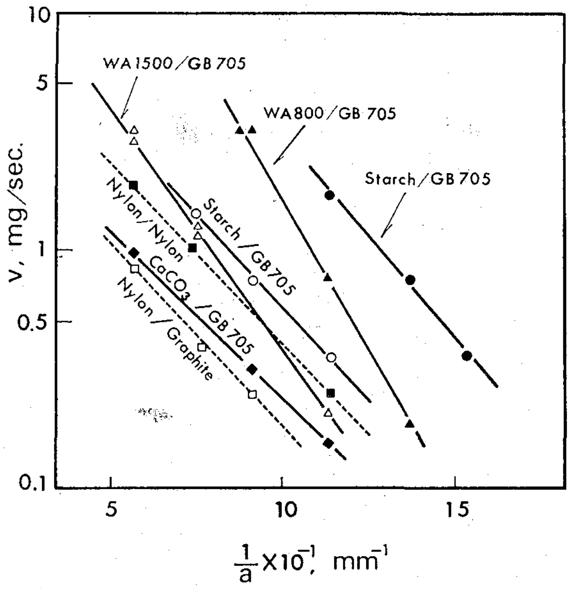

Fig. 15. Relation between amplitude of container and percolation velocity of various powder.

weight, W_p, becomes larger, it becomes easier to percolate because W_p is related to its momentum. By combining the above-mentioned factors, $(f_p/W_p)/R_\theta$ is used conveniently as a total evaluated index of the force between particles. Then f_p was measured by a shearing test of powder bed. In order to investigate the effects fo these factors, the percolation properties through beds of coarse powders of glass beads and of bronze spheres were examined by using three kinds glass beads as percolating powders, which have surfaces with silicon-coating (hydrophobic) and silver-coating and without treatment. The result is shown in Fig. 16. In this figure, the percolation velocity is indicated by a logarithm of number of percolating particles per second, n. It will be noted for the coarse

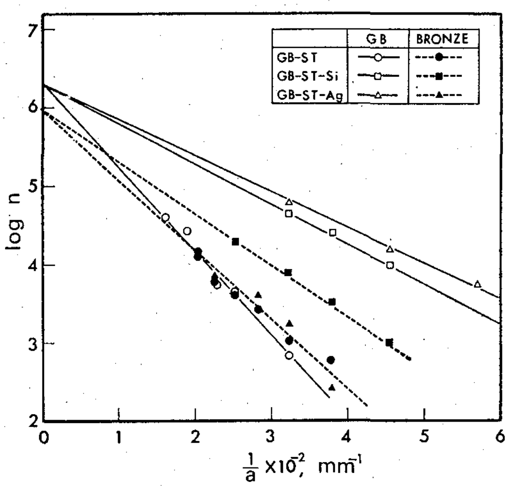

Fig. 16. Effect of surface treatment on the relation of $1/a$ and log n.

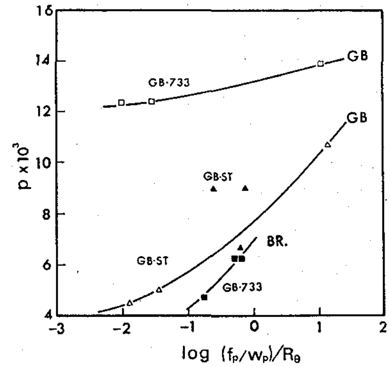

Fig. 17. Relation between $\log(f_p/W_p)/R_\theta$ and slope of $1/a \sim \log n$ plots.

powders of glass beads that the adhesion force between particles decreases and that it becomes easy for particles to percolate, because the surfaces of particles become hydrophobic owing to the effect of surface treatment. The values of intercepts of the ordinate to linear lines coincide for the same species of powders, depending upon the constant decided by the ratio of the particle size of a coarse powder to that of a fine powder and in no relation to the surface treatment. But, it is considered that the slope changes by surface treatment and relates to the interaction between particles. Therefore, the relation between the slope given from Fig. 16 and the total evaluated index $(f_p/W_p)/R_\theta$ was examined. The result is shown in Fig. 17. The more similar are the properties of particles, that is, the smaller is the value of R_θ, the larger is the value of P. Accordingly, it may be concluded that the phenomenon of segregation occurs with the difference of the surface property between particles.

IV. CONCLUSION

In the present report, the relation between the flow phenomenon of powder in the vibrating powder bed and the particle characteristics has been described. The fluidity of powder in the vibrating state can not be immediately regarded as an indication of fluidity of the general powders. However, it may be one of approaches to basic studies on dynamical powder characteristics to know the effects of the particle size, the interaction force between particles and the nature of the particle surface, on the behavior of particles in the vibrating powder bed under given conditions.

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