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Wensheng Li,a Anqing Fu,a Yan Tian,b Yafeng Ju,c Menghan Xue,d Chengxian Yin,a and Qiuli Zhangd,*

a State Key Laboratory of Performance and Structural Safety for Petroleum Tubular Goods and Equipment Materials, CNPC Tubular Goods Research Institute, Xi’an 710077, China
b Hengyang Valin Steel Tube Co., Ltd., Hengyang, Hunan 421001, China
c Petroleum Technology Research Institute of PetroChina Changqing Oilfield Company, Xi’an 710018, China
d College of Chemistry and Chemical Engineering, Xi’an University of Architecture and Technology, Xi’an 710055, China

*Corresponding author: qiulizhang@126.com

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d College of Chemistry and Chemical Engineering, Xi’an University of Architecture and Technology, Xi’an 710055, China
* Corresponding author: qiulizhang@126.com

ABSTRACT
The self-designed flow system was used to study the flow corrosion of X100 pipeline steel in simulated formation water environment by electrochemical measurements as well as computational fluid dynamics (CFD) simulation. The effects of fluid flow velocity and fluid impact angle on X100 steel were determined. When the fluid flow velocity changes between 0.5 - 2.0 m/s, X100 steel is controlled by activation, and as the flow velocity increases, the self-corrosion current $I_{corr}$ increases, the corrosion rate increases; when the impact angle increases from 30° to 90°, the self-corrosion current $I_{corr}$ decreases and the corrosion rate decreases. CFD simulations show that at different flow velocities and impact angles, the velocity field distribution on electrode surface is different. At the minimum impact angle of 30°, the electrode area has the largest flow velocity and shear stress, therefore the corrosion damage is the most serious.

Keywords: Flow Corrosion; X100 Pipeline Steel; Fluid Velocity; Fluid Impact Angle

1. Introduction
With the development of industries, the energy demand is constantly increasing, pipeline transportation becomes the main way of oil and gas transportation in China, and a number of the pipelines are scrapped due to corrosion, causing huge economic losses, safety and the environment problems.1 At present, X70 and X80 pipeline steel has been widely used, and X90 has also been successfully used in the construction of long-distance pipelines. In order to achieve the large caliber, long distance, high pressure and other transportation conditions, the application of high strength pipeline steel is essential in the future. For the new generation of pipeline steel, X100 pipeline steel has become a research hotspot due to its high strength, good pressure resistance and low cost. However, its research has focused on material properties and very few applications in corrosion.2

In the process of transportation, the problem of corrosion produced by oilfield water is particularly prominent.3,4 At present, most studies of corrosion have focused on static formation water, however the corrosion of pipelines under flow environment usually poses great threat.5,6 Compared with the static environment, on the one hand, corrosive ions move relative to the surface of the base material, which will produce electrochemical reactions, on the other hand, due to
hydrodynamic factors, both of these will have a certain effect on the corrosion of the material. From the perspective of dynamics, the fluid velocity plays an important role in flow corrosion. In general, the damage loss is quite slight when the flow velocity is low while it will increase when the flow velocity is increased. Once the flow velocity exceeds a critical value, the damage loss will increase sharply. Previous studies found that the corrosion rate of pipeline steel in flowing environment is significantly higher than that in a stagnant environment, and the larger the flow rate, the higher the corrosion rate. Sydberger et al. reported that the accelerated erosion caused by the high flow velocity of the fluid due to mechanical removal of corrosion products or mass transfer effects. At the same time, the fluid itself has a certain viscosity, so the change in the impact angle of the fluid will generate the shear stress on electrode surface. When the shear stress is large enough, the resultant mechanical effect will change, therefore, the effect of impact angle on flow corrosion also cannot be ignored. Khayatan et al. studied that the maximum erosion and corrosion rate of pure titanium (CP-Ti) occurred at an impact angle of 40°, and its rate is significantly higher than the pure erosion rate under the positive synergy of all impact angles. Burstein et al. also showed that the Al activity decreased with the increase of the fluid impact angle, and the increase of impact angle would decrease the electrode area under high velocity flow field and increase under low velocity flow field.

In this work, a self-designed flow system was developed to study the effects of flow velocity and impact angle on the corrosion behavior of X100 pipeline steel. Electrochemical impedance spectroscopy (EIS) measurement was applied to characterize corrosion behavior. The velocity flow field distribution was characterized by computational fluid dynamics (CFD) simulation. Furthermore, the corroded morphologies were observed by scanning electron microscope (SEM).

2. Experiment

2.1 Materials and experimental solution

In this study, the working electrode material was X100 pipeline steel, and the elemental composition is shown in Table 1.

Along the rolled direction X100 pipeline steel was sampled with dimensions of 10 mm(L)×10 mm(W)×3 mm(H). As shown in Fig 1., one end was welded to a copper wire using epoxy resin encapsulation, which left a work area of 1cm² that could be used as an electrode. The working face was sequentially polished using #200 to #1200 sandpaper and cleaned with acetone and deionized water. Then it was cleaned, with anhydrous ethanol, blown dry with cold air and placed in a drying box. It is used to simulate the influence of flow velocity when the wire is perpendicular to the electrode, otherwise the impact angle is simulated. (For details, please refer to Fig. S1 and Fig. S2)

The composition of oilfield formation water is shown in Table 2. The pH value of the test solution was 7.62, the temperature was 30°C, the dissolved oxygen was 8.34 mg/L and the free CO₂ was 26.5 mg/L.

2.2 Electrochemical measurements

According to the actual working conditions, a simulated flow corrosion system was designed. The principle of the working section is shown in Fig 2. (For details, please refer to Fig. S1 and Fig. S2)

Electrochemical measurements were conducted using a traditional three-electrode system with X100 pipeline steel as a working electrode (WE), high-purity graphite with a large surface area as an auxiliary electrode (CE), and a saturated calomel electrode (SCE) as a reference electrode (RE) on a CS350 electrochemical workstation from Wuhan Correst Company. Unless noted otherwise all potentials were recorded versus SCE. The prepared electrodes were placed as shown in Figure. 2.
Before the measurement, the working electrode was pre-polarized at -1.2 V for 5 min to remove the oxide film that formed in air and then soaked in the simulation solution for 30 min until the system was stable for the open circuit potential measurement. AC impedance spectroscopy under the open circuit potential was measured for 0.5 h under the following conditions (testing frequency: 100 kHz to 0.01 Hz; disturbance signal amplitude: 5 mV; and, logarithm scanning: 10 times the frequency at 10. Finally, a polarization curve was recorded at a specific parameter setting (potential range: -0.3 ~ 0.6 VOCP (vs. open circuit potential) and scan rate: 0.33 mV/s). Cv curve analysis software was used for a data fitting analysis of the potentiodynamic polarization curve, as well as ZsimpWin software for the electrochemical impedance spectroscopy test data.

2.3 Computational fluid dynamic simulation

2.3.1 Establishment of mathematical model

The law of physical conservation is a fundamental law of flow fluid. The basic conservation laws include: conservation of mass, conservation of momentum, and conservation of energy. The mass conservation equation is also called the continuity equation:

\[ \frac{\partial \rho \mu}{\partial t} + \nabla \cdot (\rho \mu v) = S \]  

Where \( \rho \) is the fluid density, \( m \) is mass, \( t \) is the time, \( v \) is the velocity vector, and \( S \) is the mass added to the continuous phase. The momentum conservation equation is a basic equation that any flow system must satisfy:

\[ \frac{\partial (\rho \mu V)}{\partial t} + \nabla \cdot (\rho \mu \nabla V) = -\Delta p + \Delta \tau + \rho g + F \]  

Where \( \rho \) is the static pressure on the fluid microelement; \( g \) and \( F \) represent the gravity volume and other external volume forces acting on the microelement, \( \tau \) is the viscous stress tensor that acts on the surface of the microelement due to the molecular viscosity. For Newtonian fluids, the viscous stress is proportional to the deformation rate of the fluid:

\[ \tau = \mu \left[ \nabla V + \nabla V^t \right] - \frac{2 \mu V}{3} \]  

The energy conservation equation is also a basic equation that must be satisfied for a flow system containing heat exchange:

\[ \frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E V) = \Delta k_{eff} \nabla T - \rho h J_j + \left( \nabla \cdot \nabla V \right) + S_e \]  

Where, \( E = h - p/\rho + V^2/2 \) represents the total energy of the fluid micelles, \( h \) is the enthalpy, \( k_{eff} \) represents the effective thermal conductivity; \( J_j \) is the diffusion flux of the component \( j \); and \( S_e \) is the heat source term.

2.3.2 Establishment of geometric model

The calculation area of the working section was divided into structural grids. The quality of the calculation grid directly affects the feasibility, convergence and calculation accuracy of the numerical calculation. In this work, two-dimensional geometric models with impact angles of 30 °, 45 °, 60 °, and 90 ° were constructed, as shown in Fig 3. ( \( \angle \alpha \) represents the impact angle, it can be adjusted by turning the wire, as shown in Fig 1). The shape of the mesh was a quadrangle, and the total number of meshes was 10320, 15334, 17235, 14330, 16580, and the grid quality was grids higher than 0.3 account for more than 97% of all grids, indicating that the model is reasonable and of high quality, and effective numerical simulation can be achieved. What we see in the two-dimensional graph model is a reducing tube, because the electrode is located in the center of the tube during the simulation process, so the part we simulate is the fluid that can flow through the electrode surface, so the simulation effect is better.

The \( \kappa - \varepsilon \) turbulence model was used to solve the simulation, where \( \kappa \) is the turbulent kinetic energy and \( \varepsilon \) is the local dissipation rate. The flow velocity at the inlet and an atmospheric pressure
at the outlet were set as the boundary conditions. The specific parameter settings are shown in Table 3.

3. Results

3.1 Influence of fluid velocity on corrosion behavior

As shown in Fig 4., the flow velocity has a small effect on the mechanism of the cathodic and anode reaction process of the polarization curve of the potential. Both the cathodic and anode processes are activated and controlled, and no passivation occurs. The dynamic polarization curves were fitted, and the fitting results are shown in Table 4. In Table 4, $B_a$ indicates the anodic Tafel slope, $B_c$ indicates the cathodic Tafel slope, $E_{corr}$ stands for the corrosion potential and $I_{corr}$ stands for the corrosion current density.

Table 4 shows that along with the increasing flow velocity, the corrosion current density increases, the corrosion rate decreases, and its value changes from 23.923 mm/a to 78.355 mm/a. It indicated that the increase of flow velocity had a significant facilitation on the corrosion rate of X100 steel.

Fig 5. shows the impedance spectroscopy of the X100 pipeline steel at different flow rates of the simulated formation water. Its impedance spectroscopy result was a single capacitive loop, and as the velocity increased, the capacitive reactance arc radius decreased first and then increased. The size of the capacitive reactance arc represents the resistance of the electrochemical reaction. The larger the capacitive reactance arc is, the greater the electrochemical resistance, and thus, the better its corrosion resistance.

The equivalent circuit in Fig 5. R (QR) used for fitting, and the results are shown in Table 5. $R_s$ represents the solution resistance, CPE is constant phase element, $n$ is a dimensionless index, which is related to the compactness and integrity of the product film, $R_{ct}$ stands for the electrochemical process transfer resistance.

Table 5. shows that the flow velocity increases from 0.5 m/s to 2.0 m/s, the $R_{ct}$ decreases first and then increases. Generally, there is only one semicircle in the entire frequency range of the impedance map to indicate the capacitive behavior of the metal electrode. The size of the semicircle at high frequency corresponds to the $R_{ct}$, which is directly related to the interface electron exchange reaction, and for impedance spectra with a larger semicircle, the $R_{ct}$ is larger, the electrode is more resistant to corrosion. As the flow velocity increases, $R_{ct}$ increases, this is because the increase of mass transfer promotes the generation of corrosion films, which will hinder the contact of corrosion ions with the metal substrate. In addition, the uneven distribution of corrosion products will also cause $R_{ct}$ values instability.

Fig 6. shows the fluid flow field distribution by CFD at different flow rates. The vertical axis data represents the velocity distribution data in the simulated flow tube. Different color bars represent different flow rates, the red bottom area represents the flow velocity distribution near the center of the tube, the same as the flow rate of the main solution. In the area close to the wall, there will be a boundary layer area, and within the boundary layer, the velocity distribution is different. Using $\Delta$ to represent the thickness of the boundary layer, simulation of flow rate from tube center to tube wall. The flow direction is parallel to the X100 steel surface. As the fluid velocity increases, the boundary layer area of the fluid surrounding the electrode changes. When the flow velocity is 0.5 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s, the width zone of velocity ($\Delta 1, \Delta 2, \Delta 3, \Delta 4$) in flow field distribution is 0.3 mm, 0.25 mm, 0.2 mm, and 0.15 mm, respectively. This is because the increase
of the flow velocity changes the fluid velocity distribution of the electrode boundary layer, which
decreases the width of the boundary layer, increases the range of high velocity regions. Therefore,
the average velocity of the electrode surface increases, the ions velocity increases, and the corrosion
rate gradually increases.

Fig 7. is a scanning electron microscopy (SEM) analysis of the surface morphology of the
samples after corrosion. As shown in Fig 7., when the flow velocity is 0.5 m/s, a small amount of
pits and corrosion points are observed on the metal surface. Meanwhile from the EDS spectrum of
point A, it can be seen that the corrosion products contain Fe, O, H elements. According to the
percentage of its atoms, the product may be Fe(OH)$_2$; at 1.0 m/s, the electrode surface is gradually
roughened and the corrosion points are increased; at 1.5 m/s, fine corrosion points have spread all
over the surface of the electrode, and dense pits appeared; at 2.0 m/s, the substrate exhibits deep
lamellar corrosion. It indicates that with the increase of flow velocity, the corrosion tends to
intensify.$^{14,15}$ All of which are consistent with the results of the polarization curve analysis.

As the flow velocity increases, the shear stress increases, the material surface damage
progresses faster. Y.Z. Lin et al.$^{16}$ reported that the synergy between electrochemistry and fluid
mechanics leads to increased corrosion. During the fluid flow process, on the one hand, an
electrochemical reaction occurs on the metal surface, and on the other hand, mechanical effects
cause the metal film to be thinned or removed. Once the protective film is damaged and lost, the
carbon steel base material is exposed to the corrosive medium, and the corrosion effect occurs again
to form a new protective film. With the increase of shear stress, the newly formed protective film
was damaged and lost again, forming an autocatalytic accelerated corrosion system.

3.2 Influence of impact angle on corrosion behavior

From Fig 8., all impedance spectra have the same characteristics, that is, there is a concave
semicircle in the high frequency range, and the radius of the semicircle increases significantly with
the increase of the impact angle. Fit the equivalent circuit in Fig 8. and the impedance parameters
are shown in Table 6. From Table 6, the impact angle increases, and $R_{ct}$ increases from 85.2 Ωcm$^2$
to 198.3 Ωcm$^2$, which indicates that the electrochemical process and mass transfer resistance
increase in the simulated formation water. Thus, the corrosion rate decreases.

Fig 9. shows the flow field distribution of X100 steel at different impact angles, it is simulated
based on the model in Fig 3. From Fig 9., the fluid velocity field on the electrode surface is different
under different impact angles. Especially at 30°, the fluid velocity of most of the surface of the
electrode is 3 m/s; when the impact angle increases to 45° and 60°, the area of the low velocity flow
field of about 2.0 m/s increases; at 90°, the entire electrode surface is at a low velocity flow field of
1.0 m/s to 1.5 m/s, and the flow field is symmetrical up and down, flowing in opposite directions.

Reynolds number $Re$ is the ratio of inertial force to viscous force, which can identify and predict
different flow states, such as laminar and turbulent flow. When the Reynolds number is low, it is
generally laminar, in which viscous forces dominate, while turbulent flow occurs at high Reynolds
numbers, inertial forces dominate, and random vortices and other fluctuations are generated in this
state. It is defined as:

$$Re = \frac{\nu l}{\mu}$$

Where $\nu$ is the fluid velocity (m/s), $l$ is the characteristic length (m), $\mu$ is the dynamic viscosity
(Pa/s), and $\rho$ is the density of the solution (kg/m$^3$). In this work, the calculated Re value is $2 \times 10^4$,
which indicates that the flow state of the system is turbulent. When the fluid impinges on the
electrode surface, mechanical shear stress is generated due to the loss of viscous energy in the
The turbulent boundary layer, and its value is related to the turbulence intensity acting on the surface.

The expression of shear stress is:

\[ s = 0.5 f u^2 \rho \]  

Where \( f \) is the coefficient of friction, which is a function of the Reynolds number \( R_e \) and its surface roughness. The calculated shear stress on the electrode surface at different impact angles is shown in Table 7. Obviously, the shear stress is related to the fluid flow rate, when the fluid flow rate is increased, the shear stress increases. The velocity distribution in the turbulent boundary layer is different, even if the bulk velocities are the same. With the strengthening of turbulent motion, the turbulent pulsation kinetic energy increases and the shear stress increases, which is beneficial to the diffusion and exchange of ions, leading to the intensification of the corrosion reaction.

When the impact angle is 30°, the velocity of the entire electrode surface is about 3 m/s, and the average shear stress on the electrode surface is 0.144 Pa as shown in Table 7, which is the highest shear stress. The mechanical effect of the shear stress makes the oxide film and corrosion product deposits thin or eliminated, and damages the electrode substrate, enhances electrode activity, and increases the corrosion rate. GA Zhang et al. found that the corrosion film on X65 steel surface became thinner under increasing flow velocity and shear stress. And there is the highest flow velocity, shear stress and corrosion rate on the microelectrode near the center. With the increase of the impact angle, the high velocity flow field area of the electrode surface gradually decreases, the area of the low velocity flow field occupied by the electrode surface increases, and the shear stress on the electrode surface decreases, thereby forming a more stable electrode, this is consistent with the findings of Burstein et al.

Fig 10. is a scanning electron microscopy (SEM) analysis of the surface morphology of the samples after corrosion. As shown in Fig 10., when the impact angle is 30°, the surface of the electrode has the most corrosion points, the corrosion is the most serious, and the phenomenon of corrosion into flakes occurs. Meanwhile from the EDS spectrum of point A, it can be seen that the corrosion products contain Fe, O, H elements. Thus, the product may be Fe(OH)\(_2\) and other Fe oxides. However, as the impact angle increases, the electrode surface smoothness increases and the corrosion point decreases; at 90°, the corrosion point is the least and the surface is the smoothest. In a turbulent state, the random vortices generated on the metal surface continue to grow and rupture, pulsating the velocity of the medium and generating additional turbulent viscosity. The surface of pipeline steel is not only affected by viscous shear stress, but also by turbulent shear stress, which results in aggravation of the electrochemical heterogeneity on the surface of X100 steel, resulting in local corrosion such as pits and spots.

4. Discussion

The corrosion mechanism of X100 steel in the oilfield formation water can be expressed as:

**Anodic reaction:**

\[ \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \]  

**Cathodic reaction:**

\[ \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- \]  

**Total reaction:**

\[ 2\text{Fe} + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 2\text{Fe(OH)}_2 \]  

\[ 4\text{Fe(OH)}_2 + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 4\text{Fe(OH)}_3 \]  

As shown in Fig 11. In the activation stage, active dissolution of the X100 pipeline steel occurs,
which generates Fe$.\textsuperscript{2+}$. The Fe$.\textsuperscript{2+}$ combines with OH$^{-}$, which is adsorbed on the steel surface to produce unstable Fe (OH)$\textsubscript{2}$ film. Furthermore, the presence of oxygen in the solution will accelerate the further oxidation of Fe (OH)$\textsubscript{2}$,\textsuperscript{21} which attaches to the steel surface. Additionally, the oilfield water contains more Cl$^{-}$ and HCO$\textsubscript{3}^{-}$. The Cl$^{-}$ has strong penetrating power and the ability to assist the formation of Fe vacancies,\textsuperscript{22} which can directly reach the substrate and corrode the metal surface; the HCO$\textsubscript{3}^{-}$ is that easily produces a FeCO$\textsubscript{3}$ film on the electrode surface. At the high flow rate, the high mass transfer rate, would enhance the transportation of Cl$^{-}$ and HCO$\textsubscript{3}^{-}$ towards the electrode surface, which provides favorable conditions for the formation of initial pits on the surface. thus, at 0.5 m/s, fewer corrosion points will be formed on the surface of the steel, as shown in Figure 7a; At the 1.0 m/s-1.5 m/s, the parts of loose Fe(OH)$\textsubscript{2}$ or FeCO$\textsubscript{3}$ film were scoured away by the main solution, which will expose more corrosion points. At the same time, according to the principle of the boundary layer, the flow velocity of the fluid in the mainstream region is higher than that near the pipe wall surface. When the dissolved Fe$.\textsuperscript{2+}$ in the mainstream zone is not saturated, the dissolved Fe in the boundary layer will continue to move to the mainstream zone. When it migrates, the metal matrix will further dissolve, as shown in Figure 7b and Figure 7c; moreover, the protective corrosion products would not dense enough on electrode surface at the high velocity of fluid, and as the result, The surface of the corrosion product becomes the cathode, and the uncorroded surface becomes the anode which will occur the galvanic corrosion, thus, the number and size of the surface points will increase around the original pits which will cause the phenomenon of flake corrosion as shown in Figure 7d. When the electrode surface is at a high flow velocity, the erosion of the surface by the fluid becomes more intense, and the newly formed corrosion products will be difficult to retain. Although the migration rate of Cl$^{-}$ and HCO$\textsubscript{3}^{-}$ in the solution accelerated, it is still difficult to produce new active points because the high flow velocity while the migrated of Cl$^{-}$, HCO$\textsubscript{3}^{-}$ can partially enter and adsorb on the original corrosion pits which will cause its more concave and increases the local corrosion.\textsuperscript{23} At the same time, the high flow velocity also increases the diffusion rate of the cathode oxygen.\textsuperscript{24} Finally, the synergistic effect of fluid mechanics and electrochemistry lead to more severe corrosion, and the surface of the metal substrate is gradually weakened.

5. Conclusion

(1) When the flow rate is 0.5-2.0 m/s, the corrosion process is controlled by activation. As the flow rate increases, $I_{\text{corr}}$ increases, the corrosion rate increases, and the pits and corrosion points on the metal surface gradually increase. Computational fluid dynamics simulation results show that as the velocity increases, the velocity boundary layer width decreases.

(2) When the impact angle is 30°-90°, as the impact angle increases, $I_{\text{corr}}$ decreases, the corrosion rate decreases, and the metal surface roughness decreases. Computational fluid dynamics simulation results show that as the impact angle increases, the flow velocity and shear stress on the electrode surface gradually decrease. When it increases to 90°, the value of the shear stress is the smallest.

(3) In the active zone, the X100 steel matrix dissolves, and Fe$.\textsuperscript{2+}$ reacts with OH$^{-}$ to form an unstable Fe (OH)$\textsubscript{2}$ film which is further oxidized to Fe (OH)$\textsubscript{3}$. At the same time, HCO$\textsubscript{3}^{-}$ and Cl$^{-}$ continuously participate in the corrosion process of the substrate, and local corrosion is intensified.

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Table 1. Chemical composition of pipeline steel (wt %)

| C  | Si  | Mn  | Ni  | P   | S   | Mo  | Cr  | V   | Fe  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.06 | 0.26 | 1.97 | 0.44 | 0.009 | 0.0008 | 0.32 | 0.35 | 0.03 | balance |
Table 2 Solution composition of oilfield formation water (mg/L)

| Composition | NaCl  | KCl  | CaCl₂ | Na₂SO₄ | MgCl₂·6H₂O | NaHCO₃ |
|-------------|-------|------|-------|--------|------------|--------|
| Content     | 17.24 | 0.54 | 0.43  | 0.37   | 0.5        | 3.98   |
| Project                  | Parameter setting       | Project Parameter setting | Parameter setting |
|-------------------------|-------------------------|----------------------------|-------------------|
| Multiphase floe flow    | VOF model               | Inlet velocity (m/s)       | 0.5/1.0/1.5/2.0   |
| Turbulence model        | $k-\varepsilon$ double equation model | Outlet pressure (Pa)       | 0                 |
| Turbulence intensity    | 1%                      | Convergence criterion      | 10^{-3}           |
Table 4. Potentiodynamic polarization curve fitting values of the X100 pipeline steel in different flow rates. “a” in the unit of corrosion rate means mean solar year (365.2422 days).

| $v/\text{m s}^{-1}$ | $B_a/\text{mV}$ | $B_c/\text{mV}$ | $I_{\text{corr}}/\text{A cm}^{-2}$ | $E_{\text{corr}}/\text{V}$ | Corrosion rate/ mm a$^{-1}$ |
|-------------------|----------------|----------------|-------------------------------|----------------|-------------------------|
| 0.5               | 246.4          | 467.8          | $4.64 \times 10^{-4}$         | -0.54           | 23.923                  |
| 1.0               | 105.7          | 231.1          | $5.06 \times 10^{-4}$         | -0.64           | 32.885                  |
| 1.5               | 151.97         | 382.4          | $5.51 \times 10^{-4}$         | -0.67           | 53.467                  |
| 2.0               | 81.6           | 177.9          | $6.32 \times 10^{-4}$         | -0.45           | 78.355                  |
Table 5. Fitting results of the AC impedance spectroscopy of X100 pipeline steel in different flow rates of the simulated formation water

| $v$/$\text{m s}^{-1}$ | $R_s$/Ω cm$^2$ | CPE$/\text{s}^{n}$ S cm$^{-2}$ | $n$ | $R_{cd}$/Ω cm$^2$ |
|----------------------|---------------|-------------------------------|-----|------------------|
| 0.5                  | 2.81          | $5.16 \times 10^{-4}$        | 1.05| 145.2            |
| 1.0                  | 3.05          | $1.76 \times 10^{-4}$        | 1.17| 36.3             |
| 1.5                  | 3.63          | $8.12 \times 10^{-4}$        | 1.33| 38.4             |
| 2.0                  | 2.29          | $9.56 \times 10^{-4}$        | 0.91| 139.8            |
Table 6. Fitting results of the AC impedance spectroscopy of X100 pipeline steel in different impact angles of the simulated formation water

| Impact angle (°) | $R_s$ / Ωcm² | CPE / $s^n$ S cm⁻² | $n$ | $R_{ct}$ / Ωcm² |
|-----------------|--------------|---------------------|-----|-----------------|
| 30°             | 1.43         | 5.69×10⁻⁴           | 1.49| 85.2            |
| 45°             | 1.68         | 3.40×10⁻⁴           | 1.34| 113.5           |
| 60°             | 1.13         | 4.69×10⁻⁴           | 2.31| 176.4           |
| 90°             | 1.34         | 2.78×10⁻⁴           | 1.18| 198.3           |
Table 7. Average shear stress of X100 steel surface at different impact angles

| Impact angle | 30° | 45° | 60° | 90° |
|--------------|-----|-----|-----|-----|
| Average shear stress (Pa) | 0.144 | 0.100 | 0.064 | 0.036 |
Figure 1. Schematic diagram of working electrode
Figure 2. Schematic structure of working section (During the flow rate test, WE is located at the pipe wall; at the impact angle, WE is located at the center of the pipe)
Figure 3. Two-dimensional structure of the shot (\( \angle \alpha \) represents the impact angle)
Figure 4. Potentiodynamic polarization curves of the X100 pipeline steel in simulated formation water at different flow rates.
Figure 5. AC impedance spectroscopy of the X100 pipeline steel in different flow rates of the simulated formation water.
Figure 6. Fluid flow field distribution by CFD at different flow rates

(a) 0.5 m/s

(b) 1.0 m/s

(c) 1.5 m/s

(d) 2.0 m/s
Figure 7. SEM surface morphologies of electrode after flow corrosion test

(a) 0.5 m/s;  (b) 1.0 m/s;  (c) 1.5 m/s;  (d) 2.0 m/s;  (e) EDS of point A
Figure 8. AC impedance spectroscopy of the X100 pipeline steel in different impact angles of the simulated formation water.
Figure 9. Fluid flow field distribution by CFD at different impact angles

(a) 30°

(b) 45°

(c) 60°

(d) 90°
(a) 30°;    (b) 45°;    (c) 60°;    (d) 90°;    (e) EDS of point B

Figure 10. SEM surface morphologies of electrode after flow corrosion test
Figure 11. Mechanism of flow corrosion process