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Research on Prediction Model of Interlayer Leakage in Separate Injection Wells in Offshore Oilfields

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Research on Prediction Model of Interlayer Leakage in Separate Injection Wells in Offshore Oilfields

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Abstract. In order to ensure effective layered water injection, it is of great significance to establish the functional relationship among the equivalent diameter of damage, leakage and pressure of sealing cylinder. In this paper, the experimental and numerical simulation experiments were carried out to study the relationship between gap flow rate, pressure drop and equivalent diameter of sealing cylinder under the conditions of uniform corrosion, fracture non-uniformity and random groove non-uniform distribution and scratches in different tubing, equivalent diameters and gap widths. Through a lot of data analysis, the relationship between the damage state and the leakage quantity is established and evaluated by physical simulation test. The research shows that the error between the established model function relation and the test data is no more than 10%. By simulating the damage condition of the shock sealing cylinder and quantitatively detecting the defect of the sealing cylinder, the model function relation can well predict the corresponding damage situation. Therefore, this model function can be used to solve sealing cylinder inspection problem, so as to judge the seal defect and leakage quantity which is independent of the experience of the person in charge of the site and able to use the data as a basis for judgment. This research provides a new technology for the effective prediction of the damage of sealing cylinder, and provides theoretical guidance for selecting matching sealing tools and realizing layered mining.
Keywords. Offshore oil field, layered mining, insert seal detection tool, experiment, model prediction.

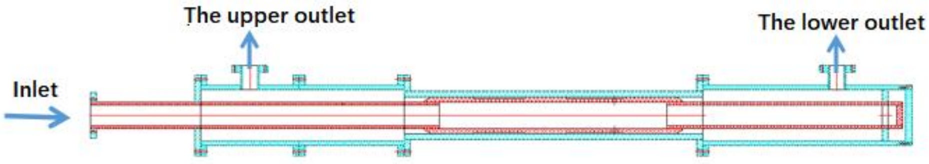
1. Introduction

Offshore oil field exploitation usually uses packer for stratified production or stratified water injection. However, the packer's sealing casing may be damaged due to liquid corrosion and rubbing during tubing operation after years of downhole operation. How to detect the damage? Whether it is necessary to replace the sealing cylinder or replace the sealing ring according to the damage of the sealing cylinder, et al., it is necessary to effectively predict the damage of the sealing cylinder [1, 2]. The self-developed insert seal detection tool can be run down the well to the sealing cylinder position, hoping to judge the damaged state of the sealing cylinder by water injection, pressure measurement and flow rate data [3, 4]. However, it is necessary to study the flow characteristics of gap flow in the complex structure how to predict the failure state of the sealing cylinder through these data.

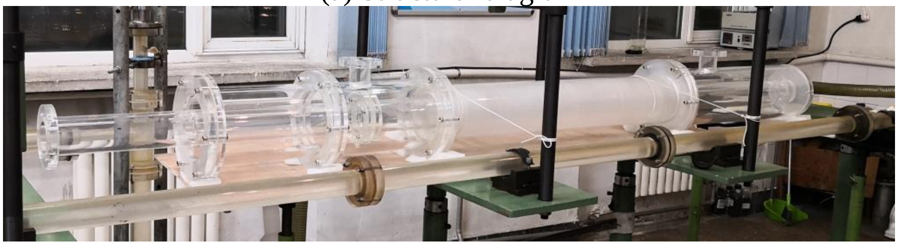
In fluid flow, slot flow is a kind of flow widely existing in machinery, such as annular clearance between plunger and cylinder, shaft and bearing [5, 6]. Due to different geometric shapes, the flow laws of slot flow are usually not universal. In order to obtain the flow laws of slot flow, predecessors have adopted numerical calculation, theoretical analysis and physical experiment methods to obtain the flow laws of slot flow [7-9]. Aiming at this new type of insert seal testing tool, in order to obtain the empirical relationship with practical guiding significance for engineering, this study comprehensively uses the above three methods, in order to obtain the flow law between the insert seal testing tool and the seal cylinder.

2. Insert Seal Test Tool Design

In order to study the flow rule of the sealing detection tool inserted downhole, the corresponding sealing detection tool is processed as shown in the figure below, where the red part is the inserted sealing detection tool and the blue part is the sealing cylinder. Insert the sealing test tool and connect the sealing cylinder through two small holes with a diameter of 9mm. The flow between the sealing cylinder and the inserted sealing detection tool is the flow of gap + annular space. The definition and overall structure of each port are shown in the figure below. The inlet is simulated by tubing, the upper outlet is simulated by the formation above the sealing cylinder, and the lower outlet is simulated by the formation below the sealing cylinder. The damaged equivalent diameters (the ratio of 4 times damaged area to damaged circumference) of 3 kinds of sealing cylinders were processed.



(a) Structural diagram



(b) Schematic diagram of physical processing

(c) Equivalent diameter 9.70mm 10.81mm 13.31mm

Figure 1. Schematic diagram of inserting the sealing test tool and sealing cylinder.

3. Insert the Seal Test Tool for Physical Test

3.1. Experimental System

For the processed objects above, the experimental system as shown in the following figure was established in the multiphase Flow Laboratory of the Institute of Mechanics, Chinese Academy of Sciences. The experimental system is composed of circulation system, control system and measurement system. Circulation system by water tank, pump, Φ50 mm transparent plexiglass tube, bucket; The control system is composed of console and valve. The measuring system consists of electromagnetic flowmeter and metering pump. During the experiment, the water pump and metering pump in the pipeline were opened by the control console, so that the water phase was transported from the water tank to the test device through the water pump, and then flowed out from the two outlets of the seal detection tool (laboratory model of washable well detection device) into the transfer sampling bucket, and finally the water was pumped back to the tank by the electric submersible pump. The flow at the two outlets is measured by a stopwatch and measuring cylinder, and the flow at the entrance is measured by an electromagnetic flowmeter. Pressure sensors are installed at the three outlets to test the pressure.

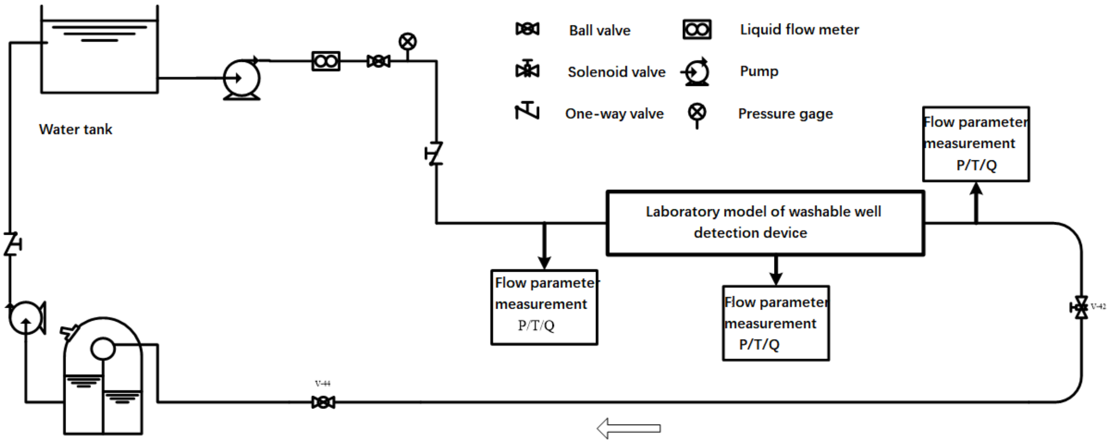


Figure 2. Schematic diagram of experimental flow.

The medium water is used in well cleaning detection, so water is used in the laboratory experiment. The temperature is controlled at about 20°C under normal pressure, and the density of the water phase is, the dynamic viscosity is.

3.2. Experimental Results

3.2.1. Impact of Shunt Ratio. The experimental device has one inlet and two outlets. The flow out of the two outlets will change, and the changing branch flow will cause different pressure drops from the inlet to the branch. For convenience of study, the ratio of the flow from the upper outlet, i.e. the simulated flow from the wellbore, to the inlet flow is defined as the diverting ratio. Figure 3 shows that with the increase of shunt ratio, the pressure drop from inlet to upper outlet increases with the increase of shunt ratio, and the pressure drop from inlet to lower outlet decreases with the increase of shunt ratio, and the relationship is approximately linear. This is because the pressure drop is related to the flow rate in the channel, and the pressure drop naturally increases as the flow rate increases.

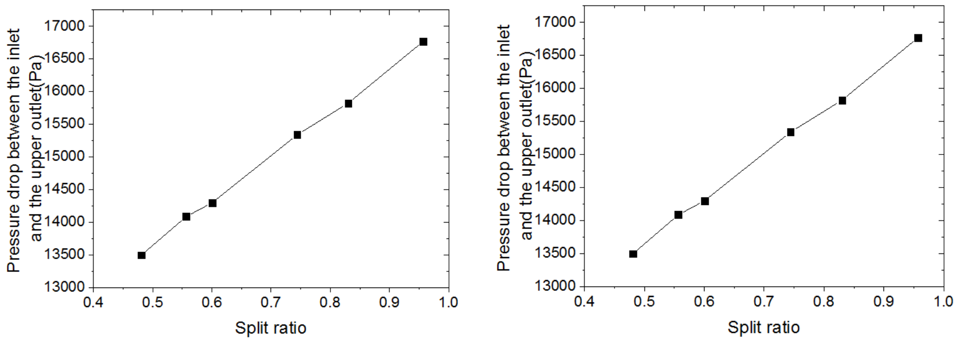


Figure 3. Influence of shunt ratio on pressure drop.

3.2.2. Impact on the Inbound Traffic. The influence of the inlet flow rate on the pressure drop of the fluid flow in the inserted seal has been investigated in the laboratory. From figure 4 it is can be seen that the pressure drop under all damage conditions increases when the inlet flow rate changes, that is, with the increase of the shunt ratio, the pressure drop from the inlet to the upper outlet increases with the increase of the inlet flow rate at all shunt ratios, and the pressure drop from the inlet to the lower outlet decreases with the increase of the inlet flow rate at all shunt ratios. With the increase of the flow rate, the overall curve is approximately shifted upward. It indicates that traffic has a large impact.

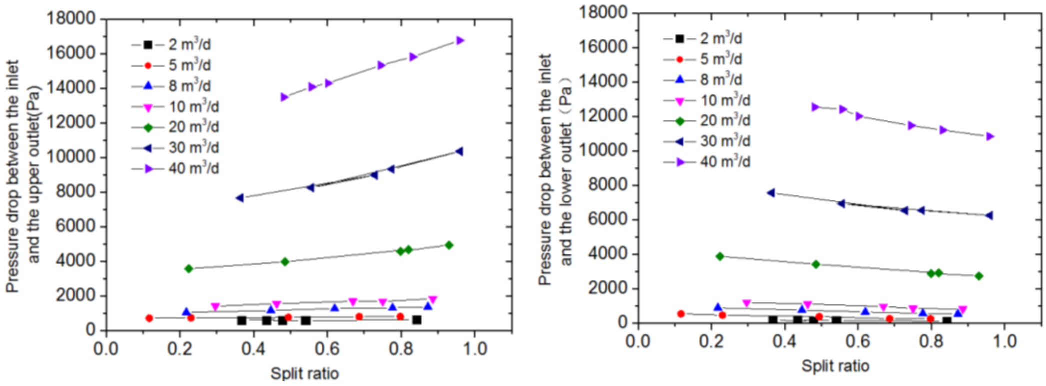


Figure 4. Influence of inlet flow on pressure drop.

3.2.3. Influence of Damage Equivalent Diameter. For the 3 damaged sealing cylinders processed in this project, the equivalent diameters I n real conditions were converted because there was no O-ring inserted into the seal. Figure 5 shows that when the inlet flow rate is 40 m^3/d, with the increase of damage equivalent diameter, the pressure drop from the inlet to the upper outlet increases uniformly and the pressure drop from the inlet to the lower outlet decreases overall under all shunt ratios. This is because when the inlet flow is constant, the larger the equivalent diameter, the larger the flow area, the lower the flow velocity through the damaged equivalent diameter, the lower the flow velocity, the smaller the wear of the fluid in the flow process, the smaller the pressure drop loss.

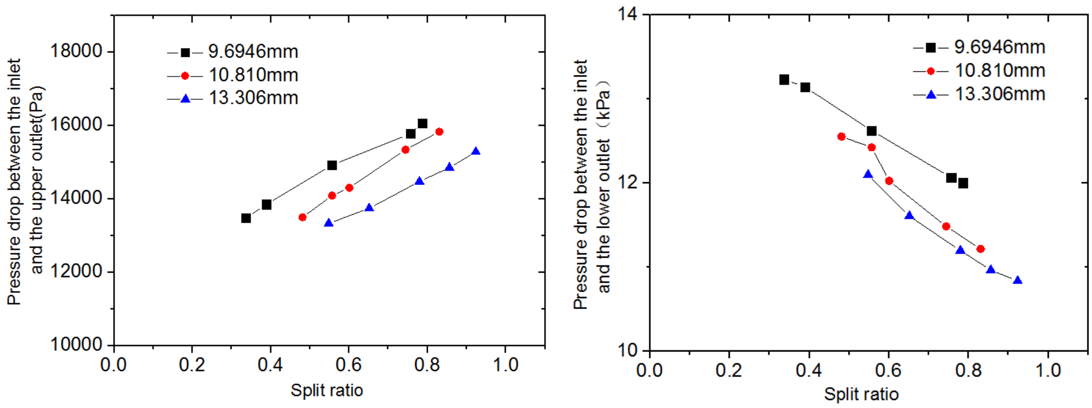


Figure 5. Influence of inlet flow on pressure drop.

4. Numerical Simulation

4.1. Governing Equation

4.1.1. Continuity Equation. The continuity equation under the constant assumption is as follows:

$$\nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

In the equation, ρ is density and $\vec{u}$ is velocity.

4.1.2. Momentum Equation. The momentum equation under the stationary assumption is as follows:

$$\nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla p + \nabla \cdot \overline{\tau} + \rho\vec{g} + \rho\left(\vec{F} + \vec{F}_{lift} + \vec{F}_{vm}\right) \tag{2}$$

In the equation, $\overline{\tau}$ is a stress tensor, among them, $\vec{F}$, $\vec{F}_{lift}$,and $\vec{F}_{vm}$ are external volume forces, lift forces, and additional mass forces, respectively.

4.1.3. Turbulence Model. Many research results show that Reynolds stress model (RSM model for short) can accurately and effectively simulate turbulent flow, so Reynolds stress model is selected here as turbulence model [10-13]. The Reynolds stress model needs to calculate six Reynolds stress components, and the corresponding partial differential transport equation is

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i'u'_j}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k'\overline{u_i'u'_j}\right) = P_{ij} + D_{T,ij} + \varphi_{ij} - \varepsilon_{ij} + F_{ij} \tag{3}$$

The specific physical meanings of each of the five terms on the right side of the equation are: P_{ij} is turbulent stress generation term, $D_{T,ij}$ is the turbulent diffusion term, φ_{ij} is the pressure strain term; ε_{ij} is the viscous dissipation term; F_{ij} is generate items for system rotation.

4.1.4. Model Validation. By comparing the pressure drop obtained from numerical calculations under different damage conditions with the results of indoor experiments, it was found that the error between the two was within 10% (figure 6), proving the correctness of the numerical calculation method.

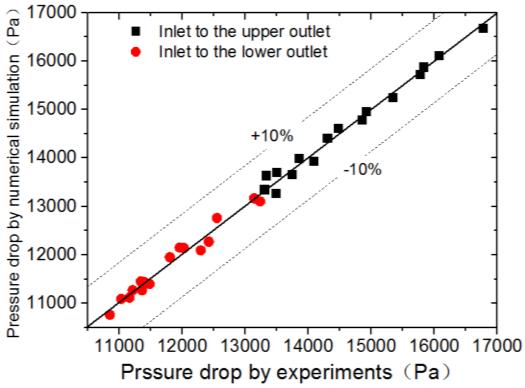


Figure 6. Evaluation of numerical experimental methods.

4.2. Numerical Simulation of Inserting a Sealing Detection Tool

4.2.1. The Influence of Different Pressure and Flow Measurement Points. Figure 7 shows that when the inlet flow rate is 50m^3/d and the equivalent diameter of the sealing tube is 9.49mm, the pressure drop calculation at different pressure and flow test points shows that the pressure drop inside the oil pipe accounts for a proportion of the entire process flow. The pressure drop between the simulated wellbore and the oil pipe in sections 2-3 is also very small, and the main loss of pressure drop is in the gap between the inserted sealing hole and the sealing tube. The pressure drop loss in this section accounts for more than 95% of the pressure drop in the entire process which can be found from table 1. Therefore, in order to save grid, only the watershed before and after the sealing cylinder can be established.

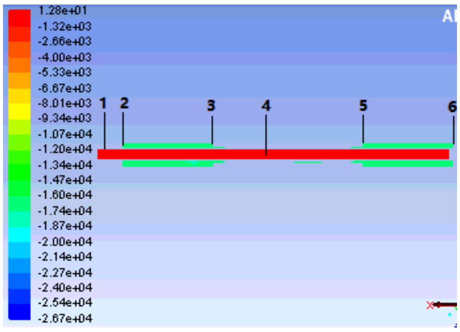


Figure 7. Setting of different pressure test points.

Table 1. Effects of Different Pressure and Flow Test Points.

Section	1-4	4-3	4-5	3-2	5-6
Pressure drop from inlet to upper outlet (Pa)	324	16781	16914	200	45
Percentage	1.87%	97.1%	97.8%	1.2%	0.26%

4.2.2. The Effect of Roughness on Pressure Drop. When the roughness of the pipe wall changes, figure 8 shows how does the pressure drop change. Research and literature review have found that the roughness of steel pipes is generally less than 100 μ m. When the inlet flow rate is 50m^3/d, numerical simulation shows that the influence of roughness on pressure drop is very small, and the pressure drop is mainly caused by local pressure drop which can be also be seen from table 2.

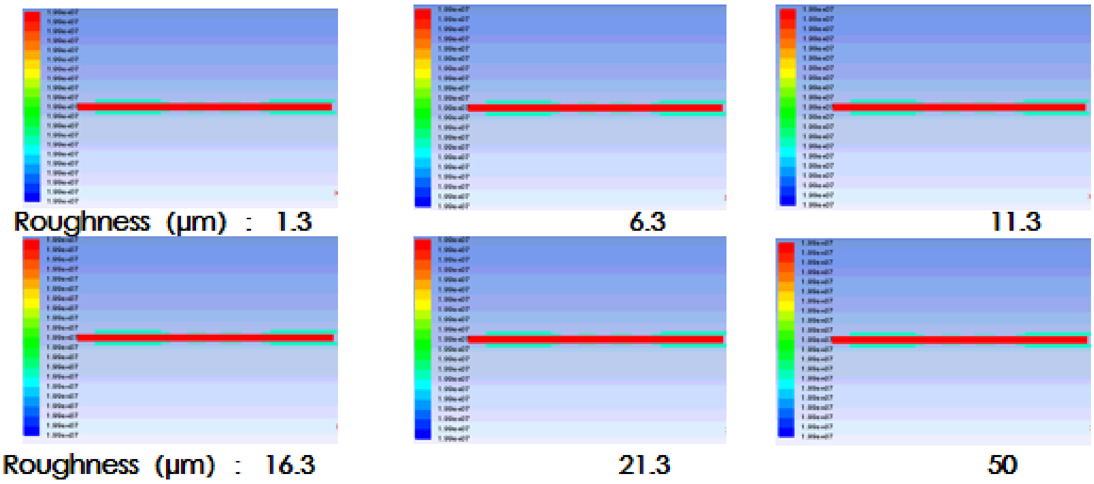


Figure 8. Flow patterns under different pipe wall roughness.

Table 2. Effect of different pipe wall roughness on pressure drop.

Roughness (μm)	1.3	6.3	11.3	16.3	21.3	100
Pressure drop (Pa)	17249	17257	17257	17267	17287	17279

4.3. Pressure Drop Calculation for Inserting Sealing Detection Tools

The flow between the inserted sealing detection tool and the sealing cylinder is a structurally unique gap flow, and there is currently no mature theoretical formula that can be used for reference. This article adopts the dimensionless parameter analysis method, and through analysis, it is found that the factors that determine the pressure drop mainly include: Water phase density ρ, water phase viscosity μ, inlet flow Q, equivalent damage diameter D, roughness e, split ratio F.

By using the π theorem, it can be obtained that:

$$\Delta P = f(\rho, \mu, Q, D, e, F) \tag{4}$$

Based on the previous research, the impact of e can be ignored. Therefore, taking Q, ρ and D are basic dimensions, which can be obtained through dimensional analysis:

$$Eu = \frac{\Delta P}{0.5\rho V^2} = \frac{2\Delta P}{\rho(Q/\pi/d_{hole}^2)^2} = f(Re = \frac{4\rho Q}{\pi D\mu}, F) \tag{5}$$

When the size of the inlet small hole d_{hole} is constant, there is a relationship between the inlet and the upper outlet:

$$\Delta P = f(Re = \frac{4\rho Q}{\pi D\mu}, F) \tag{6}$$

During the construction process of inserting sealing detection tools, it is difficult to obtain the diversion ratio F. Through previous research, it was found that there is a corresponding relationship between the diversion ratio F and the pressure drop. By studying and regressing all experimental data, the following relationship equation was obtained. The calculated results of this relationship have a high correlation with the experimental comparison which is 0.92 which is shown in figure 9:

$$\Delta P = -1005.55 + 0.287\frac{\Delta P_{1-2}}{\Delta P_{1-3}} - 2060.14Re^{-2.534}\Delta P = -1479.6 + 2726.77F + 0.0011Re^{1.49} \tag{7}$$

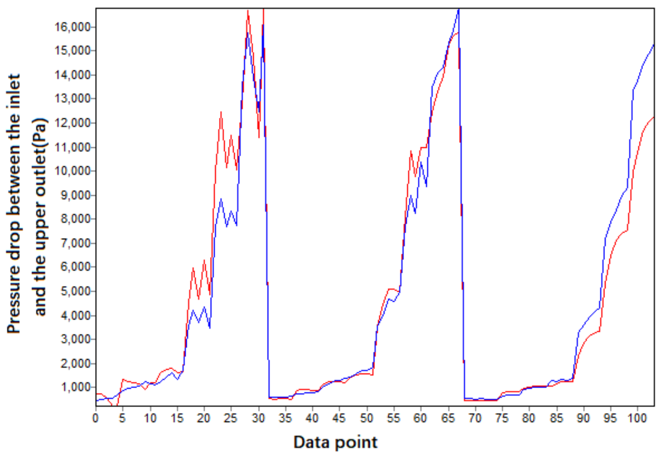


Figure 9. Comparison between the Calculation Results of Empirical Pressure Drop Equation and the Experimental Results.

5. Conclusion

Through indoor theoretical analysis, experiments, and numerical simulation research, the flow pattern of the gap between the inserted sealing detection tool and the sealing cylinder was obtained. Specifically, the study found that the pressure drop from the inlet to the upper outlet increases with the increase of the diversion ratio; The pressure drop from the inlet to the upper outlet increases with the increase of inlet flow rate at all diversion ratios; When the inlet flow rate is constant, the larger the equivalent diameter, the smaller the pressure drop loss of the fluid during the flow process. The pressure drop is mainly caused by local pressure drop, that is, the main loss of pressure drop is in the gap between the inserted sealing hole and the sealing cylinder, and the roughness has little effect on the pressure drop. The empirical relationship between pressure drop and diversion ratio, Re, was ultimately obtained through research. The working principle of the insertion sealing detection tool was obtained, providing guidance for the prediction of packer damage, layered mining of packers, and layered water injection.

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