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THE EFFECT OF INTERPARTICLE FORCES ON THE FLUIDIZATION OF FINE PARTICLES

by

Manfred G. Baerns

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ANL-7086
Chemistry
(TID-4500, 46th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

THE EFFECT OF INTERPARTICLE FORCES ON
THE FLUIDIZATION OF FINE PARTICLES

by

Manfred G. Baerns*

Chemical Engineering Division

*Resident Research Associate, Post-Doctoral Appointment from
Technische Hochschule, Hanover, West Germany. Current Address:
Institut für Technische Chemie, der Technischen Hochschule, 3
Hanover, Callinstrasse 46, West Germany.

August 1965

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NOTATION

A	Surface area	(m ²)
C _D	Drag coefficient	
D _p	Drag force exerted on a particle	(dyne)
d _p	Particle diameter	(μ)
F _p	Adhesive force of a particle	(dyne)
G _p	Gravitational force on a particle	(dyne)
g	Acceleration of gravity	(cm/sec ²)
h	Heat-transfer coefficient	(kcal/m ² -hr-°C)
m	Weight	(g)
N	Number of particles	
p	Pressure	(g/cm ²)
q	Heat flux	(kcal/hr)
Re	Reynolds number; $Re = vd_p \rho_F / \mu$	
T	Temperature	(°C)
v	Superficial gas velocity	(cm/sec)
x	Weight fraction	

Greek Letters

α	Constant	
μ	Viscosity	(g/cm-sec)
μ _f	Friction coefficient	
ρ	Density	(g/cm ³)
φ	Angle of inclination	(degrees)
ψ	Effective interparticle force	(dyne)

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ABSTRACT

The effect of interparticle forces on the feasibility of gaseous fluidization of particles in the size range of less than $50\ \mu$ was investigated. Both the onset of fluidization and the quality of fluidization were determined by measurements of pressure drop across the bed and by measurements of heat transfer between the bed and a heated plate immersed in the bed. The interparticle adhesive forces and friction coefficients were measured by the inclined-plane method.

The ratio of the incipient fluidization velocity calculated by a conventional relationship without accounting for interparticle forces, and the incipient fluidization velocity determined by the pressure-drop and heat transfer measurements was used as an index, F.I., describing the fluidizability of a particulate material. The results of this study indicate that F.I. depends mainly on the interparticle adhesive force. The limitations of the feasibility of fluidization were shown to depend on the ratio of the weight of a particle to its adhesive force; no fluidization could be obtained when this ratio was less than 10^{-3} .

SUMMARY

When fine particles in the size range of less than $\sim 50\ \mu$ are to be fluidized, difficulties are encountered that are related to interparticle forces. The objective of this investigation was to elucidate and to describe the effect of these forces on the fluidizability of fine particles and quality of fluidization. This information will be useful for processes such as the fluorination of uranium compounds, the preparation of uranium monocarbide, and the coating of reactor fuel particles.

In the current study, the following particulate materials were used:

Material	Average particle diameter (μ)
Iron	1.6, 3.3, and 18
Nickel	18, 81, and 137
Glass Balloons	19, 35, 58, 73, 137, and 194
Alumina	11, 13, 27, 68, and 96

The interparticle forces were determined by an inclined-plane method (see Sect. III). The solids were fluidized with nitrogen in 8.2- and 14-cm-ID Lucite columns. The pressure drops across the bed of particles, as well as heat-transfer coefficients between the bed and an electrically heated plate immersed in it, were measured to determine the incipient fluidization velocity. These measurements were also used as a measure of the quality of fluidization.

The ratio of the incipient fluidization velocity calculated by a conventional relationship without accounting for the interparticle forces, and the incipient fluidization velocity determined experimentally was used as an index, F.I., describing the fluidizability of a particulate material. This study indicated that the fluidizability is mainly related to the interparticle adhesive force. The effect of the interparticle frictional force was found to be negligible.

The value of F.I. decreased when the ratio of gravitational force to the sum of gravitational force and adhesive force of a particle decreased. A state of fluidization was generally achieved as long as this ratio was $>10^{-3}$; when the ratio was smaller, the particles generally could not be fluidized.

The quality of fluidization was found to be closely related to F.I. and to the force ratio. A decrease in the fluidization quality resulted from a decrease in the two parameters. The decrease was attributed to the formation of channels and, hence, to the restricted movement of particles caused by the interparticle adhesive forces.

Fluidizability and quality of fluidization could be improved by introduction of additional energy into the bed to separate the particles from one another. A suitable method appears to be the transmittance of sonic energy. This method of improving fluidization of fine particles may be investigated in future work.

I. INTRODUCTION

Fluidization of fine particles is of interest in processes such as the fluorination of uranium compounds (e.g., U_3O_8 , UO_2F_2 , UF_4), the preparation of uranium monocarbide, and the coating of reactor fuel particles. Fine particles are in general difficult to fluidize. The difficulty in fluidizing fine particles is related to interparticle forces^{1,2} which are greater than those transmitted to the particles by the fluidizing gas. The interparticle forces cause agglomeration of these particles and bridging between such agglomerates, which favors the formation of channels through which the gas passes without fluidizing the fine particles. There is evidence that fluidization can generally only be achieved when the particle size of the solids is above a certain limit;^{1,3-6} the lower size limit of the particles which can be fluidized varies for different materials.

There is general agreement in the literature⁷⁻¹⁹ upon the molecular nature of the interparticle forces. The interparticle forces that affect the fluidization of fines comprise mainly the interparticle adhesive force and to a far lesser degree the frictional forces. The adhesion is mainly attributed to the action of Van der Waals forces and particularly to the attractive "London" component of these forces,⁸ since Van der Waals forces are effective up to a distance of 100 Å, whereas the distance between two particles in a settled bed of particulate material is of the order of about 5 Å at the point of contact.⁷

There is evidence that the adhesive forces are generally not due to electrostatic charges. Itahara²⁰ bombarded agglomerates of fine particles with 3-MeV electrons for 204 sec at a flux of 10^5 electrons per sq cm, thus favoring leakage loss of any electrostatic charge present. It was found that the agglomerates did not disintegrate and did not show any decrease in adhesiveness. These results support the assumption that, in a packed bed, opposing electrostatic charges of individual particles are probably neutralized as long as the particles are in relatively close contact with each other.¹⁴ Electrostatic charges frequently observed in fluidized beds probably occur because of poor contact between the individual particles. In addition to the molecular forces originating from the solids, attraction among the particles may be also caused by molecular forces which are exerted from adsorbed fluid.¹⁴ The frictional forces between particles are negligibly small in comparison with the gravitational and adhesive forces, and do not significantly contribute to the difficulties in fluidizing fine particles.

In the present investigation, the effects of the interparticle adhesive forces on the fluidizability of fine particles and the quality of fluidization were studied. The quality of fluidization is discussed in terms of heat-transfer properties and pressure drop across the bed.

II. MATERIALS

Iron and nickel spheres, glass balloons, and irregularly shaped alumina particles were used in this investigation. Particle sizes and densities of these materials are given in Table I. Particle-size distributions of most of the materials were measured by Coulter Counter Analysis, and the average particle diameters $\bar{d}_p$ were calculated by the relation

$$1/\bar{d}_p = \sum \frac{x}{d_{p,x}}, \quad (1)$$

where x is the weight fraction of particles with the diameter $d_{p,x}$. (The particle size distributions for most of the materials are graphically shown in Figs. 8 to 11 in the Appendix.) When no Coulter Counter Analysis was available, $\bar{d}_p$ was taken the median between two sieve openings of the

TABLE I. Particle Sizes and Densities of the Materials Studied

Materials	Average Particle Size $\bar{d}_p$ (μ)	Density (g/cm ³)
Iron ^a	1.6	7.3
	3.3	7.3
	18	7.3
Nickel ^b	18	8.9
	81 (-170 +200 mesh)	8.9
	137 (-100 +120 mesh)	8.9
Glass Balloons ^c	19	0.87
	35	0.61
	58	0.30
	73	0.28
	137 (-100 +120 mesh)	0.27
	194 (-70 +80 mesh)	0.22
Alumina ^d	11	3.9
	13	3.9
	27	3.9
	68 (-200 +230 mesh)	3.9
	96 (-140 +170 mesh)	3.9

^a1.6- and 3.3- μ iron particles: Product of Antara Chemicals, Division of Aniline and Film Corporation.

18- μ iron particles: Product of Linde Company, Division of Union Carbide.

^bProduct of Federal Mogul Bower Bearings.

^cProduct of Sohio Chemical Company.

^dProduct of Aluminum Company of America.

U. S. sieve series, which are also listed in Table I. Microscopic examination showed that the iron and nickel particles as well as the glass balloons were approximately spherical. (Some characteristic pictures of several materials are shown in Fig. 12 in the Appendix.)

In some experiments, coarse material was mixed with the fine particles to improve the fluidizability. Alumina particles, $11\ \mu$ in diameter, were mixed with $200\text{-}\mu$ glass spheres, and $1.6\text{-}\mu$ iron particles with $500\text{-}\mu$ glass spheres. In two experiments the interparticle adhesive force of $137\text{-}\mu$ nickel spheres was artificially increased by suspending the spheres in a solution of vacuum oil in acetone and then drying them so that a film of oil remained on the particles. In the first test, a concentration of 0.7 w/o vacuum oil in acetone was used; in the second, the spheres were immersed in a solution containing 1.7 w/o vacuum oil.

III. APPARATUS AND PROCEDURE

The interparticle adhesive forces were measured with the apparatus shown in Fig. 1. The design of the apparatus was based upon a method suggested by Cremer *et al.*,²¹ Boehme *et al.*,¹⁷ have observed that this method does not measure the true adhesive force of a single particle, but does measure the adhesive force of a single particle surrounded by a group of particles; this information is actually what is required in the current study since the interparticle forces affecting the fluidization of a bed of particles involves the adhesive force of a particle in an environment of other particles.

The method involves rotating a plate, usually 5 by 5 cm but in some cases 8.1 by 8.1 cm, uniformly covered with the particulate specimen, and measuring the angle of inclination (angle of slide), at which the particles slide as a bulk from the plate owing to the force of gravity. Between covering the plate with the particles and rotating it, a contact time of 5 min was allowed; this time was necessary to ensure that the results were reproducible.¹⁵ To avoid interaction between the particles and the substrate, a multilayer of particles was first glued upon the surface of the plate. The apparatus was located in a glovebox which was continually purged with nitrogen to establish constant and reproducible ambient conditions.

The following equation expresses the relationship among the angle of slide, ϕ , the adhesive force F_p exerted from a particle, and the interparticle friction coefficient μ_f :

$$m_p g \sin \phi = \mu_f m_p g \cos \phi + F_p, \quad (2)$$

where m_p is the weight of the particle and g is the gravitational constant. To evaluate the results obtained by this method m , which is the total weight

of the particles of the substrate, was substituted for m_p in Eq. (2) and F_p multiplied by the number N of particles which contact the substrate. Thus, the following relation was obtained:

$$mg \sin \phi = \mu_f mg \cos \phi + F_p N. \quad (3)$$

From repetition of the measurements for different amounts of material and plotting $mg \sin \phi$ versus $mg \cos \phi$ on Cartesian coordinates, μ_f is obtained from the slope of the line and $F_p N$ from the intercept on the ordinate. To determine F_p , N has to be known. This number was approximated by dividing the area of contact (given by the dimensions of the plate) by the square of the particle diameter.

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Fig. 1. Apparatus for the Determination of Interparticle Adhesion and Friction

The apparatus used for the fluidization experiments is shown schematically in Fig. 2. Most of the tests were performed in an 8.2-cm-ID Lucite column, although a few were conducted in a 14-cm-ID column. A porous metal plate was used as the distributor for the nitrogen fluidizing gas. The nitrogen was dried with molecular sieves, and the flow rate was measured by rotameters. Two pressure probes, connected to a water manometer, were used to measure the pressure drop (Δp) across the bed.

Fig. 2. Schematic Diagram of Apparatus Used for Fluidization Experiments

Heat-transfer coefficients were determined from measurements of the surface temperature of an electrically heated plate (6.8 by 5.0 by 0.95 cm) immersed in the bed. The surface temperature of the plate was averaged from readings of four thermocouples located on the surface of the plate. This temperature, along with the bed temperature, was registered on a recorder. When the temperature difference between the heated plate and the bed was small ($<2^\circ\text{C}$), the difference was directly measured with a potentiometer to increase accuracy. The heat-transfer coefficient h , was calculated from the following equation:

$$q = hA(T_h - T_b), \quad (4)$$

where A is the surface area of the heater, $(T_h - T_b)$ is the temperature difference between the heater plate and the bed, and q is the energy input that was determined from the electrical resistance of the heater and the applied voltage.

IV. RESULTS

A. Interparticle Adhesion and Friction

The interparticle adhesive forces and friction coefficients for iron, nickel, alumina particles, and glass balloons are listed in Table II. The interparticle forces of the smaller-sized glass balloons, that is, those for

TABLE II. Interparticle Adhesive Forces and Friction Coefficients

Material	Average Particle Diameters (μ)	Adhesive Force (dyne)	Friction Coefficient
Iron	1.6	2.5×10^{-5}	0.79
	3.3	5.5×10^{-5}	1.15
	18	6.5×10^{-4}	0.49
Nickel	18	1.5×10^{-3}	0.66
	81	1.7×10^{-2}	0.62
	137	1.8×10^{-2}	0.53
Nickel (a) ^a	137	2.3×10^{-1}	0.77
Nickel (b) ^a	137	3.0×10^{-1}	0.67
Alumina	11	7.7×10^{-4}	0.61
	13	7.8×10^{-4}	1.3
	27	3.1×10^{-3}	0.77
	68	2.0×10^{-2}	0.60
	96	5.2×10^{-2}	0.51
Glass Balloons	115	1.2×10^{-2}	b
	137	3.6×10^{-3}	b
	163	1.9×10^{-2}	b
	194	1.2×10^{-2}	b
	230	1.0×10^{-2}	b

^aAdhesive force was artificially increased by coating the surfaces of the particles with a vacuum oil; (a) and (b) refer to the treatments (see p. 11).

^bReproducible values could not be obtained.

which $\bar{d}_p < 115 \mu$, could not be experimentally determined by the inclined-plane method since neither a reproducible nor a uniform sliding of the material as a bulk from the plate could be obtained. Therefore, the inter-particle adhesive force for the smaller-sized balloons was estimated from values obtained for particles of larger sizes by means of the following relationship:^{8,15,22}

$$F_p = \text{const } \bar{d}_p. \quad (5)$$

The mean value of the constant in the equation is 0.6 ± 0.3 . This value can, of course, only be used as a rough approximation because of its poor accuracy; however, it is the only value available at present. A reproducible determination of the friction coefficients for glass balloons was not possible.

B. Fluidization Experiments

The heat-transfer coefficients and pressure drops across the bed were measured as functions of gas velocity. The incipient fluidization velocity (v_{obs}) was derived from these measurements and from visual observations. The measured incipient fluidization velocities of the various materials are listed in Table III along with the incipient fluidization velocities (v_0) which were calculated²³ (see Eq. (7), p. 18) without taking inter-particle forces into account. Incipient fluidization velocities could not be

TABLE III. Experimental Results of the Fluidization Experiments^a

Run No.	Material	$\bar{d}_p$ (μ)	Depth of Static Bed (cm)	Void Reaction of Static Bed	v_{obs} (cm/sec)	v_0 (cm/sec)	h_{max} (kcal/m ² -hr-°C)	v_h (cm/sec)	$h_{max \text{ extr}}$ (kcal/m ² -hr-°C)			
1	Iron	1.6	15	0.57	b }	8.3×10^{-4}	~260	6-7	> 260			
2			17	0.65	b }							
3		3.3	7.2	0.61	2.4 }	3.5×10^{-3}						
4			10.3	0.62	2.6 }							
5			19.8	0.61	2.3 }							
6		18	6.5	0.47	0.2	1.0×10^{-1}	480	6	550			
7	Nickel	18	3.6	0.56	0.5 }	1.3×10^{-1}	410	4				
8			7.2	0.56	0.6 }		460	5				
9			10.5	0.55	0.5 }		430	3.5				
10		81	7.4	0.55	3.4	2.7	535	12.5				
11			137	16.5	0.57	5.8 }	330	40				
12 ^c	Nickel (a)	137	16.5	0.58	8.3 }	6.7	376	16				
13 ^c	Nickel (b)	137	16.5	0.58	10.4 }		386	16				
14	Al ₂ O ₃	11	9.5	0.73	b }	2.1×10^{-2}	30	10	~520			
15			5.4	0.75	b }							
16		13	12.0	0.63	75	3.0×10^{-2}						
17		27	9.2	0.62	0.6	1.3×10^{-1}				480	15	
18		68	10.8	0.66	1.3	7.8×10^{-1}				410	15.5	450
19		96	14.0	0.65	2.8	1.6	310	12.5	320			
20	Glass Balloons	19	12.0	0.62	b }	1.4×10^{-2}	9					
21			12.0	0.60	b }							
22		35	32.0	0.51	10 to 11	3.3×10^{-2}	46	11				
23		58	11.5	0.56	3 to 5 }	4.6×10^{-2}	95	6				
24			20.5	0.52	6 to 8 }		90	12				
25			33.0	0.54	4 to 6 }		120	10				
26		73	12.4	0.48	0.9 to 1.5 }	6.8×10^{-2}	75	10				
27			31	0.49	0.6 to 1.1 }							
28		137	12.5	0.56	1 to 2 }	2.3×10^{-1}	71	4.5				
29			30.5	0.42	0.6 to 1.6 }		76	5				
30		194	13.0	0.48	1 to 1.5	4.0×10^{-1}	78	6				
31			30.5	0.45	1 to 1.5	4.0×10^{-1}	61	6				

^aThe fluidized bed diameter was 8.2 cm in all runs with the exception of Runs 1 and 21, in which the diameter was 14 cm.

^bThis material could not be fluidized.

^cAdhesive force was artificially increased by coating the surfaces of the particles with a film of vacuum oil; (a) and (b) refer to treatments (see p. 11).

measured for the 1.6- μ iron spheres, 11- μ alumina particles, and 19- μ glass balloons since these materials could not be fluidized, even when the gas velocity exceeded the entrainment velocity of the particles. The maximum heat-transfer coefficients along with the corresponding gas velocities v_h which were measured for the various materials are also given in Table III. In instances in which the measured relationship between h and v indicated that a further increase of v would result in a larger h , an extrapolated maximum value of the heat-transfer coefficient is also listed. However, these extrapolated values would correspond to velocities larger than the entrainment velocities for these particles. The results of the experiments carried out with 11- μ alumina and 1.6- μ iron particles which were admixed with glass spheres are listed in Table IV.

TABLE IV. Experimental Results of Fluidization Experiments with Mixed Materials^a

Run No.	Material	$\bar{d}_p$ (μ)	Bed Depth (static) (cm)	Void Fraction	v_{obs} (cm/sec)	h_{max} (kcal/m ² -hr-°C)	v_h (cm/sec)
32	Alumina (70 w/o) + glass spheres (30 w/o)	11 200	10.8	0.62	5 to 6	~200	30
33	Alumina (52 w/o) + glass spheres (48 w/o)	11 200	13	0.56	3 to 4	160	30
34	Iron spheres (96.6 w/o) + glass spheres (3.4 w/o)	1.6 500	15	0.53	b		
35	Iron spheres (93.5 w/o) + glass spheres (6.5 w/o)	1.6 500	16	0.52	b		
36	Iron spheres (88 w/o) + glass spheres (12 w/o)	1.6 500	18.5	0.54	~10	20 to 30	20
37	Iron spheres (78 w/o) + glass spheres (22 w/o)	1.6 500	21	0.45	~10	24	21

^aThe fluidized bed diameter was 8.2 cm in Runs 32 and 33 and 14 cm in Runs 34 to 37.

^bThis material could not be fluidized.

The pressure drop Δp increased initially with increasing gas velocity for all materials in a fashion similar to that of a packed bed. However, after this initial increase, the relationship between the pressure drop and the gas velocity differed for the various materials, depending on the particle size. Based on this difference, the Δp measurements are classified into three groups which are exemplified in Fig. 3 and outlined in the following:

Case 1: The pressure drop across beds of relatively large particles (81- and 137- μ nickel spheres, 68- and 96- μ alumina particles, and 137- and 194- μ glass balloons) remained invariant at a value of $\Delta p = \Delta p_{ffb}$ (when Δp_{ffb} = weight of the bed/cross section of the bed) after fluidization commences. At velocities less than the minimum fluidization, Δp increased linearly with an increase in gas velocity. At the point at which the gas velocity approached the minimum fluidization, the relationship became markedly nonlinear, and the value of Δp may at a certain gas velocity exceed Δp_{ffb} before fluidization commences. If Δp_{ffb} had been exceeded, Δp decreased to Δp_{ffb} after the bed expanded and fluidization started; then Δp stayed constant within $100 \pm 5\%$ of Δp_{ffb} with further increase in gas

Fig. 3. Dependence of Pressure Drop on Gas Velocity

in Cases 1 and 2 (1.6- μ iron spheres, 11- and 13- μ alumina particles, and 19-, 35-, 58-, and 73- μ glass balloons) did not reach Δp_{fb} but were always 20 to 40% lower. In these instances, severe channeling was visually observed. Fluidization was achieved only with the larger glass balloons (73, 58, and 35 μ). A state of intermittent fluidization was obtained with 13- μ alumina particles, whereas the 1.6- μ iron spheres, 11- μ alumina particles, and 19- μ glass balloons could not be fluidized at all.

When the smaller sizes of either alumina or iron particles were mixed with larger glass spheres, the behavior of pressure drop was similar to that described in Case 2. A state of intermittent fluidization was obtained with 1.6- μ iron particles to which 12 or 22 w/o of 500- μ glass spheres were added. No particle motion occurred when the bed of iron particles contained less quantities (3.4 and 6.5 w/o) of glass spheres. In analogy, two different mixtures of 11- μ alumina and 200- μ glass spheres were studied; the concentration of the glass spheres were 30 and 48 w/o. These were fluidized, and the relationship between pressure drop and gas velocity was similar to that observed previously by Katz²⁴ for particles of mixed sizes.

velocity. Fluidization occurred at gas velocities just above the point where Δp had become constant, which resulted in a noticeable increase of the measured heat-transfer coefficient.

Case 2: The pressure drop across beds of smaller particles (3.3- and 18- μ iron spheres, 18- μ nickel spheres, and 27- μ alumina) increased to $\sim \Delta p_{fb}$, then decreased to a value which was about 15 to 20% smaller than Δp_{fb} . In all these instances, gas channels were observed, and particle motion occurred only in limited areas of the bed, if at all. With further increase of the gas velocity, the pressure drop began to approach Δp_{fb} again; then fluidization started, which was also indicated by a sharp increase of the heat-transfer coefficient.

Case 3: The pressure drops across beds of particles smaller than

V. DISCUSSION

The measured incipient fluidization velocities, the pressure drops across the bed as a function of gas velocity, and the heat-transfer properties followed a general pattern for all materials. Since these properties are related to the fluidizability of particles and quality of fluidization that can be achieved with a given particulate material, it is necessary to evaluate the effects of the interparticle adhesive force on the fluidizability and quality of fluidization.

A. Fluidizability

The fluidizability is quantitatively expressed by a fluidizability index (F.I.) which is defined as the ratio of the calculated incipient fluidization velocity to that observed:

$$F.I. = v_0/v_{obs} \quad (6)$$

The velocity v_0 was calculated from the following equation,²³ which assumes the absence of interparticle adhesive and frictional forces:

$$(C_D Re^2)_{\text{incipient fl}} = 0.0194 \frac{d_p^3 \rho_F g (\rho_S - \rho_F)}{\mu^2}, \quad (7)$$

where the drag coefficient C_D is given by

$$C_D = \frac{24}{Re} (1 + 0.15 Re^{0.69}), \quad (8)$$

Re is the Reynolds number, defined as

$$Re = v \rho_F d_p / \mu, \quad (9)$$

ρ_F is the density of the gas, ρ_S that of the solid, and μ the viscosity of the gas.

The dependence of F.I. on the particle diameters is presented in Fig. 4 for the four materials investigated. The plot shows the following:

(1) For relatively large particle sizes, depending on the material, F.I. is or approaches 1.

(2) With decreasing d_p , F.I. decreases sharply and becomes zero when a certain lower limit of d_p is reached. This lower limit differs with material.

Fig. 4. Dependence of Fluidizability Index on Particle Diameter

These results show that Eq. (7) is valid only for particle sizes above a certain limit, i.e., when F.I. equals 1, and that great care has to be taken in applying this equation for the calculation of incipient fluidization velocities of fine particles. An explanation for these deviations which is based on the existence of interparticle forces is presented in the next section.

Fig. 5. Simplified Model of Forces Acting on a Particle in a Bed of Particulate Material with Gas Flowing Upward

B. The Effect of the Interparticle Adhesive Force on the Fluidizability

To describe the effect of the interparticle adhesive force on the fluidizability, consider the various forces acting on a single particle in a settled bed through which gas is flowing upward. As shown in Fig. 5, three forces act on a particle in settled condition:

- (1) the gravitational force, G_p , which equals the weight of the particle;
- (2) the drag force D_p , a result of interaction between the particle and the flowing gas;
- (3) the effective interparticle force ψ between the particle and its surroundings, which is opposed to D_p .

To fluidize the settled bed, the particles have to be separated and suspended in the gas stream. To separate a particle from its surrounding and to suspend it in the gas, the following relation must be valid:

$$D_p = G_p + \psi. \quad (10)$$

The term ψ has been treated in all previously published work (see, for example, Ref. 23) as a factor which is negligibly small relative to G_p and has been ignored. However, the results of the current work indicate that ψ must be considered in determination of the true incipient fluidization velocity that is v_{obs} . The relationship between ψ and the fluidizability index can be demonstrated as follows:

The drag force D_p is given²⁵ by

$$D_p = \alpha C_D \frac{\pi}{8} d_p^2 \rho_F v^2. \quad (11)$$

When no interparticle forces have to be considered, the incipient fluidization velocity v_0 can be derived from the following equation:

$$G_p = \alpha C_{D_0} \frac{\pi}{8} d_p^2 \rho_F v_0^2. \quad (12)$$

If one considers, however, the interparticle forces, Eq. (10) has to be used, and one obtains

$$G_p + \psi = \alpha C_{D_{obs}} \frac{\pi}{8} d_p^2 \rho_F v_{obs}^2, \quad (13)$$

where ψ can be regarded as the effective interparticle force that has to be overcome, in addition to G_p , to fluidize the particles. Division of Eq. (12) by Eq. (13) gives

$$\frac{G_p}{G_p + \psi} = \frac{C_{D_0} v_0^2}{C_{D_{obs}} v_{obs}^2}$$

for any given system, since all other parameters are the same. Now, C_D may be approximated by $C_{D_0} = 24/Re$ according to Eq. (8), since Re is smaller than 1 under the experimental conditions. Then,

$$\frac{G_p}{G_p + \psi} = \frac{\frac{24 \mu}{v_0 \rho_F d_p} v_0^2}{\frac{24 \mu}{v_{obs} \rho_F d_p} v_{obs}^2} = \frac{v_0}{v_{obs}}. \quad (14)$$

Comparison of Eqs. (14) and (6) gives

$$\frac{G_p}{G_p + \psi} = F.I. \quad (15)$$

Thus, F.I. is essentially a measure of the effective interparticle force ψ as defined by Eq. (10). As a first approximation, it was assumed that ψ equals F_p . To test the validity of this assumption, F.I. and the force ratio $G_p/(G_p + F_p)$, which are given in Table V, were plotted versus each other (see Fig. 6) for all the investigated materials. The plot shows that the assumption $\psi = F_p$ is not valid and indicates that the deviation from the postulated relation (15) is similar for all materials. The relation between $G_p/(G_p + F_p)$ and F.I. shows that ψ is initially smaller than F_p ; with a decrease in the force ratio, ψ becomes equal to F_p and finally exceeds F_p . In the following, an interpretation of the relation between F_p and ψ is presented.

TABLE V. Fluidizability Indexes and Force Ratios

Run No.	Material	$\bar{d}_p$ (μ)	Fluidizability Index	Force Ratio
1,2	Iron	1.6	0	6.1×10^{-4}
3-5	Iron	3.3	1.4×10^{-3}	2.5×10^{-3}
6	Iron	18	5.0×10^{-1}	3.3×10^{-2}
7-9	Nickel	18	2.5×10^{-1}	1.8×10^{-2}
10	Nickel	81	8.0×10^{-1}	1.3×10^{-1}
11	Nickel	137	1.1	4.0×10^{-1}
12	Nickel (a) ^a	137	8.1×10^{-1}	4.9×10^{-2}
13	Nickel (b) ^a	137	6.4×10^{-1}	3.8×10^{-2}
14,15	Al ₂ O ₃	11	0	3.5×10^{-3}
16	Al ₂ O ₃	13	4.0×10^{-3}	5.4×10^{-3}
17	Al ₂ O ₃	27	2.0×10^{-1}	1.2×10^{-2}
18	Al ₂ O ₃	68	6.0×10^{-1}	2.3×10^{-2}
19	Al ₂ O ₃	96	6.0×10^{-1}	4.6×10^{-2}
20,21	Glass Balloons	19	0	2.7×10^{-3}
22	Glass Balloons	35	3.0×10^{-3}	6.2×10^{-3}
23-25	Glass Balloons	58	9.0×10^{-3}	8.6×10^{-3}
26,27	Glass Balloons	73	7.0×10^{-2}	1.3×10^{-3}
28,29	Glass Balloons	137	1.7×10^{-1}	4.2×10^{-2}
30,31	Glass Balloons	194	3.0×10^{-1}	6.3×10^{-2}

^a Adhesive force was artificially increased by coating the surfaces of the particles with a vacuum oil; (a) and (b) refer to the treatments (see p. 11).

Fig. 6. Dependence of the Fluidizability Index on the Force Ratio

Since the structure of a bed of particulate material is never completely homogeneous, the gas preferably flows through "gaps" which exist in the structure; this initiates gas channels. When the interparticle adhesive force is relatively small, such channels are unstable and disappear immediately after their formation due to the relatively free movement of particles into the channels. The channels then transform into gas bubbles. The bubbles move upward through the bed, causing further particle motion. Collision between particle agglomerates may result in their disintegration. When the gas velocity is high enough to keep the particles suspended, fluidization is

maintained. Thus, the fluidization is initiated by the instability of gas channels rather than by separating individual particles from one another by the action of the drag force. The phenomena of bubble formation owing to the collapse of a channel are illustrated by a sequence of three pictures taken with a high-speed motion-picture camera (see Fig. 7).

With a decrease in particle size, the interparticle adhesive force becomes relatively large compared with G_p ; also, the inhomogeneity of the bed structure increases, as indicated by the large void fraction of about 0.6 to 0.7 (see Table III) of the bed in static condition. The higher inhomogeneity favors the formation of gas channels and, as a consequence of the concomitant increase in interparticle adhesiveness, the stability of gas channels is increased. These channels become so stable that they extend through the whole bed, and no fluidization occurs at all. This happens, as indicated by Fig. 6, when the force ratio $G_p/(G_p + F_p)$ is of the order of 1×10^{-3} to 5×10^{-3} .

The stability of gas channels is weakened by addition of coarse particles to the bed of fines as has been shown in the tests performed with $11\text{-}\mu$ alumina particles admixed with $200\text{-}\mu$ glass spheres and $1.6\text{-}\mu$ iron particles admixed with $500\text{-}\mu$ glass spheres. In both cases, the addition of the coarse material increased the fluidizability indexes. This can be explained by assuming that the coarser particles are dislodged by their weight from the stable structure of a channel, thus, in turn, initiating particle motion.

It was mentioned above that the fluidizability is impaired when the interparticle adhesive force increases. This contention was proven to be correct by the experiments which were conducted with nickel spheres of artificially induced adhesiveness as shown in Table V.

Summarizing, it can be said that the interparticle adhesive force determines the stability of the channels which, in turn, establishes the fluidizability of a particulate material. The quantity ψ as defined by Eq. (10) is related to the adhesive force of a particle; however, also other effects such as the inhomogeneity of the bed structure influence ψ .

C. Quality of Fluidization

In the current work the quality of fluidization is described in terms of heat-transfer properties and the pressure drop across the bed because both these properties are of interest in practical applications. This method appears justified because no absolute measure is available at present to compare quantitatively the quality of fluidization of different systems, as was recently shown by Sutherland.²⁶

The maximum values, with respect to the gas velocity, of heat-transfer coefficients between a surface and the fluidized bed vary, in general,

$t = 0 \text{ sec}$

$t = 3.4 \times 10^{-2} \text{ sec}$

$t = 6.9 \times 10^{-2} \text{ sec}$

Fig. 7. Collapsing of a Gas Channel Resulting in Bubble Formation in an 8.2-cm-ID Bed of 58- μ Glass Microballoons at a Superficial Gas Velocity of 3 cm/sec

inversely as the particle size.^{27,28} The results of this work indicate, however, that this relationship is not valid for very small particles. As shown in Table III, the measured or extrapolated maximum heat-transfer coefficients increase at first with a decrease in particle diameter; then, with a further decrease in particle size, the maximum heat-transfer coefficients begin to fall off. This change in the relationship between the heat-transfer coefficient and the particle size occurs when the observed incipient fluidization velocity is significantly larger than the calculated one. Thus, the fluidization quality, as expressed by the maximum heat-transfer coefficients, decreases with decreasing particle size when F.I. becomes markedly smaller than 1.

The deviation in the measured pressure drop Δp from the case of ideal fluidization ($\Delta p = \Delta p_{fb}$), as exemplified in Fig. 3, can be also used as a measure for the quality of fluidization. Pressure drops smaller than Δp_{fb} are caused when the gas passes mainly through channels. Since channeling, in turn, results in restricted particle movement, the pressure deviation ($\Delta p_{fb} - \Delta p$), which is primarily a measure of the amount of gas flowing through channels, can also be regarded as a measure of the quality of fluidization. The difference between the observed pressure drop and the pressure drop that would occur in the case of ideal fluidization increased markedly as the bed particle size decreased. This fact also indicates that the quality of fluidization decreases with decreasing particle size if one considers the particle size range where F.I. is smaller than 1.

D. The Effect of Interparticle Adhesive Forces on the Quality of Fluidization

The effect of the interparticle adhesive force on the quality of fluidization as expressed by the heat-transfer coefficient and the pressure drop across the bed can be essentially described by the same method employed in the preceding section. As long as F_p is small in comparison to G_p , the solid particles move freely in the bed. When F_p is large in comparison to G_p , the particle circulation is impaired because of the stability of gas channels; also, agglomeration of the particles increases, resulting in a larger "effective diameter" of the moving solids. Both these phenomena, which are attributed to the interparticle adhesion of the particulate material, result in the impairment of the quality of fluidization.

VI. CONCLUSIONS AND RECOMMENDATIONS

The results obtained in this study show that the fluidizability and the quality of fluidization are determined by the relative magnitude of the adhesive force between two particles in comparison to the weights of the particles. The dependence of the fluidizability and the quality of fluidization on the interparticle adhesive force can be roughly described in terms of the force ratio $G_p/(G_p + F_p)$ for the investigated materials as follows:

(1) Zone of fluidization: $G_p/(G_p + F_p) > 5 \times 10^{-2}$. No difficulties are encountered in fluidizing the solids. The quality of fluidization is good; thus, high heat-transfer coefficients, 200 to 500 kcal/(m²)(hr)(°C), are achieved.

(2) Zone of quasifluidization: $5 \times 10^{-2} > G_p/(G_p + F_p) > 3 \times 10^{-3}$. The fluidizability decreases rapidly with diminishing force ratio and severe channeling occurs. The gas velocities necessary to fluidize are so high that significant amounts of the particulate material are elutriated. The quality of fluidization is reduced; the heat transfer is poor and heat-transfer coefficients range from 50 to 250 kcal/(m²)(hr)(°C).

(3) Zone of no fluidization: $3 \times 10^{-3} > G_p/(G_p + F_p)$. In this range fluidization is not achieved; channel formation and fines elutriation are prevalent. The heat-transfer coefficients are $h < 20$ kcal/(m²)(hr)(°C), corresponding to those of a settled bed.

The fluidizability and quality of fluidization can be approximately predicted by knowledge of the interparticle adhesive force and the particle weight of a particulate material. This conclusion, drawn from the experimental results of this study, appears to be justified since the fluidizability index and the force ratio of all the investigated materials could be correlated within certain limits (see Fig. 6) although the physical properties of the materials differed widely.

The results further indicate that the effective interparticle force ψ has to be taken into account for smaller particles to predict the incipient fluidization velocity of the gas for a given particulate material. The limiting particle size depends on the kind of material to be fluidized. To obtain a definite relationship between ψ and the interparticle adhesive force, further investigations must be performed.

When a particulate material cannot be fluidized by passing gas through the settled bed, it is necessary to introduce additional energy to dislodge the particles which are held together by the interparticle adhesive forces. The channels which are formed in the settled bed may be continuously destroyed by a mechanical device like a stirrer.⁶ This causes movement of large particle agglomerates in the bed, thus achieving bed properties similar to that of a fluidized bed with respect to heat transfer and pressure drop. The addition of coarse material to the bed of fines to unstabilize the channels also causes movement of particle agglomerates. The separation of individual particles from one another, so that they can be suspended in the upward-flowing gas stream which thus avoids the formation of channels, may be achieved by: (1) vibration of the reactor²⁹ and (2) introduction of sonic energy into the system by the gas stream.³

APPENDIX

Supplementary Information

Figures 8 to 12

Fig. 8. Size Distributions of Iron Spheres

Fig. 9. Size Distribution of Nickel Spheres

Fig. 10. Size Distributions of Glass Microballoons

Fig. 11. Size Distributions of Alumina Particles

1 division $\approx 3.75 \mu$

a: Nickel Spheres

$\bar{d}_p = 18 \mu$

1 division $\approx 3.75 \mu$

b: Iron Spheres

$\bar{d}_p = 18 \mu$

1 division $\approx 15 \mu$

c: Alumina Particles

$\bar{d}_p = 68 \mu$

1 division $\approx 15 \mu$

d: Glass Microballoons

$\bar{d}_p = 58 \mu$

Fig. 12. Photographs of Some Particulate Materials

ACKNOWLEDGMENTS

The author's sincere thanks are due to James Savage and John Phelps for their technical assistance in carrying out much of the experimental work. The continued encouragement and support rendered by Dr. D. Ramaswami and stimulating discussions with Albert A. Jonke, William J. Mecham, and Norman M. Levitz are gratefully acknowledged.

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