Mechanism of Fast Fluidization and Vertical Profile of Solid Concentration in Fast Fluidized Beds*

(Regime of Fast Fluidization)

Yukihisa FUJIMA**, Kenji TAGASHIRA***,
Hiromu TAKATSUKA****, Yoshihisa ARAKAWA****
and Takashi HASEGAWA*****

The gas velocity in the circulating fluidized beds of, for example, aluminum ore calciners, petroleum crackers and boilers is larger than the particles' terminal velocity. We propose the growing chain model, in which the particles form vertical chains in the fluidized bed, in order to determine theoretically the regimes of fast fluidization. Comparing the fluidization condition empirically recognized as the optimum operating condition for the circulating fluidized bed in boilers, the maximum fast fluidization gas velocity is found to coincide with the terminal velocity of an infinitely long chain, which is about twice as high as that of a single particle.

Key Words: Circulating Fluidized Bed, Fast Fluidization, Vertical Chain, Superficial Velocity, Terminal Velocity

1. Introduction

Circulating fluidized beds have been used in petroleum crackers, aluminum ore calciners, boiler furnaces and other reactors since Robinson's patent⁽¹⁾⁻⁽⁵⁾. In the fluidized beds, particles fed into the lower part with gas are suspended in the reactors. Particles flowing out from the top of the beds are collected and fed again into the bottom of the reactors either directly or after having undergone heat exchangers. The

suspension provides a huge area for a solid-gas reaction and stores a large amount of heat at a stable controlled temperature.

A dense suspension of particles can be formed in a gas stream which is ascending at a velocity higher than the terminal velocity of the particles. This phenomenon has many aspects and so the mechanism of the fluidization has not yet been fully clarified both theoretically and experimentally.

In this paper fluidization with high-velocity gas is called "fast fluidization". Li and Kwauk⁽⁴⁾, Reh⁽⁵⁾, Matsen⁽⁶⁾, Horio⁽⁷⁾, and Hirama et al.⁽⁸⁾ tried to classify what had been observed experimentally, but many points still remain to be clarified in and among their results. Theoretically, Wallis⁽⁹⁾, Li et al.⁽¹⁰⁾, and Wirth⁽¹¹⁾, have proposed and developed two-phase models, which are based on the assumption that the condition should be so that the energy required to sustain fluidization is a minimum. However, many points still require further investigations in each model, because of their lack of generality and because of the dependence on experiments as far as essential correlations are concerned.

Zenz and Othmer⁽¹²⁾ and Reh⁽⁵⁾ have already

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 - ** Nagoya Univ. CIRSE, Furo-cho, Chikusa-ku, Nagoya 464-01, Japan
 - *** Mitsubishi Heavy Industries, Ltd., Technical Headquarters, Nagasaki R & D Center, 5-717-1 Fukahori-machi, Nagasaki 851-03, Japan
 - **** Mitsubishi Heavy Industries, Ltd., Power Systems Engineering Center, 3-3-1 Minatomirai, Nishi-ku, Yokohama 220, Japan
 - ***** Mitsubishi Heavy Industries, Ltd., Power Systems Engineering Dept., Yokohama Dock Yard & Machinery Works, 1-8-1 Sachi-ura, Kanazawa-ku, Yokohama 236, Japan

suggested that the wake of particles is the origin of the fast fluidization. However, insufficient knowledge of the interactions between particles has prevented this theory from being developed.

In this study, a model is proposed which can be used to describe the mechanism of fast fluidization. It is based on the observation that there are dense vertical strings of particles in the fluidized bed. The characteristic features to be analyzed using this model are (1) the regime, (2) the diffusive nature, (3) the vertical profile of particle concentration and (4) the sudden change in the concentration profile of fast fluidization with change in the gas velocity.

In this report the first subject of these is discussed.

Nomenclature

- Ar : Archimedes number $= d^3 \rho_g (\rho_s - \rho_g) \cdot g / \mu_g^2$
 C : volumetric concentration of particles
 C_D : total drag coefficient on a particle
 C_{D0} : C_D of a single particle
 C_{Di} : C_D of the i -th particle in a chain of particles
 d : diameter of particle
 g : acceleration due to gravity (980 cm/s)
 l : distance between centers of two adjacent particles
 N : number of particles in a chain of particles
 Re : Reynolds number
 Re_A : terminal Re of particles in a uniform distribution
 Re_F : terminal Re of a chain
 Re_{FF} : terminal Re of an infinitely long chain
 Re_T : terminal Re of a single particle
 S : blockage factor (the fraction of the area projected onto a plane perpendicular to the stream, which is occupied by particles)
 $y = Re_A / Re_T - 1$
 ρ_g : gas density
 ρ_s : particle density
 μ_g : dynamic viscosity of gas

2. Model

The concentrations of particles are typically $1 \times 10^{-3} \sim 5 \times 10^{-2}$ and 0.2 in the upper and lower regions of the fast fluidized bed respectively⁽¹³⁾. Although there is no distinct lower limit of concentration at which fast fluidization occurs, 3×10^{-4} is considered to be the practical limit⁽⁶⁾. The relationship between the concentration of particles and the distance between the centers of two adjacent particles in a uniform array of particles of the same diameter is given by

$$\frac{l}{d} = \left(\frac{\pi}{6C} \right)^{1/3}, \quad (1)$$

l/d is no larger than 12 even at the lowest concentration, at which fast fluidization occurs, 3×10^{-4} , and is

approximately the same as the length of the wake behind a particle. The drag, which the stream exerts on each particle in a chain, is smaller than that exerted on a single particle. In other words, particles become not to be carried up, even when the velocity of the gas flowing vertically upwards exceeds the terminal velocity of a single particle.

Figure 1 shows schematically the cycle of vertical chain formation and its dissociation. The top left section of Fig. 1 shows the uniform distribution of particles. If the distance between two vertically adjacent particles is slightly decreased, the upper particle is attracted to the lower one under the strong influence of its wake, which reduces the drag on the upper particle, to start a chain. Because this chain is heavier than single particles, it continues to drop onto other particles at lower positions on the same stream line to form a longer chain. With the increase in the chain length and the consequent increase in the relative velocity of the chain to that of the stream, the weight of each particle becomes equal to the drag exerted by the stream and the compression force between two adjacent particles vanishes. Therefore, long chains can be broken easily by any weak force to form single particles again. This particle behaviour results in a broadening of the range of the relative velocity of the particles and the stream, which causes vertical stirring and diffusive mixing, which are characteristics of fluidization, in a gas flowing upward at a velocity higher than the terminal velocity of a single particle.

Figure 2 explains the joining of particles in more detail. It is assumed that particles distribute uniformly in the vertical direction as shown by open circles, and that two of them join to form a chain, as indicated by filled circles. Since this chain has a larger relative velocity than the single particles, it joins single particles below it to form a longer chain. In this model, the influence of particles distributed horizontally is

Fig. 1 Cycle of chain formation and dissociation

Fig. 2 Growing chain model

assumed to be negligible.

3. Sphere and Stream

Some fundamental facts are discussed below as a basis for the investigation of fast fluidization using the above model.

3.1 Wake behind sphere

Bevilaqua and Lykoudis⁽¹⁴⁾ investigated experimentally the velocity profile behind a steel ball 2.54 cm in diameter suspended by a straight wire 0.05 cm in diameter at the center of a pipe 45 cm in diameter. The blockage factor of the ball is 0.003 and the effect of the pipe wall on the flow through the pipe can be neglected. The experiment, which was performed at $Re=78\,000$, indicated that (1) the diameter of the wake is nearly equal to that of the particle and (2) the ratio of the velocity on the wake axis to that far from the wake is given by $1-0.38 \times (x/d)^{-0.686}$ (for $x/d > 5$). At a distance of 12 times the particle diameter from the particle center, the velocity ratio is 0.93. This distance may be considered to be the length of the wake.

3.2 Influence of blockage factor of sphere on the drag

The blockage factor of spheres which are distributed in a cubic array, one axis of which is directed along the stream is given by

$$S = \frac{\pi \left(\frac{d}{l} \right)^2}{4} = \frac{\pi \left(\frac{6C}{\pi} \right)^{2/3}}{4} \quad (2)$$

A particle concentration of $10^{-4} \sim 10^{-1}$ corresponds to a blockage factor of $2.6 \times 10^{-3} \sim 2.6 \times 10^{-1}$. While the interaction between spheres and the stream does not have an influence in directions normal to the stream, that is, horizontally, when the blockage factor is small, the influence becomes notable when the blockage factor increases because of the smaller distance between adjacent particles.

Modi & Akutsu⁽¹⁵⁾ experimentally investigated the drag on a sphere set on the central axis of a horizontal square duct, 20.3 cm², by changing the

Fig. 3 Influence of blockage factor of particles on drag⁽¹⁵⁾

diameter of the sphere from 3.8 cm to 12.7 cm. The duct was 2.44 m long and equipped with a honeycomb straightener at the inlet. A mixture of water and glycerol was used as the fluid. The drag coefficients at blockage factors of $S=0.196$ and 0.306 are reported to be 1.56 times and about 2 times as large as that at $S=0.027$ respectively. The stream velocity used to calculate the drag coefficient was given by dividing the volumetric flow rate by the cross-sectional area of the duct, to give the so-called superficial velocity. The total drag coefficient appears to increase with increasing blockage factor because of the eventual higher velocity of the fluid through the clearance between the ball and the duct walls.

Figure 3 shows the correlation between C_D and Re calculated by dividing the flow rate by the complement of the blockage in order to examine the influence of the flow speed around the sphere on the total drag coefficient. Because Re contains the relative velocity between the fluid and the particle and the drag coefficient is a ratio of forces, the particle gets from the fluid, to the dynamic pressure times the cross-sectional area of a particle, the two numbers in Fig. 3 were calculated using Eqs. (3) and (4) from those evaluated with the superficial velocity.

$$Re = Re^*/(1-S) \quad (3)$$

$$C_D = C_D^* \left(\frac{Re^*}{Re} \right)^2 = C_D^* \cdot (1-S)^2, \quad (4)$$

where * denotes the values calculated with the superficial velocity. Figure 3 shows that the relation between C_D and Re is not greatly affected by the blockage factor S in the range of S smaller than 0.2. Although C_D at $S=0.306$ is larger than that for $S < 0.2$ the difference is only about 10%. The blockage factors $S=0.2$ and 0.3 correspond to concentration of 0.067 and 0.123 respectively. These concentrations are approximately equal to the highest volumetric concentrations observed in fast fluidization.

3.3 Drag of particles on a straight stream line

Using this model we investigate the behavior of particles which exist on a stream line. The drag on a

Fig. 4 Drag of upstream and downstream particles⁽¹⁶⁾

particle, which is under the influence of the wake of the adjacent upstream particle, was estimated with the theoretical prediction by Taniguchi and Asano⁽¹⁶⁾. Their results are shown in Fig. 4. The calculation was performed for the range of ratios of the center-to-center distance to the particle diameter from 1.5 to 9.99 and for the range of Re from 1 to 30. Simple correlations were proposed for the drag of each particle.

$$\frac{C_D}{C_{D0}} \left[0.32 \left(\frac{l}{d} \right)^{-1.40 Re^{0.42}} + 1.0 \right]^{-1} \quad \text{(Upstream particle)} \quad (5)$$

$$\frac{C_D}{C_{D0}} = \left[0.53 \left(\frac{l}{d} \right)^{-0.90 Re^{0.06}} \times Re^{0.31} + 1.0 \right]^{-1} \quad \text{(Downstream particle)} \quad (6)$$

Here, C_{D0} means the drag on a single isolated particle. The drag on an upstream particle is nearly the same as that on a single particle but the drag on a downstream particle decreases as Re increases. In this model it is necessary to estimate the drag on each particle in a chain in which there is no clearance between two adjacent particles. Although Fig. 4 indicates that the drag on the upstream particle depends on Re , Eq. (5) gives a constant equal to 0.757 for $l/d = 1$ independently of Re . In this study, the drag is estimated by fitting to the extrapolation of the calculation for $l/d = 1$ in Fig. 4.

$$\frac{C_D}{C_{D0}} = 1 - \exp(-1.204 Re^{0.2164}) \quad \text{(Upstream particle)} \quad (7)$$

As far as the downstream particle (particle B in Fig. 4) is concerned, Eq. (6) gives the drag extrapolated to $l/d = 1$ in Fig. 4 fairly accurately. Re is lower than 1000 in fast fluidization as mentioned later.

4. Drag of Particle Group

4.1 Influence of surroundings perpendicular to the stream line

According to the investigations cited in sections

3.1 and 3.2, the influence of surroundings perpendicular to the stream line on to the drag is practically negligible, if the blockage factor is lower than about 0.2 and the influence is not large up to a blockage factor of 0.3. The blockage factors 0.2 and 0.3 correspond to concentration of 0.067 and 0.123 respectively. On the other hand, Avidan and Yerushalmi⁽¹⁷⁾ examined the relationship between the superficial velocity and the concentration on a log-log graph and reported that the gradient of the curves changes sharply at a concentration of 0.05. The center-to-center distance is about twice as large as the particle diameter at this concentration. Therefore, it is expected that a particle may move quite freely through the voids between distributed particles if the concentration is lower than 0.05, while the ease with which particles move may change in mixtures with a concentration greater than 0.05. At a concentration of 0.185, it becomes necessary for a particle to push aside other particles in a direction normal to its direction of motion. These facts indicate that the drag on a particle in the gas flow in the vertical direction is not influenced by particles distributed horizontally if the concentration is lower than 0.15. It is assumed here for simplicity that the essential relationship, referred to above, are valid up to a concentration of $\pi/6$, at which particles on adjacent points of a cubic lattice are in contact.

4.2 Drag at high Reynolds number

The analysis by Taniguchi and Asano is limited to a Re value of 30. However, it is assumed here that Eqs. (5)–(7) can be extrapolated up to a Re of 2×10^3 , which is probably larger than the highest value for fast fluidization, taking into consideration the fact that the wake of a sphere is stable up to $Re = 260$ and the flow around a sphere is laminar even at $Re = 10^3$.

4.3 Drag of more than two particles

While previous work⁽¹⁶⁾ focused investigation on two particles on a straight stream line, the behavior of more than two particles is discussed in this study. The drag on the upstream particle is larger than 80% of that on a single particle and the dependence on the center-to-center distance is weak as shown in Fig. 4. This suggests that the influence of the downstream particle on the drag on the upstream particle is small, especially at high Re . At low Re , the drag of the two particles is nearly equal. Therefore, it is assumed that the drag on any particle behind the one which is furthest upstream can be estimated using Eq. (6).

5. Terminal Velocity of Particle Chain

The terminal velocity of some principal particle states is calculated in this chapter. This calculation is necessary in order to analyze fast fluidization using the proposed model.

5.1 Terminal velocity of uniformly distributed single particles

Here we estimate the velocity of particles of a certain diameter, which are distributed in a cubic array, one axis of which is vertical, falling in a still gas without acceleration. The balance of the two forces is given by

$$Ar = \frac{3}{4} C_D \cdot Re^2, \quad (8)$$

where Re are calculated from the relative velocity of the particles and the gas. Because each particle in an infinite uniform distribution is thought to be influenced most strongly by the nearest upstream particle, the drag on it is assumed to be equal to that of the downstream particle in Taniguchi and Asano's analysis. That is, C_D in Eq. (8) is estimated to be the product of C_{D0} in Eq. (6) and l/d in Eq. (2). Therefore, Re for the terminal velocity of uniformly distributed particles is a function of only Ar and concentration, as shown in Fig. 5.

While the terminal velocity at a concentration of 1×10^{-4} is approximately equal to that of a single particle in an infinitely large still gas, it becomes 1.5 to 3.0 times large at a concentration of $\pi/6$, at which adjacent particles in the cubic array are in contact. Re at the concentration of $\pi/6$ is shown numerically in Fig. 5. The curve for $Ar=600$ is shown again on a linear scale graph in Fig. 6, which shows that the terminal velocity increases rapidly at first from 16.3 as the concentration increases from 0 and then increase

Fig. 5 Terminal velocity of uniformly distributed particles

more slowly up to 31.7.

y , defined by $Re_A = Re_T(1+y)$, can be expanded near the point where concentration $C=0$ as

$$y = 0.265 \left(\frac{6}{\pi} \right)^{0.3} Re_T^{0.31} \cdot C^{0.3 Re_T^{0.06}} \quad (9)$$

The power of C is smaller than 1 for particles with a diameter larger than $0.1 \mu\text{m}$, which results in a negative second differential with respect to C . This feature is important in investigating the region of fast fluidization where there is sharp change in the concentration.

5.2 Terminal velocity of a vertical particle chain

The balance of forces on a particle chain is given by

$$Ar = \frac{3}{4} Re^2 \left(\sum_{i=1}^N C_{Di} \right) \frac{1}{N} \quad (10)$$

where i is the number related to the position of a particle in a chain, and 1 is the lowest i.e. the most upstream. C_{D1} is given by Eq. (7) and C_{Di} is given by Eq. (6) with $l/d=1$ for every position, regardless of the actual dependence on the position.

$$\frac{C_{Di}}{C_{D0}} = (0.53 Re^{0.31} + 1)^{-1} \quad (11)$$

Thus, the right-hand side of Eq. (10) contains only Re and the number of particles. Figure 7 shows the general relationships between the terminal velocity and the number of particles for $Ar=1000, 500$ and 200 . The terminal velocity increases to 1.8 to 2.0 times its initial value as the number of particles increases to around 100, but the rate of increase decreases and Re reaches a definite value, which is a function of Ar . The final Re is called Re_{FF} hereafter. Figure 8 shows Re_{FF} as a function of Ar together with the terminal Re_T for a single particle. The ratio of Re_{FF} to Re_T is between 1.5 and 3.0 and increases as Ar increases. The agreement of Re_A at the concentration of $\pi/6$ in Fig. 5 with Re_{FF} is attributed to the neglect of the horizontal influence up to the concentration of $\pi/6$, at which adjacent particles come into contact. The

Fig. 6 Terminal velocity of uniformly distributed particles (in normal scale for $Ar=600$)

Fig. 7 Terminal velocity of particle chain as a function of number of particles

Fig. 8 Terminal velocity of single particle and infinitely long chain

weight of each particle and the drag exerted on it by the stream become almost equal in a chain of more than 100 particles and the compression force between two adjacent particles decreases to less than 1% of the weight of a single particle. This suggests that any slight disturbance may result in the breakage of the chain.

6. Regime of Fast Fluidization

The regime of fast fluidization is discussed, comparing the terminal velocity of a particle chain estimated above with empirical findings and taking the behaviour of the wake of a particle into consideration.

6.1 Range of gas velocity

The relative velocity of any particle to the stream cannot be larger than the terminal velocity of the infinitely long chain as shown in Fig. 5 and Fig. 8. Particles descend in a long chain and ascend in a short chain, which makes it possible for particles to reside

	Ar	Re	CFB	Circulating Fluidized Bed Boiler (Nominal Load)
W (18)	1 620	10		
	2 620	31.4		
	3 17	3.2		
	4 17	10.0	[3]	$Ar \propto Re^3$
AK (19)	5 290	13.4		
	6 410	15.1		
K (20)	7 5000	100		
	8 5000	200

Fig. 9 Regime of fast fluidization

in the fluidized bed and to exchange positions vertically. This is thought to be the essential mechanism of fast fluidization.

Next we discuss the significance of Re_{FF} , relating it with the satisfactory operation of three circulating fluidized beds.

Particles with diameters between 0.1 and 1.0 mm are fluidized in gas stream flowing upwards with a superficial velocity between 5 and 10 m/s, at pressure of 0.1 MPa and temperature between 800 and 900°C in the two circulating fluidized bed furnaces. The concentration of particles is of the order of 10^{-3} at the top of the furnace. The fluidization is controlled precisely by adjusting the gas velocity with an accuracy of less than 0.5 m/s. Wein⁽¹⁸⁾ reported a parallelogram region for the appropriate operation area of this furnace on a $\log(Re) - \log(Ar)$ graph. Figure 9 shows the region;

- (1) $Ar=620$ $Re=10$
- (2) $Ar=620$ $Re=31.6$
- (3) $Ar=17$ $Re=3.2$
- (4) $Ar=17$ $Re=10.0$

The two broken curves [3] through points (1) and (2) represent two gas velocities, the higher of which is three times larger than the lower. This indicates that this furnace was operated at a load of between 100% and 30%. The ratio of Ar for points (1), (2) to for (3), (4) gives the width of particle size distribution. In this case the ratio of Ar is 36.5 and that of the particle size is 3.3. It is noteworthy that

point (2) falls exactly on the curve FF. A particle with $Ar \approx 620$ has the characteristics of fast fluidization at a 100% load. A fraction of the larger particles sink into the lower portion of the furnace at lower gas velocities and smaller particles maintain the fast fluidization instead.

The operation of another circulating fluidized bed test combustor is indicated by the two points (5) and (6) in Fig. 9⁽¹⁹⁾. The diameter in Ar is put equal to the diameter, the fraction of particles larger than which is 5% by weight as given in the original report.

It was reported that, iron ore particles of high density could be fluidized satisfactorily in the fast mode at the points (7) and (8) in a cold testing⁽²⁰⁾.

The small area denoted by CFB includes data for operation points at the nominal load for other circulating fluidized bed boilers, which were taken from field reports. Consequently, Fig. 9 shows that Re_{FF} gives the upper limit of the gas velocity for a stable circulating fluidized bed.

6.2 Range of Archimedes number

According to Modi and Akutsu, the wake of a sphere, axi-symmetrically stable at low Re , becomes asymmetric when Re increases to around 260 and unstable such that it oscillates periodically with further increase in Re ⁽¹⁵⁾. An asymmetric or unstable wake may prevent the formation of a stable chain of particles and, thus, the establishment of fast fluidization. $Re=260$ gives an Ar value of $10^4 \sim 4 \times 10^4$ on the curves Re_{FF} and Re_T in Fig. 9. Horio considered that fast fluidization cannot be observed at values of Ar larger than 2×10^4 based on a careful study of various experimental reports, both by himself and other investigators⁽²¹⁾. The two Reynolds numbers agree reasonably well, which implies that the conditions for fast fluidization are the symmetry and stability of the wake.

The ratio of C_D/C_{D0} by Eq. (6) with $l/d=1$ to C_D/C_{D0} by Eq. (7) is given by

$$\frac{C_D(\text{Down stream})}{C_D(\text{Up stream})} = \frac{1 - 0.53Re^{0.31}}{1.204Re^{0.2164}} \quad (12)$$

It is clear that fast fluidization does not occur, if the drag become equal both for the upstream and the downstream particle. Re value for this situation is given by Eq. (12)=1, which gives $Re=0.104$ equivalent to $Ar=1.87$. Therefore, the range of Ar for fast fluidization is thought to be between 2 and 2×10^4 . It seems that there is no accurate experimental verification of the lower limit at present. Although Ar is between 1 and 10 in catalytic crackers for petroleum, in which the catalytic particles are about 50 μm in diameter and have a density of 1~1.5 g/cm, the actual value of Ar is assumed to be much larger than the theoretical value because of agglomeration.

7. Conclusion

In this study we propose a model which can be used to analyze the principal mechanism of formation of a fluidized bed in a gas stream flowing vertically upwards at a velocity larger than the terminal velocity of a single particle. In this model, it is assumed that the symmetry and stability of the wake are the necessary conditions for the occurrence of fast fluidization. Using this model the regime of fast fluidization is investigated and compared with actual circulating fluidized beds, in which fast fluidization is applied.

It is concluded that:

(1) The upper limit of the gas velocity is the terminal velocity of an infinitely long chain of particles.

(2) The upper limit of Re is 260, which is equivalent to an Ar value of 2×10^4 .

(3) The predicted lower limit of Re is 0.104 which corresponds to an Ar value of 1.87, but no accurate experimental evidence is available at present.

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