Prediction of the Volume Loss by Using Slurry Jet Test on SCS6

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Abstract

Slurry erosion with sand particles is a serious problem for pumps operating at the Yellow River pumping station. Therefore, a technique to predict erosion volume loss is required for selecting erosion resistant material and determining specification of the maintenance period. This paper reports a method to predict the volume loss of SCS6 specimen using slurry jet apparatus. An equation for prediction is derived from combining an analysis of sand particle behavior in the slurry jet apparatus with measurement of surface profile on specimens obtained by slurry jet test by silica sand of approximate 60 μm in mean diameter. There is a critical value for kinetic energy of particle above which erosion occurs being about 1.0x10^-6N・m for SCS6. It was found that the loss was a maximum at an impact angle of about 40 degrees. The equation can predict the wear depth on the slurry jet test with the Yellow River sand of approximate 30µm in mean diameter.

Key words: Life Prediction, Numerical Analysis, Erosion, Slurry Erosion, Slurry Jet, SCS6

1. Introduction

River water pumps and other fluid machines used in major rivers containing much sand and mud, such as the Yellow River and the Yangtze River in China, are confronted with the slurry erosion of their materials. This erosion is caused by fine solid particles in the fluid repeatedly impinging on the material surface; such erosion results in serious problems, including deteriorated equipment performance and shorter service life due to component damage. Pump impellers, in particular, are one of components most subject to erosion damage, since slurry flow velocity is high on the surface. Therefore, a technique for predicting the wear depth of materials is essential for material selection and maintenance.

In our previous paper (1), we reported a method for simply determining the dependency of slurry erosion on the impact angle for various metal materials based on the analysis of particle flow behavior in a slurry jet test apparatus and the results of a slurry jet test. Previously, particle behavior at a nozzle angle of 90° was analyzed to predict the erosion rate at smaller nozzle angles. Particle behavior at smaller impingement angles, however, must be analyzed to improve prediction accuracy. Also, a low flow velocity of 10 m/s was used in the previous study; conditions with higher flow velocity must be examined before applying the prediction technique to the prediction of wear depth for actual pump impellers.

In this study, we have performed a slurry jet test and particle behavior analysis using silica sand in order to establish a method for predicting the slurry erosion rate at different impact angles. Based on these results, we have also examined the possibility of predicting the erosion rate at different flow velocities, sand concentrations, and impact angles for the
Yellow River sand.

2. Experimental procedure

The slurry jet test was conducted using the slurry jet test apparatus shown in Figure 1. The apparatus comprised a specimen, a specimen mount, a slurry jet nozzle, a tank for storing the mixture of water and solid particles, and a slurry transfer pump. A nozzle with an inner diameter of 3 mm was attached 25 mm away from the specimen surface in an opposing position. The nozzle produced a jet of slurry that impinged on and damaged the specimen surface. Each specimen was fixed in such a way that its surface was at 90° or 30° in relation to the slurry jet direction. The slurry flow velocity was set to 20 and 40 m/s; the velocity was determined by measuring the time elapsed until a separately provided tank was filled to a predetermined level with slurry injected from the nozzle. The slurry storage tank was equipped with a water-cooling jacket to keep the slurry temperature between 20 and 35 °C. As slurry, a mixture of tap water (80 L) and a predetermined amount of silica sand (particle size corresponding to the 50 % cumulative weight (d50) = approximately 60 µm) or the Yellow River sand (d50 = approximately 30 µm) was used. Figure 2 shows the particle size distribution of each sand type. The densities of silica sand and the Yellow River sand were calculated based on their chemical compositions to be 2300 and 2500 kg/m³, respectively.

The specimens were made of a casting martensitic stainless steel SCS6 (Fe-13Cr-4Ni), which is often used for pump impellers. They were prepared by heating the material at 1050 °C for 2.2 hours, then rapidly quenching it to 620 °C, maintaining it at the same temperature for 2.5 hours, and then air-cooling it. The Vickers hardness of the material was 285.

The wear depth of each specimen was measured at predetermined intervals using a surface profiler (Tokyo Seimitsu Co., Ltd’s SURFCOM 1400D-3DF-12 with an accuracy of 0.01 µm). The test surface of the specimens was lap-finished to obtain a mirror surface.

3. Result and discussion

3.1 Results of the slurry jet test

Figure 3 shows the specimen surface profile for each exposure time at a flow velocity of 20 m/s, as well as the relation between the exposure time and the wear depth at each impact position up to 1.8 mm away from the center of the specimen surface. The figure shows W-shaped curves, which are typically observed in the slurry jet test apparatus that causes more intensive erosion in the area surrounding the center of the jet flow than at the jet flow
center. At impact positions 0.2 to 1.8 mm away from the specimen center, the wear depth linearly increases in proportion to the exposure time.

Figure 4 shows the specimen surface profile for each exposure time at a flow velocity of 40 m/s. As is the case with the test at a flow velocity of 20 m/s, the figure shows W-shaped curves; at impact positions 0.2 to 1.8 mm away from the specimen center, the wear depth linearly increases in proportion to the exposure time.

Figure 5 shows the coordinates of slurry jet test apparatus at an impingement angle of 30°. The center of the nozzle outlet shape projected on the specimen surface was defined as the specimen center. For analysis at an impingement angle of 30°, the impact position on the side of the specimen nearest the nozzle was indicated as a negative distance from the specimen center, while the impact position on the side farthest from the nozzle was indicated as a positive distance from the center.

Regarding the test at an impingement angle of 30°, Figure 6 shows the specimen surface profile for each exposure time at a flow velocity of 20 m/s. The maximum wear depth is
observed at a position - 2.3 mm away from the specimen center. Regardless of the impact position, the wear depth increases in proportion to the exposure time.

3.2 Derivation of an equation for predicting the wear depth

3.2.1 Numerical analysis of particle behavior at an impingement angle of 90°

Based on stationary solutions obtained from single-phase (water) flow analysis using Star-CD, general-purpose flow simulation software, the behavior of individual particles was tracked with the Lagrange method. Analysis with the Lagrange method employed a model using a single-particle drag coefficient. The fluid drag force on particles was taken into account, but neither the particle drag force on the fluid nor the rotation of particles was considered. Due to low particle concentration, no interaction between particles was taken into account. For single-phase flow analysis, the standard k-ε model was used as a turbulent flow model.

Providing an initial particle velocity of 20 or 40 m/s (the same velocity as that of water) in the nozzle, the simulation was conducted for particle sizes of 10, 30, 50, 80, 120, 160, 200, and 300 µm. The number of times each particle impinged on the specimen surface was one; behavior analysis for the particle was stopped at the first impingement. Since there is almost no difference in the particle density between silica sand (2300 kg/m³) and Yellow River sand (2500 kg/m³), the particle density was set to 2300 kg/m³ in this test.

Figures 7 shows mesh divisions used for analysis at impingement angles of 90°. The analysis region for the test at an impingement angle of 90° was axisymmetrically configured, and the periodic boundary was set at an angle of 60°.
Figure 8 shows the relations between the impact position on the specimen surface and the impact velocity and between the impact position and the impact angle at an impingement angle of 90° and a flow velocity of 20 m/s. The impact velocity is low at or near the specimen center; it increases as the position moves away from the center. At the same impact position, the impact velocity is lower for smaller particle sizes. The impact angle is almost 90° at or near the specimen center; it decreases as the position moves away from the center. At the same impact position, the impact angle is smaller for smaller particle sizes.

3.2.2 Numerical analysis of particle behavior at an impingement angle of 30°

Figures 9 shows mesh divisions used for analysis at impingement angles of 30°. 707 particles were arranged at 0.1 mm intervals in the initial position.

Figure 10 shows the relations between the impact position on the specimen surface and the impact velocity and between the impact position and the impact angle at an impingement angle of 30° and a flow velocity of 20 m/s. Regardless of the particle size, the impact velocity is at minimum at a position of xc = -3.0 to -2.5 mm (on the side nearest the jet nozzle); it increases as the position moves away from the jet nozzle. At the same impact position, the impact velocity is lower for smaller particle sizes. The impact angle is approximately 50° on the side nearest the jet nozzle (particle size of 10 µm); it decreases as
the position moves away from the jet nozzle. At the same impact position, the impact angle is smaller for smaller particle sizes.

3.2.3 Derivation of an equation for predicting the wear depth

An equation for predicting the slurry wear depth is derived from the results of particle behavior analysis described above and the results of a slurry jet test with a silica sand concentration of 1%, a flow velocity of 20 or 40 m/s, and an impingement angle of 90° or 30°.

Assuming the kinetic energy of solid particles as $E (N \cdot m)$, the erosion rate $W(X)$ (mm/s) at the particle impact position X can be expressed as follows.

$$W(X) = C \times E = C \times \frac{1}{2} m \times V^2$$

(1)

$C$, $m$, and $V$ represent the constant, particle mass, and particle velocity upon impact on the specimen surface. A wide distribution of slurry particle sizes makes it difficult to study the dependency of slurry erosion on the impact angle for each particle size. As an example of observed erosion, Figure 11 shows a SEM image of erosion caused at a flow velocity of 40 m/s, a Yellow River sand concentration of 1%, an impingement angle of 30°, and an impact position of -3 mm. Since cutting marks and lips formed by plastic deformation are observed, the erosion mechanism may be based mainly on the combination of cutting damage and plastic deformation. However, no method for quantifying the effect of the impact angle for individual damage factors has been established yet.

By setting the mean particle diameter as a reference particle size ($D_0 = 80 \mu m$) and the nozzle jet velocity as a reference velocity ($V_0 = 20 m/s$), the relation between the volume loss per particle $Y$ (mm$^3$) and the impact angle $\alpha$ (deg.) is expressed by the following cubic function.

$$Y = a \cdot \alpha^3 + b \cdot \alpha^2 + c \cdot \alpha$$

(2)

The values of $a$, $b$, and $c$ in the equation above are unknown. Using the cubic function is convenient for expressing both curves having peaks at a large impact angle and those having peaks at a small impact angle. $Y$ is a material-specific value and corresponds to $C$ in Eq. (1). The effect of the particle shape, which is difficult to formulate, has been ignored in the prediction equation. For tests and calculations, it is necessary to use particles with the same characteristics as those in actual environments.

Since the amount of volume loss must be considered for each particle size, particle sizes are divided into 40 levels in a range between 10.09 and 296 µm. Considering the contribution of each particle, the erosion rate $W(X)$ at the impact position $X$ is expressed as follows.

$$W(X) = \sum_{i=10}^{296} \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0 \cdot \alpha D_0$$

(3)

$D_0$, $V_0$, and $F_{D,0}$ represent the impact angle (deg.), particle size (µm), particle velocity (m/s), and impact frequency (1/(mm$^2$·s)). With non-dimensional values $D_0$ and $V_0$ of the particle mass and velocity, the particle density is removed from Eq. (3). The values of $a$, $b$, and $c$ are determined by selecting three positions $X$ on the erosion surface after the
slurry jet test and by formulating a simultaneous equation.

The positions \( X \) were selected so as to satisfy: 1) a position in which particles of all sizes impinge and 2) a position in which particles impinge at a wide range of impact angles from small to large angels. Thus, two positions 0.2 and 1.8 mm away from the specimen center were selected for the test at an impingement angle of 90°; \( y = \pm 2 \) mm was selected for the test at an impingement angle of 30°. The left side value \( W \) in Eq. (3) is expressed as \( W_{90\text{deg}}(0.2), W_{90\text{deg}}(1.8), \) or \( W_{30\text{deg}}(-2.0) \). These values are obtainable from the test results.

\( F_{10.09,X} \) to \( F_{296,X} \) in Eq. (3) at an impingement angle of 90° are determined as follows.

Figure 12 is a pattern diagram of the slurry jet test at an impingement angle of 90°, showing the position of particle emission from the nozzle and the impact position on the specimen surface. The emission area on the nozzle \( A_s(X) \) (mm²) and the impact area on the specimen surface \( A_e(X) \) (mm²) shown in the figure are calculated. The emission position \( X_s \) and the impact position \( X \) are linearly proportional to one another when the impact position is approximately 2 mm or less away from the specimen center. The relation between these positions is expressed by the following linear function.

\[
X_s(X) = D_s \times X
\]  
(4)

Accordingly, the emission area \( A_s \) is obtained as follows.

\[
A_s(X) = \pi \times \left[ \left( X_s(X + 0.05) \right)^2 - \left( X_s(X - 0.05) \right)^2 \right]
\]  
(5)

The impact area \( A_e \) is obtained as follows.

\[
A_e(X) = \pi \times \left( X + 0.05 \right)^2 - \left( X - 0.05 \right)^2
\]  
(6)

The slurry particle supply amount per unit time and unit area \( s \) (kg/(s•mm²)) is obtained by the following equation.

\[
s = \nu \times \frac{c}{100} \times \frac{f}{100} \times 10^{-6}
\]  
(7)

\( \nu \) is the velocity in the nozzle (m/s), \( c \) is the particle concentration (1 %), and \( f \) is the particle frequency in volume distribution (%). According to Eqs. (4) to (7), \( F_{D,X} \) is obtained by the following equation.

\[
F_{D,X} = \frac{s(A_s(X)/A_e(X))}{m_D} \quad (D = 10.09 \text{ to } 296)
\]  
(8)

\( m_D \) is the mass (kg) of one particle with a diameter \( D \). \( F_{10.09,X} \) to \( F_{296,X} \) obtained above are substituted into Eq. (3) to obtain the relation between \( W(X) \) and \( a, b, \) and \( c \).

\( F_{10.09,X} \) to \( F_{296,X} \) in Eq. (3) at an impingement angle of 30° are determined as follows.

Figure 13 is a pattern diagram of the slurry jet test at an impingement angle of 30°, showing the position of particle emission from the nozzle and the impact position on the specimen surface. In the figure, the emission area on the nozzle is defined as \( A_s(X) \) while the impact area on the specimen surface is defined as \( A_e(X) \) (mm²). \( A_e(X) \) is calculated for each impact position.

The slurry particle supply amount per unit time and unit area \( s \) (kg/(s•mm²)) is obtained
by Eq. (8). Using the obtained results, the impact frequency is determined by the following equation.

$$F_{D,x} = \frac{s(A_x / A(X))}{m_D} \quad (D = 10.09 \text{ to } 296) \tag{9}$$

Figure 14 shows the distribution of kinetic energies of silica sand at an impact position of \(1.8\) mm and a flow velocity of 20 or 40 m/s calculated based on the particle behavior analysis. The left-hand scale of ordinate represents the particle size, and the abscissa represents kinetic energy per particle. The right-hand scale of ordinate represents a value obtained by multiplying kinetic energy per particle by the impact frequency \(1/(\text{mm}^2 \cdot \text{s})\). The sums of the kinetic energy of all particles supplied to the impact positions at flow velocities of 20 and 40 m/s per unit time and unit area are 6764 and 58738 (\(\text{Nm/} \text{mm}^2 \cdot \text{sec}\)), respectively. If the amount of volume loss is proportional to the kinetic energy, the ratio of the erosion rate at a flow velocity of 40 m/s to that at 20 m/s is \(58738 / 6764 \approx 8.7\) at an impact position of 1.8 mm. However, the ratio actually obtained from the test results is 34.

According to a report by Wang (3), sand of a certain particle size or less has almost no effect on the slurry erosion of fluid machines. Assuming that "impinging particles with a certain level of kinetic energy or less does not cause material damage," the ratio of the sum of kinetic energy (the shaded region of the bar chart in the figure) at a flow velocity of 40 m/s to that at 20 m/s in the range of \(1.0 \times 10^{-6} \text{ N} \cdot \text{m}\) or more is \(8943 / 240 \approx 37\), which is almost the same as the value obtained from the test results. Thus, \(1.0 \times 10^{-6} \text{ N} \cdot \text{m}\) is defined as a critical value.

Based on the approach above, the following equation can be obtained by using the results of the test at a flow velocity of 20 m/s and by excluding the effect of particles smaller than the particle size corresponding to the critical value for kinetic energy from Eq. (3).
\[
\begin{align*}
W_{\text{vol}}(0.2) &= 8.3333 \times 10^{-4} \cdot a + 6.0805 \times 10^{-6} \cdot b + 8.0055 \times 10^{-8} \cdot c \\
W_{\text{vol}}(1.8) &= 3.5139 \times 10^{-6} \cdot a + 4.2813 \times 10^{-8} \cdot b + 1.1745 \times 10^{-10} \cdot c \\
W_{\text{vol}}(-2.0) &= 3.9222 \times 10^{-6} \cdot a + 2.6899 \times 10^{-8} \cdot b + 4.6095 \times 10^{-10} \cdot c 
\end{align*}
\]

Solving the simultaneous equation (10) provides the values of \(a\), \(b\), and \(c\). Figure 15 shows the relation between the volume loss per particle and the impact angle with a reference particle size of 80 \(\mu\)m and at a reference velocity of 20 m/s, data for which is obtained by substituting the obtained values of \(a\), \(b\), and \(c\) into Eq. (2). The maximum volume loss is observed near an impact angle of 40\(^\circ\); this result agrees with the previous report\(^{(4)}\) that the erosion rate is at maximum at a smaller impact angle for ductile materials.

![Graph showing the relation between the particle impact angle and the calculated volume loss per particle](image)

**Fig. 15** Relation between the particle impact angle and the calculated volume loss per particle (particle diameter: 80 \(\mu\)m, impact velocity: 20 m/s)

### 3.3 Comparison between the results of a test using Yellow River sand and the results of volume loss prediction

In Section 3.2, an equation for volume loss prediction on SCS6 was derived by combining the results of the slurry jet test using silica sand of approximately 60 \(\mu\)m in mean diameter and the results of the particle behavior analysis. With the prediction equation, the volume loss was predicted for Yellow River sand, the particle size distribution of which is different from that of silica sand. Then, the prediction results were compared to the test results.

First, the test results and calculated values at an impingement angle of 90\(^\circ\) were compared. Figures 3 and 4 show a tendency for the position with the maximum wear depth to move gradually away from the specimen center with time. This fact suggests that particle behavior near the maximum wear depth changes as the wear depth locally increases. Accordingly, the comparison region was defined in a range between 0.2 and 1.8 mm away from the specimen center. Figure 16 shows erosion profiles obtained from a 30-minute test using Yellow River sand of 1 % concentration at a flow velocity of 20 m/s and obtained by calculation. Figure 17 shows erosion profiles obtained from a 30-minute test using Yellow River sand of 1, 2, and 3 % concentrations at a flow velocity of 40 m/s and obtained by calculation. The experimental value agrees well with the predicted value. Thus, the amount of volume loss can be predicted with the slurry jet test apparatus by using particles that have particle size distributions differing from those of Yellow River sand, but are almost equal in composition to the sand.
Next, the test results and calculated values at an impingement angle of 30° were compared. Figures 18 and 19 show erosion profiles obtained from a test using Yellow River sand of 1% concentration at flow velocities of 20 and 40 m/s and obtained by calculation. Although the experimental value almost agrees with the predicted value, the former is slightly higher than the latter near the maximum wear depth. As with the test at an impingement angle of 90°, the discrepancy may be attributed to the fact that particle behavior near the maximum wear depth changes as the wear depth locally increases. In the slurry erosion of actual pump impellers, however, locally deep erosion as seen in this study hardly occurs. Therefore, there is no problem in applying the prediction technique to actual cases.
4. Conclusions

A slurry erosion test and particle behavior analysis for SCS6 were conducted at impingement angles of 90° and 30° to examine a method for quantitatively predicting the slurry wear depth. As a result, the following conclusions have been obtained.

1) A slurry jet test and particle behavior analysis using silica sand of approximately 60 µm in mean diameter at a flow velocity of 20 m/s were conducted to derive an equation for wear depth prediction. This equation was used to predict the erosion profile to be generated with Yellow River sand of approximately 30 µm in mean diameter, and the predicted value agreed well with the experimental value.

2) The maximum volume loss occurs near an impact angle of 40°.

3) The kinetic energy of impinging particles contributing to slurry erosion may have a critical value. When sand mainly containing SiO₂ is used, the critical value for SCS6 is approximately 1.0 x 10⁻⁶ N·m.

4) The equation for wear depth prediction proposed in this paper can be applied to the prediction of slurry wear depth for ductile materials like SCS6.

References


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