Research on erosion model based on AISI 8630

Xin Rong¹ and Hongwu Zhu
China University of Petroleum (Beijing), Beijing, China

¹E-mail: 2018314008@student.cup.edu.cn

Abstract. Subsea oil tree is the key equipment for offshore oil and gas extraction, and erosion will cause wall-thinning phenomenon of equipment, which will decrease the equipment's pressure-bearing capacity and cause great safety risks. In this paper, a new erosion model is proposed by studying the erosion law of the common material (AISI 8630) in subsea tree. The mechanism of erosion is explained by observing the change in the surface micro-morphology of the erosion pit photographed by scanning-electron microscope. The effect of five factors including particle size, particle impact velocity, particle impact angle, particle concentration and impact duration on the erosion are also investigated. And the AISI 8630 erosion model is obtained through data analysis. By comparing the results of experiment and numerical simulation, it is found that the simulation error of the AISI 8630 erosion model is the smallest between four common erosion models. So, it can be concluded that the AISI 8630 erosion model can be used to study the erosion of underwater tree.

1. Introduction
Erosion refers to the phenomenon caused by solid particles on the surface of materials under following fluid [1]. This phenomenon widely exists in the process of conversion, extraction and transportation of petroleum gas, and is an important cause of failure of oil and gas equipment such as pipelines and valves [2]. Due to complex offshore operating environment, solid particles in oil and gas will cause erosion to the production channel of subsea tree, which will result in a reduction in pressure capacity and hidden danger. Therefore, it is of great engineering value to study the erosion of subsea tree.

A new erosion model is used to predict and calculate erosion amount in this paper. In recent years, there have been at least 28 erosion models proposed by researchers all over the world, but each model has its limitations [3]. DNV model, E/CRC model and Oka model are currently widely used in research. The DNV erosion model was proposed by Det Norske Veritas. It is fitted on the basis of a large amount of experimental data, and the form is relatively simple. This model can be applied to various engineering sites [4]. The E/CRC erosion model was proposed by the Erosion/Crosion Research Center of the University of Tulsa. They considered the impact of the hardness of impacted materials and particle shape on erosion [5]. Japanese scholar Oka et al. chose different solid particles and different impacted material for erosion experiments, taking into account more factors such as particle hardness, particle diameter, and material properties [6]. Hang et al. considered the removal of material due to both deformation damage and cutting [7]. Arabnejad et al. [8] proposed a semi-mechanistic model for the erosion of different target materials due to solid particles. In 2019, a new erosion equation that considers the effect of applied load on erosion ratio (ER) was proposed by Wang et al. [9] based on available test data and E/CRC erosion equation.
2. Experiment

2.1. Experimental device
Figure 1 shows the schematic diagram of erosion experiment device. The device mainly includes 5 parts: a gas conveying unit, a particle feeding unit, an erosion generating unit and a particle velocity measuring unit. The solid particles fall into the hopper in the upper part of the Venturi tube due to vibration, and the compressed air is accelerated in the first half of the tube inside the Venturi tube. The sprayed high-speed air creates a negative pressure below the atmospheric pressure in the throat, and sucks particles falling from the hopper into the mixing chamber. The high-speed gas accelerates the particles in the intermediate mixing chamber and sends them to the second half of the pipe, whose inner diameter gradually increases. After that, the velocity of gas gradually decreased and the static pressure increased, completing the pneumatic conveyance of the particles [10].

![Sketch of erosion test facility.](image)

In the experiment, erosion test specimen is made of AISI 8630 alloy steel, and its surface has been polished before the test. The specimen holder can achieve the propose of changing the impact angle of solid particles within the range of 0°~ 90°.

2.2. Selection of solid particles
After multi-layer screening by an electric vibrating screener, a Malvern laser particle size analyzer is used to measure the particle size of different groups of quartz sand particles. The measurement results are shown in Table 1, and the particle density is 2650 kg/m³.

Table 1. Results of size measurement of quartz sand.

| No. | Screen mesh number (mesh) | Median particle size (μm) |
|-----|--------------------------|--------------------------|
| 1   | 300-400                  | 56.8                     |
| 2   | 250-300                  | 88.3                     |
| 3   | 200-250                  | 114.4                    |
| 4   | 180-200                  | 137.3                    |
| 5   | 150-180                  | 156.8                    |
| 6   | 120-150                  | 176.5                    |
| 7   | 100-120                  | 224.3                    |

2.3. Experimental conditions
The horizontal distance between the outlet of nozzle and specimen is 20 mm. High-speed camera is used to capture particle motion at nozzle outlet. The inlet pressure of acceleration pipe section is changed by adjusting the compressor discharge volume. The erosion rate $E$ (mg/g) is used to quantify
the erosion degree, which is defined as the ratio of erosion amount $\Delta m_s$ (mg) of the specimen to the mass $m_p$ (g) of particles consumed in the same time. In order to reduce the measurement error, the erosion duration of each group of experiments is set to 1 hour to obtain a sufficient amount of erosion.

2.4. Analysis of erosion mechanism

When the particle size is 114.4 μm, the average speed is 72 m/s, and the impact duration is 1 hour, the appearance of specimen after erosion is shown in Figure 2.

In order to further determine the erosion mechanism of AISI 8630 material, scanning electron microscopy is used to photograph the morphology of specimen surface before and after experiment. As shown in Figure 3, the surface of the specimen is basically smooth and flat before the test, with only a few minor scratches and small pits caused by sandpaper grinding.

When the impact angle is 15°, obvious flaky scratches appear on the surface of specimen. The solid particles are like "ploughs", which continuously cause band-shaped metal shavings on the surface of specimen and fall off continuously. Therefore, when the impact angle is small, the erosion mechanism is consistent with the micro-cutting theory proposed by Finnie [11].

When the impact angle is 90°, dimples and lips appear on the surface of specimen. The lips are plastically deformed under the continuous impact and compression of subsequent solid particles. Once the deformation reaches its limit, the raised lip will peel off from the wall surface, causing wear. It can be seen that under vertical impact conditions, the erosion mechanism is consistent with the forging extrusion theory proposed by Levy [12].

![Figure 2](image1.png)

**Figure 2.** Appearance of erosion pits with different impact angle.

When the impact angle is 45°, there are both scratches, pits and lips on the surface of the test piece, indicating that both micro-cutting and forging extrusion exist. When particles with sharp angles hit the wall, it is easier to "cut" scratches and lips on the wall like an axe, while particles with obtuse angles can directly form dimples and lips. Lips peel off under the impact and compression of subsequent particles, which causes wear.

In conclusion, the erosion wear mechanism of AISI 8630 is mainly micro-cutting. With the increase of the impact angle, erosion wear is a process from micro-cutting to forging extrusion.

2.5. Results and analysis

2.5.1. Effect of impact duration. In order to analyze the impact of impact time on the erosion of AISI 8630 material, quartz sand particles with a median diameter of 114.4 μm are selected, and erosion experiments are performed under the conditions of an impact velocity of 59 m/s and an impact angle of 90°. The experiment consumed 220 g of solid particles in total and took about 60 min.

It is known from Figure 4 that when the particle consumption is less than 80 g (the first 22 minutes), the mass lost by the specimen gradually increases with the increase of the particle consumption. After the particles consumed 80 g (22-60 min), the weight loss of the specimen increased almost linearly with the increase of the particle consumption. At the same time, the erosion rate also reached a stable value, and erosion wear entered a steady-state erosion period [13]. However, the erosion latency is relatively short compared to steady state period, so the entire erosion can be regarded as a steady state.
Therefore, in order to reduce the error, the erosion rate in steady state is used for calculation in this context.

![Figure 4](image.jpg)

**Figure 4.** Effects of impact duration on erosion ratio.

![Figure 5](image.jpg)

**Figure 5.** Effect of particle concentration on erosion wear.

2.5.2. **Effect of particle concentration.** Erosion experiments are performed on solid particles of different diameters at different speeds. The results are shown in Figure 5. It can be seen that the trends of the curves are basically the same under different particle diameters and impact speeds. As the mass flow rate increases, the erosion rate is stable.

2.5.3. **Effect of impact angle.** Figure 6 shows the relationship between erosion rate and impact angle for particles with a diameter of 114.4 μm. It can be seen from Figure 6(a) that the change trend of erosion rate under different impact speed conditions is almost the same: when the impact angle of the particles is less than 15°, the erosion rate increases significantly with the increase of the impact angle; when the impact angle is between 15° and 30°, the erosion is the most serious; when the impact angle is greater than 30°, the erosion rate gradually decreases as the impact angle increases.

![Figure 6](image.jpg)

**Figure 6.** Effects of particle impact angle on erosion ratio and normalized result.

2.5.4. **Effect of impact speed.** When the impact angle was 90°, solid particles with diameters of 88.3 μm, 114.4 μm, and 224.3 μm were selected for erosion experiments. Figure 7 shows the relationship between the erosion rate of material surface and the impact velocity of particles when the impact angle is 90. Obviously, as the impact velocity increases, the erosion rate increases exponentially. In the logarithmic coordinate system, the curves are almost parallel, indicating that the two factors of particle size and impact speed are independent of each other.
2.5.5. Effect of particle size. Figure 8 shows the effect of particle size on erosion ratio with different impact velocities when the impact angle is 90°. It can be seen that the erosion rules under two impact velocities are the same: when the particle diameter is less than 200 μm, the erosion rate gradually increases as particle size increases; when the particle size is larger than 200 μm, the erosion rate remains basically stable. This phenomenon is called "particle size effect" [14]. There are many explanations for this effect, such as strain rate and secondary wear [15].

3. AISI 8630 erosion model

Since the impact of particle concentration on erosion wear is small and the impact of impact angle, velocity and particle size on erosion are independent of each other, the erosion model of AISI 8630 can be assumed as:

\[ E = f(\alpha)g(v)h(d) \]  

(1)

Where, \( f(\alpha) \) is the impact angle function, \( g(v) \) is the impact velocity function, and \( h(d) \) is the particle size function.

① Angle function \( f(\alpha) \)

Figure 9 is obtained by combining Figure 6(b) and Figure 6(d). It is known from Figure 9 that the change trend of erosion rate is basically the same whether the particle size and speed are the same, so the erosion model can be simplified as Equation (2). The expression of the impact angle function \( f(\alpha) \) can be expressed as Equation (3) after data analysis.

\[
E = E_{90}f(\alpha) \\
E_{90} = g(v)h(d) \\
f(\alpha) = 0.8213\sin5\alpha - 10.9589\sin4\alpha \\
+ 26.5203\sin3\alpha - 26.2244\sin2\alpha \\
+ 10.8417\sin\alpha
\]

(3)

\[
E_{90} = \begin{cases} 
  h(d_1)g(v) = 0.827(v/100)^{0.18} & d_1 = 88.3\mu m \\
  h(d_2)g(v) = 0.655(v/100)^{1.18} & d_2 = 114.4\mu m \\
  h(d_3)g(v) = 0.568(v/100)^{2.18} & d_3 = 224.3\mu m 
\end{cases}
\]

(4)

\[
g(v) = \left(\frac{v}{100}\right)^{3.208}
\]

(5)

② Impact velocity function \( g(v) \)

According to Section 2.5.4, the erosion rate \( E_{90} \) is divided by their respective coefficients \( h(d) \). The results are shown in Figure 10, and the impact velocity function \( g(v) \) can be obtained as Equation (5).
Figure 9. Curve of particle impact angle function.

Particle size function $h(d)$

According to Formula (2), when the impact velocity is 40 m/s, $g(40) = 0.43208$; when $v = 51$ m/s, $g(51) = 0.513208$. The erosion rates corresponding to impact speeds of 40 m/s and 51 m/s in Figure 11 are divided by the values of $g(40)$ and $g(51)$, respectively. Figure 11 shows a particle size function curve $h(d)$ obtained by fitting new data points.

Figure 10. Curve of impact velocity function.

Figure 11. Curve of particle velocity function.

Erosion model

The erosion rate can be obtained by combining Formulas (1), (3), (5), and (6). In order to improve the accuracy of the model, the coefficient $C$ is introduced to modify the model.

$$h(d) = \begin{cases} 46.94E - 9d^3 - 36.15E - 6d^2 + 9.27E - 3d & d < 213.8\mu m \\ 0.78 & d \geq 213.8\mu m \end{cases}$$

$$E = Cg(v)f(\alpha)h(d)$$

$$C = \frac{1}{n} \sum_{i=1}^{n} C_i$$

$$E = 1.02 \times 10^{-3} \left( \frac{v}{100} \right)^{3.208} f(\alpha)h(d)$$

Among them, $E_i$ is the erosion rate obtained by experiments, $E_c$ is the erosion rate calculated by Formula (1), $i$ is the experimental sequence number, and $n$ is the total number of experiments.

All the experimental values and related calculation values appearing in Sections 2.5.3 to 2.5.5 are taken into Equation (8), and the value of $C$ can be obtained ($C=1.02$). After dimensionless treatment, the erosion model of AISI 8630 alloy steel can be expressed as Equation (9), where $f(\alpha)$ and $h(d)$ are shown in Equations (3) and (6).
4. Numerical simulation and model verification

The accuracy of four erosion models (DNV, E/CRC, Oka, and AISI 8630 model) are compared in this section through simulation.

4.1. Theory

4.1.1. Geometry. Referring to the true size of the fluid domain in the back of the venturi tube of the erosion test, a geometric model is established as shown in Figure 12.

4.1.2. Boundary conditions and solution settings. The pressure inlet and pressure outlet are used as the boundary conditions. All wall in the calculation domain are considered as set to be no-slip adiabatic without considering surface roughness. The standard k-ε turbulence model and standard wall function are used, and the second-order upwind discrete format consisted with SIMPLE algorithm are applied. The residual is set to $1 \times 10^{-6}$.

4.1.3. Four erosion models. The erosion model (including DNV, E/CRC, Oka and AISI 8630) is defined by UDF. The numerical simulation results and experimental results are compared, and the applicability of the four models to this case is analyzed.

1) DNV model

$$E = Af(\alpha) v'$$

$$f(\alpha) = \sum_{i=1}^{n} (-1)^i A_{i\alpha}$$

$$E = C(BH)^{-0.59} F_S v^n f(\alpha)$$

$$E = 1.0 \times 10^{-9} \rho_n K_f(\alpha)(H_V)^{g_2} \left( \frac{v}{v'} \right)^{g_3} \left( \frac{d}{d'} \right)^{g_4}$$

In the Equation (10), $E$ is the dimensionless erosion rate. $A$ is a constant. For steel targets, $A = 2.0 \times 10^{-9}$. $f(\alpha)$ is the angle function, $\alpha$ is the incident angle (radian value) of the particles impacting the wall. $v$ is the velocity at which the particles hit the wall, m/s. $n$ is the velocity index, taken as 2.6. The value of parameters $A_i$ are $A_1 = 9.370$, $A_2 = 42.295$, $A_3 = 110.864$, $A_4 = 175.804$, $A_5 = 170.137$.

2) E/CRC model

In the Equation (11), $C$ is a constant with the value of $2.17 \times 10^{-7}$; $BH$ is the Brinell hardness of the impacted surface, N/mm$^2$; $F_S$ is the shape coefficient of the solid particles; $n$ is the speed index, $n = 2.41$; $f(\alpha)$ is the angle function and $\alpha$ is the particle impact angle of incidence (radian value) of the wall.

3) Oka model

In Equation (12), $\rho_n$ is the wall density, kg/m$^3$; $H_V$ is the wall Vickers hardness, GPa; $v'$ is the reference particle impact velocity, m/s; $d'$ is the reference particle size, µm.

| Table 2. Numerical simulation results and experimental results of different models. |
| --- |
| No. | Particle size $d$ (µm) | Particle impact angle $A$ (°) | Experimental value of erosion rate $E_r$ (10$^{-3}$) | DNV $E_r$ | $\eta$ | E/CRC $E_r$ | $\eta$ | Oka $E_r$ | $\eta$ | AISI 8630 $E_r$ | $\eta$ |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | 114.4 | 30 | 0.358 | 0.340 | -5.05 | 0.389 | 8.76 | 0.345 | -3.77 | 0.358 | -0.03 |
| 2 | 114.4 | 60 | 0.291 | 0.276 | -5.15 | 0.296 | 1.58 | 0.270 | -7.31 | 0.291 | -0.21 |
| 3 | 114.4 | 90 | 0.242 | 0.270 | 11.78 | 0.249 | 2.98 | 0.254 | 4.92 | 0.245 | 1.41 |
| 4 | 114.4 | 90 | 0.110 | 0.126 | 13.35 | 0.128 | 15.78 | 0.119 | 8.03 | 0.109 | -1.44 |
| 5 | 88.3 | 90 | 0.069 | 0.065 | -6.24 | 0.069 | 1.31 | 0.071 | 3.05 | 0.069 | 0.87 |
| 6 | 224.3 | 90 | 0.083 | 0.071 | -13.68 | 0.089 | 8.11 | 0.082 | -0.36 | 0.081 | -1.57 |
4. AISI 8630 model

As known from Section 3, the expression of AISI 8630 erosion model is expressed as Equation (9).

4.2. Results and analysis

Models of DNV, E/CRC, Oka, and AISI 8630 are used to calculate erosion rates under different conditions. The relative error between each numerical simulation value and the experimental value are shown in Table 2. It is known from Table 2 that the maximum errors of DNV and E/CRC are -13.68% and 15.78%, which is obviously not suitable in this paper. In contrast, the maximum error of the AISI 8630 model is only -1.57%. It can be seen that the AISI 8630 erosion model can be applied to study the erosion wear of underwater oil tree.

5. Conclusions

(1) The morphology of the erosion pit was photographed with a scanning electron microscope, and the erosion mechanism of AISI 8630 was revealed: under low-angle impact conditions, the erosion of AISI 8630 material is mainly micro-cutting; under high-angle impact conditions, erosion is mainly in the form of forging extrusion. With the increase of the impact angle, erosion is a process from micro-cutting to forging extrusion.

(2) Analysis of the erosion test data of AISI 8630 found that when the angle of the quartz sand particles impacting the test piece was below 15°, the erosion rate increased significantly with the increase of the impact angle; when the impact angle is between 15° and 30°, erosion wear is the worst; when the impact angle is greater than 30°, the erosion rate gradually decreases as the impact angle increases. With the increase of the impact velocity of the quartz sand particles, the erosion rate increases exponentially. When the particle size is less than 200 μm, the erosion rate gradually increases with the increase of the particle size; when the particle size is larger than 200 μm, the erosion rate is basically unchanged as the particle size increases.

(3) Based on the data obtained from erosion experiments, regression analysis obtained the erosion model of AISI 8630 material. Compared with DNV, E/CRC, and Oka erosion models and experimental data, the maximum error of the erosion model obtained in this paper is 1.57%, and the accuracy is greatly improved compared with foreign classic models.

References

[1] Chen X, Mclaury B S and Shirazi S A 2004 Computers & Fluids 33 1251
[2] Singh A 2014 Offshore Technology Conf. (Houston) pp 24710
[3] Wallace M S, Dempster W M and Scanlon T 2004 Wear 256 927
[4] DNV RP-O501 Erosion Wear in Piping Systems 2007
[5] Zhang Y, Reuterfors E P and Mclaury B S 2007 Wear 263 330
[6] Oka Y I, Okamura K and Yoshida T 2005 Wear 259 95
[7] Huang C, et al. 2008 Powder Technology 187 273
[8] Arabnejad H, et al. 2015 Wear 56 pp 332-1044
[9] Wang H K, et al. 2019 Tribology International 137 387
[10] Li Y and Chen S X 2003 China Powder Science and Technology 9 30
[11] Finnie I 1960 Wear 3 87
[12] Levy A V 1986 Wear 108 1
[13] Lippmann D and Kessel D 1994 Annals of the New York Academy of Sciences 715 525
[14] Dong G and Zhang J Y 2003 Journal of Materials Science and Engineering 21 307
[15] Parsi M, Najmi K and Najafifard F 2014 Journal of Natural Gas Science & Engineering 21 850