Modeling and Durability Behavior of Erosion—Corrosion of Sand Control Screens in Deepwater Gas Wells

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ABSTRACT: Deepwater gas wells usually have high production rates, which result in high-speed sand movement along with the gas flow and acid components such as CO₂ in the gas flow. The erosion and corrosion effect intensifies the damage to sand screens and can further lead to sand control failures, which endanger the safety of production operations. In this paper, using a differential rotation device to simulate erosion, corrosion, and erosion—corrosion, experiments observing the impacts of several factors on sand screens were carried out. The factors include CO₂ partial pressure, temperature, flow velocity, sand content, and sand particle size. Their impacts on erosion, corrosion, and erosion—corrosion rate are inspected independently, and the sensitivity of factors to the erosion—corrosion rate of a sand screen was determined using the range method. Traditional erosion models involving flow rate, sand content, and sand grain size and traditional corrosion models involving CO₂ partial pressure and temperature are taken as references, and an erosion—corrosion coupled model of sand screens is established based on the experimental results using the multivariate regression analysis. With critical damage thickness taken as the failure criterion of a sand screen, a prediction method for sand screen failure is formed and is applied to the case study of the S deepwater gas field. The results show that under the experimental conditions, the screen loss rate due to erosion—corrosion is significantly higher than that of erosion only or corrosion only and is even higher than the sum of both. The erosion—corrosion rate increases with the increase of CO₂ partial pressure, temperature, flow velocity, sand content, and sand particle size. It has an exponential relationship with the negative reciprocal of temperature, a linear relationship with the partial pressure of CO₂, and power fitting relationships with flow velocity, sand content, and sand particle size. The ranking of sensitivities to the erosion—corrosion rate of high-quality screens is as follows: sand content > flow velocity > temperature > sand particle size > CO₂ partial pressure. The error between the predicted results by the proposed model and the experimental results is in the range of 0.44—9.47%. The erosion—corrosion rate of sand screens in each production well of the S gas field is in the range of 0.0111—0.0521 mm/a, while the durability of the screens is 14—68 years. The erosion—corrosion rate model of a sand screen and the prediction method for sand screen failure proposed in this paper provide theoretical support to the durability evaluation of sand screen in deepwater gas wells, which is of great significance for ensuring the safe and efficient development of offshore oil and gas resources.

1. INTRODUCTION

Low compaction degree and loose cementation are common characteristics of deepwater formations, which can lead to a high possibility of sand production. Deepwater gas wells have high flow velocity, and with sands present in the gas flow, severe erosion of sand screens can be expected. If the produced gas is accompanied by acid gases such as CO₂, CO₃ corrosion will reduce the strength of the pipe and worsen the erosion; the erosion will peel off corrosion products from the pipe surface and further intensify the corrosion. The interaction between erosion and corrosion can be a coupled process accelerating the failure of sand screens, which will cause a series of hazards, such as erosion and corrosion of downhole pipe strings and equipment above ground, and the increase of underground operation times. These hazards may even cause gas wells to stop production in severe cases. Therefore, it is of great significance to ensure the safe and efficient development of offshore oil and gas resources by accurately controlling the
erosion and corrosion rate of sand screens and evaluate the durability of the screens in real time.

Erosion—corrosion of sand screens refers to the phenomenon of the screen filter medium being damaged by the long-term interaction of the impact of sand-containing flow (including gas, a certain concentration of CO2, a small amount of water) and electrochemical corrosion. For CO2 corrosion problems, corrosion rate prediction models are generally classified into three categories, namely, semiempirical prediction model, empirical prediction model, and mechanism prediction model. De Waard (1975) proposed a representative semiempirical model, the De Waard prediction model, which had been improved and modified continuously in the following decades by introducing factors such as flow velocity, pH level, and oil film. Based on a large number of indoor experimental data at low temperatures and field data at high temperatures, the Norwegian Institute of Energy Technology (2005) established the Norsok corrosion empirical model. This model can predict the uniform corrosion rate of materials, but for irregularly shaped areas (such as pitting corrosion and platform corrosion), the predicted results are often lower than the actual corrosion rate. Nesic et al. (2003) proposed a CO2 corrosion kinetic model as a mechanism model, which considers the single-phase chemical reaction and ion exchange of film formation on the metal surface. At present, most corrosion models are in static states, without considering the impact of flow velocity on the corrosion process.

For erosion studies, there are deformation wear theory, microcutting theory, elastoplastic indentation rupture theory, and forging extrusion theory. However, in actual erosion processes, there are several factors taking effect and cannot be explained by a single theory. In cutting and abrasion studies, the impact of flow velocity was inspected but that of multiphase flow was not. The indentation fracturing theory established a model of erosion by solid particles in two-phase flow on the basis of microcutting theory, involving particle mass flow rate, flow velocity, and particle size. The current erosion model involves the factors of flow velocity, sand content, and sand grain size.

Cameron et al. (2007) established an empirical model of sand parameters and erosion rate according to the erosion experiments of woven wire screens and wire-wrapped screens by the SwRI Institute. They pointed out that the quality loss limit of the woven wire screen is more than 2% with erosion and propose that the durability of the screen can be predicted based on the results of the quality loss limit. Gilledipie et al. (2009) carried out erosion experiments on metal mesh screens under different sand velocities and sand concentrations and proposed a failure criterion of sand screens based on weight loss and established a durability prediction model for sand screens. Procky et al. (2015) carried out erosion experiments with metal mesh screens and quantitatively analyzed the relationships between the parameters and erosion rate by changing flow velocity, sand content, and sand particle size. Combined with computational fluid dynamics (CFD), an empirical model for metal mesh screens is proposed.

The above research on erosion—corrosion of sand screens is focused on single erosion or corrosion effect, without coupling the both. The sand screen erosion—corrosion process in deepwater gas reservoirs is a complex interaction of corrosion and erosion, and its mechanism is currently unclear due to multiple affecting factors and the uncertainty of the development of erosion—corrosion. Research on erosion—corrosion coupling topic is insufficient.

In this paper, we carried out erosion, corrosion, and erosion—corrosion coupling simulation experiments with consideration of the influence of factors such as CO2 partial pressure, temperature, flow velocity, sand content, and sand particle size. The coupled erosion—corrosion pattern of sand screens is studied, and the sensitivity of each factor is analyzed. An erosion—corrosion rate model of sand screen and a sand control failure prediction method is proposed and applied for a case study. This study provides a new method for sand screen durability prediction in deepwater gas reservoirs, through which the screen loss degree can be predicted under different sanding and working conditions. The method can provide support to the safe development of offshore gas wells.

2. EXPERIMENTAL RESEARCH ON SCREEN EROSION—CORROSION COUPLING LAW

2.1. Experimental Method. 2.1.1. Experimental Device. Figure 1 shows the differential rotation device for erosion—corrosion simulation.

![Figure 1. Schematic diagram of the differential rotation device for erosion—corrosion simulation.](https://doi.org/10.1021/acsomega.1c02960)
hanging piece into sodium hydroxide to neutralize the acid. Then, immerse it into anhydrous ethanol and then dry the hanging piece with filter paper. Slightly polish the surface of the hanging piece with fine sandpaper until the metal color is exposed and weigh the hanging piece to calculate the loss rate.

2.1.2. Experimental Materials. 2.1.2.1. Hanging Pieces. Specifications of the 316 L steel mesh hanging piece are shown in Table 1, and the samples are shown in Figure 2.

| Screen hanging piece specifications | Warp wires | Warp density |
|------------------------------------|------------|--------------|
| 72 mm × 12 mm × 1.2 mm             | 120 μm     | 1 piece/mm   |

Figure 2. Screen hanging piece samples.

2.1.2.2. Corrosive Media. The formation water samples were prepared by mixing N₂ and CO₂ gases, and the compositions were adjusted to have the corresponding density, pH value, salinity, and ion concentrations. The compositions of formation water sample are shown in Table 2.

2.1.2.3. Sand. Vibrating screens are used to prepare sands of 100 mesh (45 μm), 200 mesh (78 μm), and 300 mesh (150 μm).

2.1.3. Calculation Method. 2.1.3.1. Surface Area of the Screen Hanging Piece. In the experiment, 316 L high-quality screen mesh hanging pieces were used. The screen mesh structure is woven with a full-wrapped twill. The surface area calculation model of the screen mesh hanging piece is shown in Figure 3.

Warp number

\[ n_1 = \frac{a}{\rho_b} \quad (1) \]

Warp length

\[ L_1 = b \quad (2) \]

Weft number

\[ n_2 = \frac{b}{D} \quad (3) \]

Weft length

\[ L_2 = \frac{D}{\sin \arctan \frac{\rho_b}{T}} \times (n_1 - 1) \quad (4) \]

The surface area of the screen mesh hanging piece is as follows

\[ A = \pi D (L_1 n_1 + L_2 n_2) + \frac{\pi D^2}{2} \times (n_1 + n_2) + \pi d c - \frac{\pi d^2}{2} \quad (5) \]

2.1.3.2. Erosion—Corrosion Rate. The loss rate of the sample is calculated according to the weight loss, and the formula can be expressed as

\[ V^- = \frac{m_0 - m_1}{A \times t} \quad (6) \]

The depth characterization of the conventional erosion—corrosion rate is as follows

\[ V_{\text{cor—ero}} = \frac{V^- \times 8760}{\rho} \quad (7) \]

2.1.3.3. Equivalent Liquid Flow Rate. Sand particles may settle in water-carrying gas, and the erosion and corrosion effects of water-containing natural gas carrying sand on the screen in actual production are simulated by the erosion and corrosion effect of sand particles carried by corrosive media on the hanging pieces. According to energy balance theory and the quantitative relationship between sand velocity and medium (oil, gas, water) velocity in the Salama multiphase flow model (2000), the relationship between gas velocity and equivalent liquid velocity can be derived as follows

\[ \frac{V_k}{V_l} = \left( \frac{\rho_k \rho_1}{\rho_1 \rho_k} \right)^{0.17} \left( \frac{\rho_k - \rho_1}{\rho_k - \rho_1} \right)^{0.24} \quad (8) \]

2.2. Erosion—Corrosion Coupling Results. To analyze the effect of each factor, orthogonal experiments are designed for corrosion, erosion, and erosion—corrosion, respectively. The corrosion experiment has three factors at four levels (CO₂ partial pressure × temperature × flow velocity). The erosion experiment has the three factors at four levels (sand content × sand particle size × flow velocity). The erosion—corrosion coupling experiment has five factors at four levels and supplementary experiments. The factors and their levels are shown in Table 3.

2.2.1. Effect of Temperature. With a CO₂ partial pressure of 0.6 MPa, sand particle size of 78 μm, and sand content of 0.3 wt % (pure corrosion experiment is without sand), the results of corrosion and erosion—corrosion rate with temperature and flow velocity are shown in Figure 4.

As shown in Figure 4, under the experimental conditions, the corrosion rate and the erosion—corrosion rates both increase with temperatures, showing exponential relationships with the negative reciprocal of temperature. The rate of change gradually decreases with increasing temperature, and the curves eventually tend to be flat. The loss rate of the mesh screen...
under erosion–corrosion is significantly affected by temperature, and the rate of change is significantly higher than that under pure corrosion. The high temperature can positively affect the speed of corrosion on the screen surface. After the impact of sand particles peel off the corrosion products covering the surface, the corrosion can take place faster; therefore, the entire loss of the screen material increases.

2.2.2. Effect of CO2 Partial Pressure. With a temperature of 85 °C, sand particle size of 78 μm, and sand content of 0.3 wt % (pure corrosion experiment is without sand), the results of corrosion and erosion–corrosion rates with CO2 partial pressure and flow velocity are shown in Figure 5.

As shown in Figure 5, under the experimental conditions, the erosion and erosion–corrosion rates both increase with the increase of CO2 partial pressure, showing a linear relationship. The loss rate of the screen under erosion–corrosion is more affected by CO2 partial pressure. The rate of change is higher than that under pure corrosion. The acidity of the flow rises with the increase of CO2 concentration, speeding up the corrosion process and increasing the screen loss rate.

2.2.3. Effect of Flow Velocity. 2.2.3.1. Effect of Flow Velocity on Erosion, Corrosion, and Erosion–Corrosion Rates. With a temperature of 85 °C, sand particle size of 78 μm, CO2 partial pressure of 0.6 MPa (pure erosion experiment is without CO2), the results of erosion and erosion–corrosion rates with sand content and flow velocity are shown in Figure 6.

As shown in Figure 6, under the experimental conditions, the erosion and erosion–corrosion rates both increase with the increase of flow velocities according to a power law fitting. Besides, the rate of change gradually decreases, and the curves tend to be flat. The screen loss rate under erosion–corrosion is more affected by flow velocities, and the rate of change is higher than that under pure erosion. The movement speed of sand particles increases with flow rate, and the sand particles can peel off the corroded film from the surface faster, exposing more area to be further corroded; therefore, the screen loss rate increases.

2.2.4. Effect of the Particle Size. With a temperature of 85 °C, sand content of 0.3 wt %, and CO2 partial pressure of 0.6 MPa (pure erosion experiment is without CO2), the experimental results of the rate of erosion and erosion–corrosion coupling with particle sizes and flow velocities are shown in Figure 7.
As shown in Figure 7, under the experimental conditions, the erosion and erosion−corrosion rates both increase with the increase of particle size according to a power law fitting, and the rate of change gradually decreases. The loss rate of the screen is more affected by sand particle size under erosion−corrosion, where the rate of change is higher than that under pure erosion. Larger sand particles have larger mass and impact area, and the corroded film will be eroded more easily, thus speeding up the erosion−corrosion effect.

2.2.5. Effect of Sand Content. With a temperature of 85 °C, flow velocity of 1.2 m/s, and CO2 partial pressure of 0.6 MPa (pure erosion experiment is without CO2), the results of erosion and erosion−corrosion rates with sand content and particle size are shown in Figure 8.
As shown in Figure 8, under the experimental conditions, the erosion and erosion-corrosion rates both increase with the increase of sand content, following power function patterns. The rate of change gradually decreases, and the curves tend to be flat. Under the condition of erosion-corrosion, the loss rate of the screen is more affected by the sand content, where the rate of change is higher than that under pure erosion. Higher sand contents can cause worse erosion by constantly breaking the integrity of the corroded film and exposing more uncorroded material, thereby worsening the whole erosion-corrosion of the screen.

2.2.6. Comparison of Erosion, Corrosion, and Erosion-Corrosion. With a temperature of 85 °C, sand particle size of 78 μm, sand content of 0.3% (single corrosion test without sand), and CO2 partial pressure of 0.6 MPa (pure erosion experiment is without CO2), the results of erosion, corrosion, and erosion-corrosion with flow rates are as shown in Figure 9.

As shown in Figure 9, under the experimental conditions, the screen loss rate under coupled erosion and corrosion is significantly higher than the pure erosion loss rate or pure corrosion loss rate. Moreover, it is also higher than the sum of pure corrosion and erosion. By the regression analysis of the relationship between the coupled effect and the single effects, the coupled erosion-corrosion rate model can be obtained.

\[ V_{\text{cor-ero}} = 0.179 + 0.011 \ln v_{\text{ero}} + 0.021 \ln V_{\text{cor}} \]  

The errors of the predictive values by the coupled effect model and the single effect models are as shown in Table 4. The errors between the predictive values and the experimental results are in the range of 0.49−5.66%. The coupled erosion-corrosion rate model obtained has acceptable accuracy.

| number | measured value (mm/a) | predictive value (mm/a) | error value (%) |
|--------|-----------------------|-------------------------|----------------|
| 1      | 0.0244                | 0.0231                  | 5.66           |
| 2      | 0.0607                | 0.0604                  | 0.49           |
| 3      | 0.0677                | 0.0684                  | 1.01           |
| 4      | 0.0703                | 0.0694                  | 1.30           |

2.3. Sensibility Analysis. According to the orthogonal experiment, the range method is used to analyze the sensibilities of the influencing factors of the erosion-corrosion rate. The sensibility of each influencing factor on the research objective is judged by analyzing the range of the experimental results. The larger the range, the stronger the sensibility of the factor to the research objective. The range is calculated as follows

\[ k_j = \frac{1}{m} \sum_{i=1}^{m} x_{ij} - \bar{x} \quad (10) \]

\[ R_j = \max(k_j) - \min(k_j) \quad (11) \]

After analyzing the variance of the results of the orthogonal experiment, the results of the range analysis of each influencing factor are shown in Table 5.

From the ranges of the factors affecting erosion-corrosion rates, it can be seen that the sensibility ranking of the factors to the erosion-corrosion rate of high-quality screen mesh is as follows: sand content > flow velocity > temperature > sand particle size > CO2 partial pressure.
Table 5. Results of Range Analysis of Each Influencing Factor

| factor | temperature | CO₂ partial pressure | sand content | sand particle size | flow velocity |
|--------|-------------|----------------------|--------------|-------------------|---------------|
| k₁     | 0.035       | 0.033                | 0.019        | 0.038             | 0.031         |
| k₂     | 0.035       | 0.037                | 0.047        | 0.043             | 0.031         |
| k₃     | 0.041       | 0.038                | 0.042        | 0.037             | 0.045         |
| k₄     | 0.051       | 0.044                | 0.048        | 0.044             | 0.056         |
| Rᵢ     | 0.016       | 0.011                | 0.029        | 0.013             | 0.025         |

3. EMPIRICAL EROSION–CORROSION COUPLING MODEL

3.1. Relationship between Erosion–Corrosion Rate and Various Factors. At present, research on erosion and corrosion mainly focuses on pure corrosion and pure erosion. Theoretical studies and experimental studies have been carried out for the laws of corrosion and erosion, and some mathematical models have been established.

3.1.1. Relationship between Corrosion Rate and Influencing Factors in Traditional Corrosion Models. At present, the most widely used corrosion models include the Norsok model, the De Waard model, and the B.Mishra model. Table 6 shows the relationships between corrosion rate and various factors in the traditional corrosion models.

Table 6. Relationship between Corrosion Rate and Various Factors in Traditional Corrosion Models

| prediction model of corrosion rate | influencing factor |
|-----------------------------------|--------------------|
| Norsok model                      | v_{cor} \propto P_{CO₂} |
| De Waard model                    | v_{cor} \propto P_{CO₂} |
| B. Mishra model                  | v_{cor} \propto P_{CO₂} |

3.1.1.1. Relationship between Erosion Rate and Influencing Factors in Traditional Erosion Models. In terms of erosion, many scholars have proposed a variety of relevant theories and calculation methods for loss rates, including deformation wear theory, microcutting theory, elastoplastic deformation wear theory, microcutting theory, forging extrusion theory, indentation rupture theory, etc. etc. Table 7 shows the relationship between erosion rate and various factors in traditional erosion models.

3.2. Erosion–Corrosion Coupling Empirical Model. 3.2.1. Relationship between Erosion–Corrosion Rate and Influencing Factors Based on Experimental Results. According to the experimental results of corrosion, erosion, and erosion–corrosion coupling, we quantitatively analyzed the relationships between erosion–corrosion rate and factors of CO₂ partial pressure, temperatures, flow rates, particle sizes, and sand content. The relationships between each factor and erosion–corrosion rate are shown in Table 8.

Table 8. Relationship between Erosion–Corrosion Rate and Various Factors Based on Experimental Results

| factor | relationship |
|--------|--------------|
| v_{cor} \propto \phi_{\text{fl}} \frac{T_v}{P_w D v T} |

Based on the relationships confirmed from experimental results and that of existing models of single erosion and corrosion, the screen’s erosion–corrosion rate prediction model related to the temperature, CO₂ partial pressure, flow velocity, particle size, and sand content is proposed and is expressed as

\[ V_{cor-\text{ero}} = \epsilon^{\frac{b}{T}} P_{CO₂} \omega D v^n \]

3.2.2. Multifactor Linear Regression Analysis. The undetermined coefficients are determined by multifactor linear regression analysis of the orthogonal experiments, and then the results are incorporated into eq 12. The erosion–corrosion coupling prediction model is as follows

\[ V_{cor-\text{ero}} = \epsilon^{-728.86/T} P_{CO₂}^{0.334} D^{0.074} v^{-0.3} \]

The verification results of the model of erosion–corrosion coupling are shown in Table 9.

As shown in Table 9, the error values between model predictions and experimental results are within the range of 0.44–9.47%, indicating that the established erosion–corrosion model has good accuracy.

3.3. Sand Screen Life Prediction Method. Fang Dake et al. (2020) proposed to use 40% of the screen thickness as the critical damage thickness. Therefore, from the screen’s erosion–corrosion rate, we can have the durability prediction model of the screen as

\[ T = nR \frac{d}{V_{cor-\text{ero}}} \]

4. FIELD APPLICATION AND LIFE PREDICTION OF SAND SCREENS

4.1. Working Conditions. The formation temperature of the S gas field is 80–93 °C, the CO₂ content is 0.15–1.8%, the daily gas production is 30–193 m³, the corrosive medium density is 1048 kg/m³, the kinematic viscosity is 1.01 mPa·s, the natural gas density is 0.7174 kg/m³, the kinematic viscosity is 0.1 mPa·s, and the sand density is 2650 kg/m³. The selected screen material is 316 L stainless steel, with a material density...
of 7.98 g/cm³ and sand retaining precision of 120 μm. The critical damage thickness of the screen is set to 0.48 mm, which is 40% of its thickness. The number of screen layers is two, and the damage time factor of screen blocking is 80%.

4.2. Results and Discussion. The average erosion–corrosion rate can be calculated from the prediction model, and then the screen durability is calculated using eq 14. The screen durability prediction results for production wells in the S gas field are as shown in Table 10.

From Table 10, it can be seen that the erosion–corrosion rates of sand screens in the production wells of the S gas field are within 0.0111–0.0521 mm/a, and the durability of screens is 14–68 years. Well S3 is the most severely affected by erosion–corrosion. Wells S1, S3, and S8 are most severely affected by erosion–corrosion by comparing production years and predicted durability, and there is a risk of sand control failure. The durability is 19, 14, and 23 years, respectively.

5. CONCLUSIONS

(1) From the erosion, corrosion, and erosion–corrosion coupling experiments, it can be concluded that the erosion–corrosion rate increases with the increase of CO₂ partial pressure, temperatures, flow velocities, sand content, and sand particle sizes. It satisfies an exponential relationship with the negative reciprocal of temperature, a linear relationship with CO₂ partial pressure, and a power law relationship with flow velocity, sand content, and particle size. The sensibility of each factor ranks as sand content > flow velocity > temperature > sand particle size > CO₂ partial pressure. The erosion–corrosion rate is significantly higher than that of pure erosion or pure corrosion and is also higher than the sum of the two.

(2) The relationship between erosion, corrosion, and erosion–corrosion rate and various factors obtained from the experiments validate the traditional single erosion and corrosion models. Based on the traditional models, a model of erosion–corrosion rate for the sand screen is established. The error of prediction is in the range of 0.44–9.47% as compared with the experimental results. From the established model of erosion–corrosion coupling rate, a prediction method for sand screen failure is formed using the critical damage thickness of the screen as the criterion of failure.

(3) The prediction results of sand screen durability for gas wells in the S gas field show that the erosion–corrosion rates of the sand screens in production wells are within 0.0111–0.0521 mm/a, and the durability of the screens is 14–68 years. Wells S1, S3, and S8 are most severely affected by erosion–corrosion, and there is a risk of sand control failure. The durability of their sand screen is 19, 14, and 23 years, respectively.

Table 9. Prediction Results of the Coupled Model

| number | measured value (mm/a) | predictive value (mm/a) | error value (%) | segment | measured value (mm/a) | predictive value (mm/a) | error value (%) |
|--------|-----------------------|-------------------------|----------------|---------|-----------------------|-------------------------|----------------|
| 1      | 0.0666                | 0.0669                  | 0.44           | 9       | 0.0719                | 0.0775                  | 7.17           |
| 2      | 0.0685                | 0.0677                  | 1.15           | 10      | 0.0475                | 0.0522                  | 9.14           |
| 3      | 0.0705                | 0.0789                  | 7.22           | 11      | 0.0813                | 0.0816                  | 0.46           |
| 4      | 0.0724                | 0.0795                  | 8.88           | 12      | 0.0298                | 0.0312                  | 4.50           |
| 5      | 0.0607                | 0.0663                  | 8.55           | 13      | 0.0508                | 0.0545                  | 6.78           |
| 6      | 0.0658                | 0.0609                  | 8.07           | 14      | 0.0107                | 0.0107                  | 2.92           |
| 7      | 0.0685                | 0.0677                  | 1.15           | 15      | 0.0186                | 0.0178                  | 4.49           |
| 8      | 0.0666                | 0.0669                  | 0.44           | 16      | 0.0104                | 0.0095                  | 9.47           |

Table 10. Prediction Results of Screen Durability for Production Wells in the S Gas Field

| well number | temperature (°C) | CO₂ partial pressure (MPa) | sand content (wt %) | sand particle size (μm) | flow rate of corrosion medium (m/s) | flow rate of natural gas (m/s) | predicted rate of erosion–corrosion (mm/a) | predicted life (year) |
|-------------|------------------|---------------------------|---------------------|------------------------|-----------------------------------|-----------------------------|---------------------------------------------|----------------------|
| S1          | 92.6             | 0.2963                    | 0.25                | 120                    | 0.753                            | 8.25                        | 0.0396                                       | 19.37                |
| S2          | 90.5             | 0.1131                    | 0.5                 | 120                    | 0.645                            | 7.07                        | 0.0198                                       | 38.87                |
| S3          | 91.3             | 0.6843                    | 0.1                 | 120                    | 1.743                            | 19.10                       | 0.0521                                       | 14.75                |
| S4          | 95.3             | 0.1355                    | 0.15                | 120                    | 1.687                            | 18.48                       | 0.0122                                       | 63.08                |
| S5          | 91.1             | 0.1355                    | 0.15                | 120                    | 1.764                            | 19.33                       | 0.0117                                       | 65.40                |
| S6          | 90               | 0.1001                    | 0.2                 | 120                    | 1.037                            | 11.36                       | 0.0111                                       | 68.96                |
| S7          | 93.1             | 0.2372                    | 0.21                | 120                    | 0.558                            | 6.11                        | 0.0329                                       | 23.38                |
| S8          | 95.5             | 0.2372                    | 0.19                | 120                    | 0.75                             | 8.22                        | 0.0295                                       | 26.07                |
| S9          | 95.5             | 0.1246                    | 0.1                 | 120                    | 0.505                            | 5.53                        | 0.0141                                       | 54.61                |
| S10         | 95.4             | 0.1246                    | 0.1                 | 120                    | 0.522                            | 5.72                        | 0.0139                                       | 55.19                |
| S11         | 93.7             | 0.2144                    | 0.11                | 120                    | 0.693                            | 7.59                        | 0.0225                                       | 34.14                |

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NOMENCLATURE

| Symbol | Definition |
|--------|------------|
| A      | surface area of the hanging piece (mm$^2$) |
| $n_1$  | warp number (piece) |
| a      | hanging piece length (mm) |
| $p_0$  | warp density (piece/mm) |
| b      | hanging piece width (mm) |
| $L_1$  | warp length (mm) |
| $n_2$  | weft number (piece) |
| D      | wire diameter (mm) |
| $L_2$  | weft length (mm) |
| l      | Warp hole distance (mm) |
| $V^-$  | quality characterization of the sample loss rate (g/(cm$^2$.h)) |
| $m_0$  | initial weight of the sample (g) |
| $m_1$  | weight after experiment (g) |
| t      | experiment time (h) |
| $V_{cor-ero}$ | depth characterization of the corrosion–erosion rate (mm/a) |
| $\rho$ | density of sample (g/cm$^3$) |
| $V_c$  | superficial velocity of corrosive medium (m/s) |
| $V_g$  | superficial velocity of natural gas (m/s) |
| $\rho_c$ | corrosive medium density (kg/m$^3$) |
| $\rho_g$ | natural gas density (kg/m$^3$) |
| $\mu_c$ | corrosive medium viscosity (mPa.s) |
| $\mu_g$ | natural gas viscosity (mPa.s) |
| $k_i,j$ | average value of the index experiment results corresponding to the $i$ level in the $j$ column |
| $x_{in}$ | index value corresponding to the $n$th experiment at the $i$ level |
| $\bar{x}$ | mean value of the corresponding index of all experiments |
| m      | number of repetitions of levels |
| $R_j$  | range value of the corresponding factor in the $j$ level |
| $V_{ero}$ | depth characterization of the erosion rate (mm/a) |

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