MECHANISM OF THE FAILURE OF AGGREGATES IN FLOW FIELD

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Introduction

Although the failure of aggregates in flow fields has been studied, its mechanism has scarcely been analysed because of its complexity.

Aggregates in flow fields are broken up by two kinds of forces, fluid dynamic force and collision with an obstacle. The fluid dynamic force may be induced by the following three flow fields: the uniform flow field around the aggregates induced by relative velocity between fluid and the aggregate, simple laminar shear and turbulence. It has been shown experimentally[7,9] and theoretically[8] that of these four causes of the failure above described, collision with an obstacle is is the most effective, uniform flow is next and the two others are less effective.

To analyse theoretically the break-up mechanism of aggregates, we consider the mechanism to be composed of several steps as shown in **Fig. 1**. According to Fig. 1, we review here in brief some important work reported hitherto. In the case of experimental work concerning the break-up of aggregates due to uniform flow around them and collision with an obstacle, only the characteristic velocity U in a disintegrator and the particle size after the break-up, d_p, were measured, and their relationship was written or rewritten by the following equation[4].

$$d_p \cdot U^m = K \tag{1}$$

In **Table 1**, the values of m obtained by several workers under several conditions are shown.

In the case of theoretical work Yoshida, Kousaka and Okuyama[8] analysed the mechanism of the failure due to collision of aggregates with an obstacle and showed theoretically and experimentally that the value of m is 0.5. For break-up due to uniform flow around the aggregate, Bagster and Tomi[2] analysed the stresses on the surfaces within the spherical aggregate theoretically. Yoshida, Kousaka and Okuyama[8] assumed that the aggregate is composed of two particles of different sizes and calculated the stresses on the surface of both particles contacting each other. From these theoretical studies, in Stokes' case, the stresses breaking up the aggregate can be written as

$$\sigma, \tau \propto u_r/d_{ag} \tag{2}$$

where u_r is the relative velocity and d_{ag} is the aggregate size.

In this report, we attempt to obtain Eq. (1) from Eq. (2) theoretically, by analysing the break-up mechanism due to the relative velocity.

1. Break-up of Aggregates due to the Relative Velocity

1.1 Stokes' region

To derive Eq. (1) from Eq. (2) theoretically, as shown in Fig. 1, it is necessary to define the strength of aggregates and analyse the manner of break-up. As the strength of aggregates is affected by the manner of break-up, in the first place we analyse the manner of the break-up. As it has already been confirmed experimentally that coordinate number of the primary particles and cohesive force are distributed,[1,3] the local coagulate force in an aggregate should be distributed. Therefore, when the aggregate has parts weaker than the failure forces, it is assumed that break-up of the aggregate is induced from these weak parts. In the case of break-up due to relative velocity, the strength of the aggregate is determined not by the average strength but by the number of weak coagulated parts. It can be assumed that the strength, σ_{ag}, is inverse to the number of weaker parts, $n(\sigma_H < \sigma_{\max}, \tau_{\max})$.

$$\sigma_{ag} \propto \frac{1}{n(\sigma_H < \sigma_{\max}, \tau_{\max})} \tag{3}$$

If the distribution of local coagulate forces in any size aggregate is the same and all local coagulate parts weaker than the failure forces contribute to breaking up the aggregate, $n(\sigma_H < \sigma_{\max}, \tau_{\max})$ in Eq. (3) is in proportion to the number of primary particles building up the aggregate and the volume of the aggregate.

$$n(\sigma_H < \sigma_{\max}, \sigma_{\max}) \propto n(d_{p1}) \propto d_{ag}^3 \tag{4}$$

On the contrary, if it is assumed that the aggregate breaks up on the surface or at a section within the aggregate, then the number of weaker coagulate parts contributing to failure can be proportional to the square of the aggregate size.

$$n(\sigma_H < \sigma_{\max}, \tau_{\max}) \propto d_{ag}^2 \tag{5}$$

The relationship between the strength of aggregates

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Table 1 Values of m

Reporter	m	Apparatus or style
Jimbo and Fujita[4]	0.8–2.0	suction of aggregates
Jimbo, Tsubaki and Nagahiro[5]	1.0	sudden deceleration of aggregates
Watanabe[6]	0.6	ejector
Yamamoto and Suganuma[7]	0.6	capillary
Yoshida, Kousaka and Okuyama[8]	0.5	capillary, orifice
Yoshida, Kousaka and Okuyama[8]	<0.25	venturi

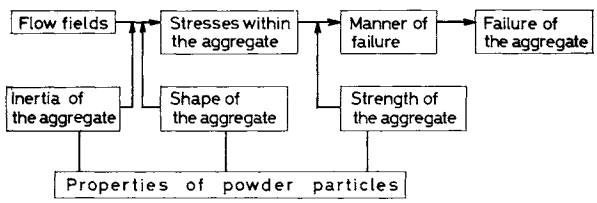

Fig. 1 Failure mechanism of aggregates in flow fields

and the failure forces thus is assumed as shown in **Fig. 2**. As is obvious from Fig. 2, all aggregates larger than $d_{ag\,\mathrm{crit}}$ must be broken up, where $d_{ag\,\mathrm{crit}}$ is the aggregate diameter satisfying the following equation.

$$\sigma_{\max},\ \tau_{\max}=\sigma_{ag} \tag{6}$$

When the strength of aggregates is proportional to the cube of the aggregate size, the following equation is obtained by substituting Eqs. (2)–(4) into Eq. (6).

$$d_{ag\,\mathrm{crit}}\cdot u_r^{0.5}=K \tag{7}$$

When the strength is proportional to the square of the aggregate size, then the relation of

$$d_{ag\,\mathrm{crit}}\cdot u_r=K \tag{8}$$

is obtained from Eqs. (2), (3), (5) and (6). The definitions of particle size and air velocity in Eqs. (7) and (8) are different from those in Eq. (1). But it is thought to be reasonable that Eqs. (7), (8) derived theoretically coincide with the experimental equation, Eq. (1), because the value of the index m is not so much affected by the definition of particle size after failure, for example fifty percent, eighty percent diameter or $d_{ag\,\mathrm{crit}}$. Besides, when the aggregates are accelerated or decelerated by air flow instantaneously, the relative velocity can approximate a characteristic velocity in the disintegrator.

1. 2 The transition region and Newtons' region

Dividing the drag force of a sphere by its projected area, in Stokes' region we obtain the equation

$$f_D\propto u_r/d_p \tag{9}$$

which is equal to the equation of the stresses within the sphere, Eq. (2). If the relationship between the drag force and the stresses is the same in the transition and Newton's regions, the stresses of each region are written by Eqs. (10), (11).

$$\sigma_{\max},\ \tau_{\max}\propto u_r^{1.5}/d_p^{0.5} \quad \text{(the transition region)} \tag{10}$$

$$\sigma_{\max},\ \tau_{\max}\propto u_r^{2} \quad \text{(Newton's region)} \tag{11}$$

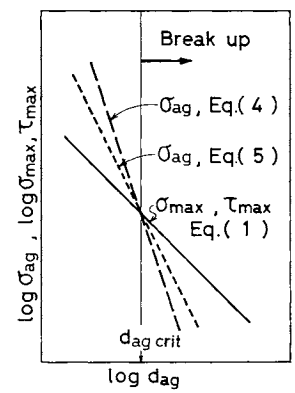

Fig. 2 Relationship between the strength of aggregates and failure force

Using Eqs. (10), (11) instead of Eq. (2), the index, m, of Eq. (1) is equal to 0.6–1.0.

It has become clear theoretically that the index, m, of Eq. (1) is 0.5–1.0 at all Reynolds number values of a particle. The values coincide with the experimental results shown in Table 1, except the results using venturi and suction tube in which the aggregates are accelerated gradually. From the above, it is concluded that the index, m, expresses the manner of failure and the constant, K, expresses the strength of aggregates. The constant, K, depends mainly on the properties of powder particles. We examined experimentally the relationship between the constant, K, and properties of powder particles[5], details will be published in the following paper.

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