Calculation of Electrochemical Corrosion Rate at Elbow of Supercritical CO₂ Pipeline

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Abstract. Based on the CCUS project planned to run in a domestic oil field, the electrochemical corrosion at the bend of supercritical CO₂ pipeline was studied by means of high-temperature and high-pressure reaction kettle hanging plate experiment, and the corrosion rate of X80 pipeline steel in unsaturated, saturated and supersaturated supercritical CO₂ with water content was obtained. Then through COMSOL simulation of the corrosion rate of 90° bent pipe in the supercritical CO₂ corrosion atmosphere, the maximum corrosion rate position of electrochemical corrosion generated under the action of flow accelerated corrosion (FAC) generated by supercritical CO₂ fluid in the bent pipe was obtained, and corresponding anticorrosion Suggestions were put forward according to the research results.

1. Introduction
Most CO₂ mixture captured at the source contains a certain amount of water [1]. When CO₂ mixture in carbon steel pipeline is not dehydrated strictly and fully, free water and local high-pressure CO₂ combine to form carbonic acid, resulting in a sharp increase in corrosion rate of carbon steel pipeline [2–4]. Different corrosion solutions exist [5]. Compared with X65 and X70 pipeline steel [6–7], X80 steel has greater yield strength and corrosion resistance [8–10]. The corrosion rate at the pipe bend is much higher than that of the straight pipe, and when the pipe bend is 90°, the corrosion rate is higher than that of the pipe bend at other angles. In other words, X80 pipeline steel is used as the material of the pipe bend at 90°. COMSOL simulation was combined with high temperature and high pressure reaction kettle plate test. Finally, the experimental results and simulation results were compared and analysed.

2. Hanging test of X80 pipeline steel in autoclave
X80 pipeline steel was sliced and polished, and the distilled water was subjected to oxygen removal treatment to reduce the influence of oxygen in the distilled water.

The set pressure is 8 MPa, temperature is 40 °C, experimental time is 48 hours. Experimental apparatus: PARR-4578 high temperature and pressure reaction kettle produced by American Parr Company. The corrosion rate was calculated by the weight loss method.

2.1. Corrosion morphology analysis
Figure 1 shows the macroscopic corrosion profile of the pipeline steel coupons used in the supercritical CO₂ pipeline. Unsaturated, saturated, supersaturated. In each group, the left image is the coupon before the reaction, and the picture on the right is the coupon after the reaction.
It can be found from Fig 1 the hanging pieces after the reaction appear obvious pits, the surface has become uneven, from the color point of view, the film changed from a metallic luster to a blackish gray, and the rust-free trace from the start of the reaction changed to a slight rust, which may be caused by the local corrosion of the salt solution in the reactor [11].

In the case of a hanging piece under the condition that the humidity in the corrosive environment is supersaturated. From the surface leveling degree, the surface of the hanging piece after the reaction becomes rough and uneven, from the color point of view, the rear hangs changed from the original metallic lustrous to the dark brown lustrous [12-13]. By observation, it can be found that the surface has a loose and corrosive product, which can cause the corrosion products to fall off due to slight touch.

2.2. Experimental results
The corrosion rate results are shown in Table 1.

| Environment     | Material | Unsaturated | Saturated | Supersaturated |
|-----------------|----------|-------------|-----------|----------------|
| Supercritical   | X80      | 0.1676      | 0.3653    | 17.2493        |

2.3. Analysis and discussion
The corrosion rate of X80 pipeline steel increases with the increase of water content. In supersaturated environment, the corrosion rate increases exponentially and reaches the maximum value. According to the microscopic morphology of the corrosion products, it was found that some of the corroded products were rolled up. The corrosion products are easily detached by the flushing of the fluid, causing further corrosion damage to the pipe wall.
3. Numerical simulation of electrochemical corrosion at the elbow of supercritical CO$_2$ pipeline

3.1. Simulation methods and boundary conditions

COMSOL software was used to model the 90° elbow of the supercritical CO$_2$ pipeline. The turbulence model, the lean mass transfer model and the surface reaction model were coupled, meshed, and mass transfer of CO$_2$ molecules. The solution reacts with the chemical reaction of the inner wall of the CO$_2$ pipeline and the flow of the carbonate solution to construct an electrochemical corrosion rate model with free water in the supercritical CO$_2$ pipeline [14]. The rate of corrosion of the carbonic acid solution on the inner wall of the pipeline steel pipe under the condition that the supercritical CO$_2$ fluid in the pipe is stationary and flowing.

The pipe material is set to X80. The length of the inlet and outlet section of the elbow is both 400mm. The diameter is set to 200mm, and the radius of curvature of the elbow is set to 1.5D. The proposed inlet flow rate of the supercritical CO$_2$ pipeline in China oil field is 2m/s; so, the inlet boundary condition is set to 2m/s for velocity inlet; Set to a pressure outlet of 8 MPa, the temperature is set to 40°C; in the rest state the inlet flow velocity of the 90° elbow of the supercritical CO$_2$ conveying pipeline is set to 0 m/s, and the remaining boundary conditions and dynamic simulation experiments conditions are consistent.

3.2. Numerical simulation under static conditions

The simulation results are shown in Table 2 under the condition that the static condition carbonic acid concentration is 0.05 mol/L.

| Time (s) | Corrosion rate (mm/a) |
|---------|-----------------------|
| 0       | 0.35                  |
| 50      | 0.16                  |
| 100     | 0.06                  |
| 150     | 0.02                  |

According to Table 2, the average corrosion rate in the 90° elbow of the supercritical CO$_2$ conveying pipe of X80 material is about 0.15mm/a. According to scholar Visser[15], under the supercritical CO$_2$ environment at temperature of 40°C, When the carbonic acid concentration is about 0.05mol/L, the water content is about 750000ppmw. Combined with the high temperature and high pressure reactor hanging piece test, the corrosion rate of X80 pipeline steel in unsaturated NaCl solution can reach 0.16mm/a.

Under static conditions, there will be a significant concentration gradient that will provide power for the transport of carbonic acid molecules to the surface of the sample. Carbonate is bent toward 90° due to the consumption of corrosive carbonic acid in the fluid. The rate of mass transfer on the inside surface of the tube is significantly reduced, and the corrosion of the inner surface of the CO$_2$ transport pipe by carbonic acid also shows a downward trend due to the consumption of carbonic acid.

Using COMSOL with the concentration of carbonic acid as the variable, the flow rate of the medium was chosen to be 2m/s, and the concentration gradient of carbonic acid was set to 0.01mol/L, 0.02mol/L, 0.03mol/L, 0.04mol/L. The remaining simulation parameters were in accordance with dynamic CO$_2$. The relationship between the carbonic acid concentration and the corrosion rate shown in Table 3.

| Carbonic acid (mol/L) | Corrosion rate (mm/a) |
|-----------------------|-----------------------|
| 0.01                  | 0.121                 |
| 0.02                  | 0.133                 |
| 0.03                  | 0.125                 |
| 0.04                  | 0.140                 |
| 0.05                  | 0.168                 |

It can be seen from table 3 that the corrosion rate of the inner wall surface of the 90° elbow of the supercritical CO$_2$ conveying pipe increases with the increase of the carbonic acid concentration. The corrosion rate of the 90° elbow near wall reached a maximum when the carbonic acid concentration is 0.05 mol/L and value of 0.168 mm/a.

3.3. Numerical simulation under dynamic conditions

When the static condition is the most serious, use COMSOL to model the 90° elbow of the supercritical CO$_2$ pipeline. The inlet speed of the 90° elbow is set to 2m/s, and the other strips remain unchanged. Corrosion rate distribution cloud map, as shown in Figure 2.
Comparing the static and dynamic results, the corrosion rate obtained by the dynamic simulation results is much larger than the corrosion rate under the static conditions. The reason is caused by different mass transfer modes. Rani [16] performed numerical values on the mass transfer results. The mode shows that the mass transfer coefficient (MTC) of the bend has undergone a circumferential change, and the MTC is the most important parameter for predicting the position of the highly sensitive FAC.

It can be seen from Fig 2 that when the near wall carbonization concentration is 0.05 mol/L and the inlet flow velocity is 2 m/s, the carbonation corrosion is the most serious at the transition point of the elbow and the outlet section of the 90° elbow, which is about 0.6 m/a. The scholar ZHANG [17] combined the array electrode technology with computational fluid dynamics (CFD) simulation to obtain the corrosion rate of the inner wall of the elbow is significantly higher than the outer wall corrosion rate; the maximum corrosion rate appears at the innermost side of the elbow, the minimum corrosion rate appears on the outermost side of the elbow; as time increases, the wall will appear thinner. Kim [18] for the partial wall of the elbow an intuitive visual experiment and numerical analysis were carried out. It was concluded that flow accelerated corrosion (FAC) is the main reason for the thinning of the wall thickness.

3.4. Analysis and discussion
(1) The average corrosion rate obtained by fitting the simulation data under static conditions is 0.15 mm/a. The corrosion rate of the X80 pipeline steel obtained from the high temperature and high pressure reaction reactor coupon test is 0.16 mm/a, which is slightly larger than the simulation result. This may be caused by impurities in the water used in the high temperature and high pressure reactor coupon test.

(2) When the supercritical CO₂ fluid flows through the elbow at a certain speed, the turbulent kinetic energy and the wall shearing force are relatively large at the inner wall surface, which accelerates the mass transfer and the corrosion of the corrosive material under dynamic conditions. Therefore, under dynamic conditions, the corrosion rate of the inner wall surface of the elbow is greater than that under static conditions, and the addition of corrosion inhibitor can effectively reduce corrosion.

4. Conclusion
(1) The corrosion rate of X80 pipeline steel increases with the increase of water content. In supersaturated environment, the corrosion rate increases exponentially and reaches the maximum value. The water content of CO₂ gas source should be strictly controlled;

(2) The corrosion rate inside the 90° elbow is greater than the corrosion rate on the outside. Therefore, when the pipe is corroded and perforated by increasing the wall thickness at the 90° elbow, the thickening of the inner side of the 90° elbow should be slightly higher than the outer side;

(3) In actual conditions, it is far more than a carbonation corrosion. If the control is not good, other water-soluble impurities such as H₂S will also cause corrosion of the carbon steel pipeline. Therefore, CO₂ should be strictly controlled during pipeline transportation.
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