

Development of an Erosion Simulator

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In order to predict and evaluate the erosion to products that accompanies particle-gas flow, an erosion simulator has been developed. The simulator comprises the following components: (1) an erosion prediction model; (2) a basic erosion test; and (3) particle movement analysis with CFD. In this research, the equations of Finnie and Bitter have been adopted for the erosion prediction model. The experimental fixed values in the model have been obtained with a centrifugal erosion tester. In order to ascertain the validity of this method, the simulation was compared with erosion test data for the erosion depth of a 12×4 tube array. The results showed that the analysis generally agrees with the erosion depth experimental results for the tube array, demonstrating the simulator is able to estimate the characteristics of tube array erosion.

1. Introduction

Erosion occurs in equipment with solid-gas flow, such as powder conveying pipes and fluidized beds, when solid particles collide against the equipment surface, eventually causing the equipment to be damaged or fail. Predicting how erosion is distributed and how fast it develops makes it possible to not only improve repair efficiency but also prevent damage to the equipment in the design phase, and helps improve the soundness of the equipment.

Much of the previous research on erosion prediction focused on simple systems such as elbows, and not many of them focused on application to complicated geometries. Therefore, this research is intended to develop an erosion prediction/evaluation technology, or an erosion simulator, which consists of (1) an erosion prediction model, (2) a basic erosion test, and (3) particle movement analysis with CFD (Computational Fluid Dynamics). In this research, to verify the validity of this prediction/evaluation method, an erosion test was performed with a system simulating a tube array, and this paper reports on the results of comparison of the erosion depths obtained by the test and those obtained

by this prediction/evaluation method.

2. Erosion prediction/evaluation method

Figure 1 shows an outline of the erosion simulator. First, the gas flow rate, material, and other operating conditions are input in the erosion prediction model. Then, the experimental constants are determined by a basic erosion test to obtain erosion characteristics. These constants are applied to the particle collision area of the CFD to calculate the erosion distribution.

(1) Erosion prediction model

The erosion characteristics of the colliding particle and the collided material are predicted by erosion prediction equations (1) to (3),⁽¹⁾ which combine Finnie⁽²⁾ and Bitter⁽³⁾ equations. The total erosion amount W can be represented by the sum of the cutting erosion amount W_c and deformation erosion amount W_d . As shown in **Fig. 2**, in cutting erosion, W_c , particles collide at a small angle which cuts the material surface, and in deformation erosion, W_d , particles collide at a large angle which deforms the material surface. Calculating these erosion amounts

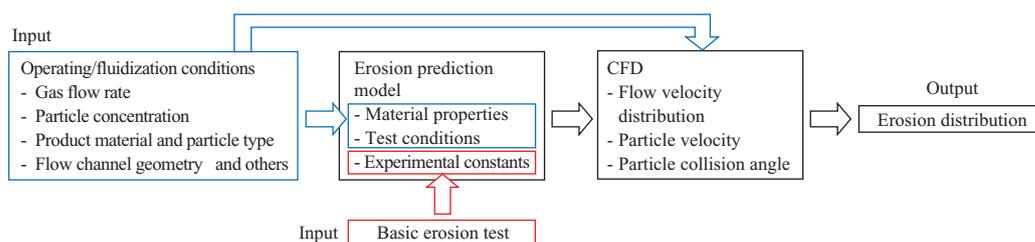


Fig. 1 Outline of erosion simulator

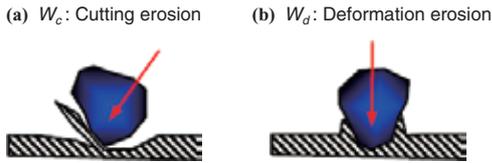


Fig. 2 Erosion mode

requires the particle velocity, collision angle, number of colliding particles, and other collision conditions to be substituted into the equations and in addition, some experimental constants to be obtained.

$$W_c = \begin{cases} \frac{\rho_t M C V^2}{P \Psi} \left[\sin 2\alpha - \frac{2(1 + m_p r_p^2 / I_p)}{K} \sin^2 \alpha \right] \\ \quad \because \tan \alpha \leq \frac{K}{2(1 + m_p r_p^2 / I_p)} \\ \frac{\rho_t M C V^2}{P \Psi} \left[\frac{K \cos^2 \alpha}{2(1 + m_p r_p^2 / I_p)} \right] \\ \quad \because \tan \alpha > \frac{K}{2(1 + m_p r_p^2 / I_p)} \end{cases} \dots\dots\dots (1)$$

$$W_d = \frac{1}{2} \frac{\rho_t M (V \sin \alpha - K')^2}{\epsilon} \dots\dots\dots (2)$$

$$W = W_c + W_d \dots\dots\dots (3)$$

- M : Total amount mass of colliding particles (kg)
- W : Total removed mass of target material (kg)
- ρ : Density (kg/m³)
- α : Particle collision angle (rad)
- V : Particle collision velocity (m/s)
- m_p : Particle mass (kg)
- r_p : Particle radius (m)
- I_p : Particle inertia moment (kg·m²)
- K : Ratio of the vertical and horizontal forces at the time of particle collision (-) (experimental constant)
- K' : Collision velocity at which the stress on the collided material reaches the elastic limit (m/s)
- P : Vertical component of maximum contact stress (N/m²)
- Ψ : Cutting erosion constant (-) (= 2 constant)
- ϵ : Energy needed to strip the eroded material per unit volume (J/m³) (experimental constant)
- C : Experimental constant (J/m³)
- Index notation t : Eroded material
- p : Particle

(2) Basic erosion test

To obtain experimental constants C , K , and ϵ of the erosion prediction model, an erosion test needs to be performed with the target particles and eroded

material. Because the erosion characteristics are greatly affected by the particle collision velocity and angle, a centrifugal erosion tester⁽¹⁾ was produced for this research (Fig. 3). The centrifugal erosion tester injects particles by centrifugal force at reduced air pressure to more accurately quantify the particle velocity and collision angle. In the test, particles dropping from the supply tank are fed into the center of the rotating disk where they are accelerated and then ejected at the test pieces installed around the disk to erode them. The particle ejection velocity can be set by changing the rotational speed of the rotating disk, and the collision angle can be set by changing the installation angle of the test pieces.

(3) Particle movement analysis with CFD

A solid-gas flow analysis is performed with CFD to calculate the particle velocity, collision angle, number of colliding particles, and other collision conditions needed to predict the erosion amount. The erosion prediction equations obtained in (1) and (2) are introduced to obtain the erosion distribution. This research uses the analytical mode shown in Table 1.

3. Results and discussion

3.1 Basic erosion test

An erosion test and a tube array erosion test, which is described later, were performed with the same combination of ash and carbon steel. Figure 4 shows the sample and erosion rate obtained by the basic test. The erosion rate is defined as the ratio of the eroded mass to the colliding particle mass. The particle collision velocity was set to

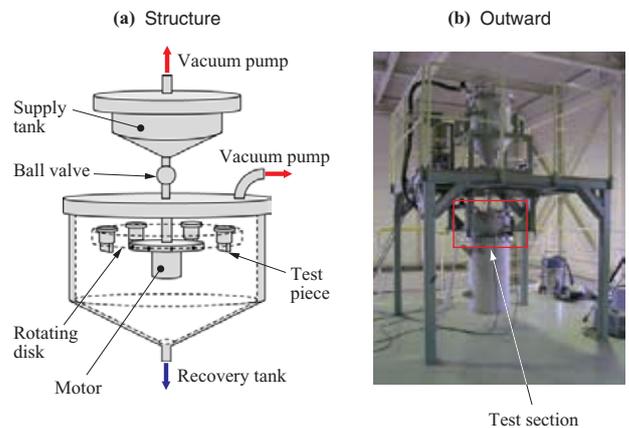


Fig. 3 Centrifugal erosion tester

Table 1 Analysis model

CFD Code	Fluent 13 [®] *1
Fluid model	Unsteady/incompressible NS
Discretization scheme	Second-order upwind
Turbulence model	k-ε Realizable*2
Wall boundary	Wall function
Particle model	Discrete Phase Model (DPM) 2-way
Turbulent particle dispersion	Random walk

(Notes) *1 : CFD software by ANSYS Inc.
*2 : Reynolds averaged model

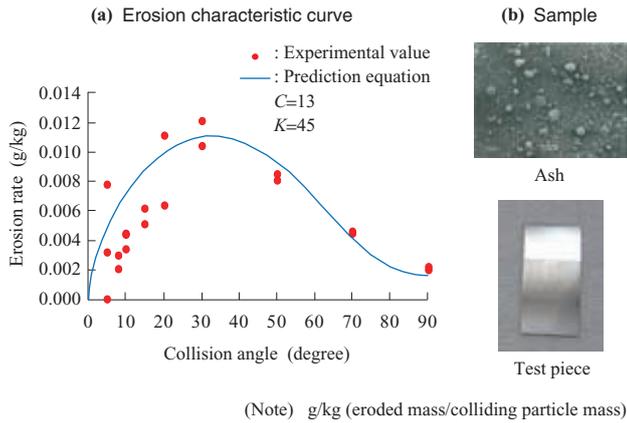


Fig. 4 Basic test

50 m/s, the test atmosphere was at normal temperature and the atmospheric pressure was reduced to 50 ± 40 Pa. From Fig. 4, it can be seen that there is a peak around where the collision angle is 30 degrees. The solid curve in Fig. 4 is drawn so that the erosion prediction equation fits the experimental values, and there are more deviations at lower angles. This is presumably because the projected area of the test piece is small in relation to the particle injection area

and the absolute number of particles colliding against the test piece with a low angle is small.

3.2 Simulator accuracy verification

To verify the accuracy of the erosion simulator, an erosion test was performed with a tube array (12 rows \times 4 columns) to analyze and compare the erosion depth. Table 2 shows the test conditions. To eliminate the effect of the walls, the measurement was performed with the two inner columns, and the erosion depths were measured in the longitudinal direction of the pipes at intervals of 30 degrees as shown in Fig. 5-(c).

Figure 6 shows the results of the tube array erosion test. Using a laser displacement meter, the erosion depth

Table 2 Tube array test condition

Item	Unit	Specification
Test atmosphere	—	Normal temperature and pressure
Loading ratio	—	5.7×10^{-2}
Inlet air flow rate	m/s	10
Total amount of particles fed	kg	5 000
Mass averaged particle diameter	μm	42
Particle/eroded material	—	Ash/carbon steel

(Note) Loading ratio : Particle mass flow rate/gas-phase mass flow rate

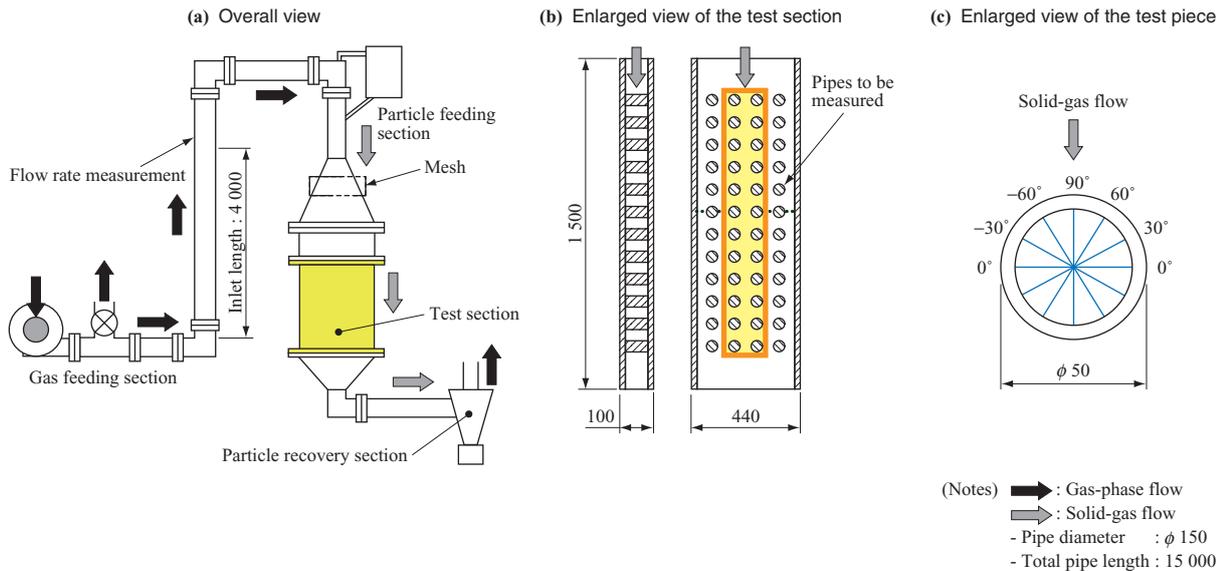


Fig. 5 Tube array erosion tester (unit:mm)

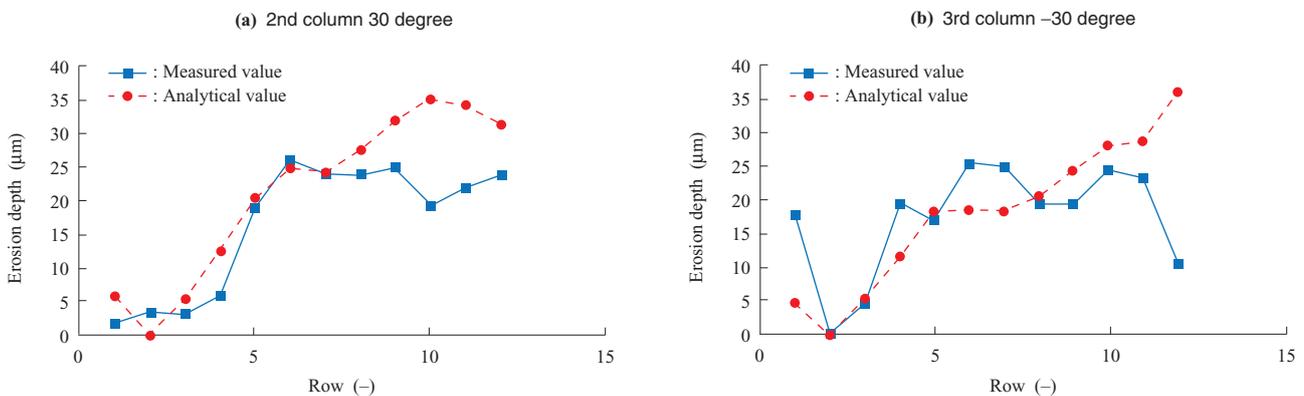


Fig. 6 Averaged erosion depth

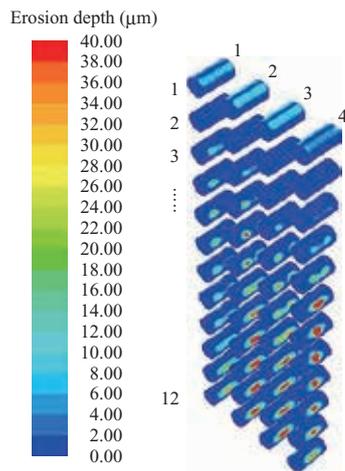


Fig. 7 Distribution of erosion depth

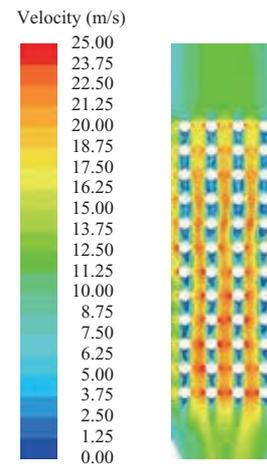


Fig. 8 Distribution of velocity

in the longitudinal direction of the tube was measured at the measuring point with the most significant erosion (± 30 degrees) and the measured values were averaged.

Figure 6 shows the average erosion depth obtained by the analysis as well as the measurement results. Figure 7 shows the distribution of the erosion depth. The erosion depths of the analysis were calculated by dividing the erosion masses of the small area by the density of the eroded material. From Fig. 7, it can be seen that many particles collide with the 1st row where the particles flow evenly over the entire surface of each tube. The particles flowing to the left and right of each tube in the 1st row pass over the sides of the tubes in the 2nd row causing the least amount of erosion to these tubes. Then in the 3rd and subsequent rows, the particles begin colliding with tubes again and the amount of erosion is greater at lower rows. This is presumably because, as can be seen from the flow rate distribution in Fig. 8, the flow rate is higher at lower rows, which accelerates erosion.

Comparison between the test and analysis results found that the erosion depth is almost the same, and that in both the test and analysis, the flowing particles erode the 1st row and flow over the sides of the 2nd row, causing little erosion, and the amount of erosion increases in subsequent rows. However, the subsequent rows have a slightly larger analytical value. This is presumably because the analysis was performed with particles of a single mass average particle diameter and did not take into consideration particles with a small diameter, which more easily flow

with the gas, and therefore, the number of colliding particles was estimated to be larger than that in the experiment, resulting in a larger amount of erosion.

4. Conclusion

In this research, an erosion simulator was developed to verify the tube array erosion test. As a result, it was found that the estimated erosion depths were almost the same as the experimental values. In the future, one of our goals will be to establish this simulator as a more practical erosion prediction tool by using it with various combinations of particles and materials subject to erosion, and with materials of various geometries. Also, it will be important to ascertain the analytical accuracy of the simulator and to compare experiments that have clear boundary conditions with the phenomena of systems that have a wide range of operating conditions, in order to take into consideration the impact of differences in conditions on operation prediction.

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