Research and development of injection valves for HPHT, high wax content, and deep condensate gas reservoirs

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ABSTRACT

In response to the wax deposition problem in high-temperature, high-pressure (HPHT), high-wax content deep condensate gas reservoirs, taking the Bozi condensate gas field in the Tarim Basin, China as an example, a development method of injection valve for HPHT, high-wax content deep condensate gas reservoirs is proposed utilizing principles of mechanics and structural design methods, which includes analysis of material selection, post-heating mechanical properties of the materials, and the structure of the injection valve. The valve strength, connection strength, and pressure-bearing capacity under high pressure were calculated. Compared with the allowable strength of the material, the effectiveness of the design method has been verified. Meanwhile, laboratory experiments were conducted on chemical injection valves, including rupture disc rupture test, bottomhole flow pressure injection test, and 2000 m injection pipeline flow friction test. It was found that, firstly, under normal temperature conditions, the rupture disc rupture pressure was 42 MPa. Under the working condition of 100°C, the rupture pressure of the rupture disc is 44 MPa, which is greater than the design pressure of the rupture disc (40 MPa) and can meet the requirements of underground operations. Secondly, under different pressures, a large amount of liquid flows out of the outlet end of the relief valve and the injection valve opens, indicating that the test is qualified. Thirdly, Under the maximum injection flow rate of 0.76 L/min designed for the injection valve, the frictional resistance of the 2000 m pipeline is approximately 67 MPa. The maximum downhole flow pressure at the injection point is calculated at 90 MPa. The opening pressure of the injection valve is 10-15 MPa, and the 2000 m pipeline can meet the on-site injection requirements. The research results will reduce unsafe incidents such as wax deposition in wellbores and column blockages, and improve the efficiency of condensate gas reservoir exploitation.

Keywords: HPHT, condensate gas, injection valve, high wax content, structural design

1. INTRODUCTION

Wax deposition is a common phenomenon in oil and gas production[1]. It occurs when the temperature and pressure are higher than the saturation pressure, and caused the fluid system to remain in a single phase. However, with the pressure and temperature decrease in fluid enters the wellbore, wax crystals start to precipitate and eventually deposit. The wax deposition leads to wellbore blockage, which severely affects the safe and stable production of oil and gas wells, such as asphalt deposition, wax molecular aggregation and deposition, sand production, scaling of highly mineralized formation water, and scaling of acidic salt substances. The problem of wellbore wax blockage is particularly common.

The wax deposition process in oil wells is complex and influenced by multiple factors. Scholars have made numerous achievements in studying the wax deposition mechanisms and predictions under different flow conditions[2,3]. To remove or alleviate wax blockage problems, many scholars have proposed wax removal and prevention techniques, including physical, chemical, and biological methods. These techniques include mechanical wax removal processes[4], surface energy prevention processes[5], strong magnetic prevention processes[6], thermal wax removal processes[7], chemical wax removal processes[8], and microbial wax removal processes[9]. Among them, chemical wax removal processes have been widely used in oilfields due to their unique advantages. The chemical injection process for wax removal is the injection of chemical agents into the tubing string through an injection pipeline (annulus of the production casing). This process involves injecting the chemical agents into the wellbore blockage location without affecting the normal production of oil and gas

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wells, thereby preventing wax deposition. The chemical agents can also have a dewaxing and viscosity reduction effect, resulting in significant wax removal, which can be divided into two categories (wax removers and chemical wax inhibitors). Some scholars have conducted corresponding research on the injection valve of conventional fuel engines, mainly studying the flow calculation method of the injection valve and the failure problem during the operation process of the injection valve, but have not conducted research on the structural design of the injection valve[10-13]. The development of chemical wax removal processes has always been a focus of attention for experts, scholars, and oilfield chemical companies[14,15]. Among them, the chemical injection valve is the device suitable for high-temperature and high-pressure condensate gas wellbore[12,13]. Wax inhibitors and wax removers are injected into the tubing string through the chemical injection valve by controlling the pressure inside the pipeline. In the implementation process, there is no well control risk, and the injection valve system is run down the completion tubing, so there is no later in tubing operation. Therefore, it is the most commonly used technique in the current oil and gas field production process[16-20].

The new contribution in the work included as: firstly, the development methods of injection valve for HPHT, high-wax content deep condensate gas reservoirs are proposed utilizing principles of mechanics and structural design methods, which includes analysis of material selection, post-heating mechanical properties of the materials, and the structure of the injection valve. Secondly, the laboratory experiments were conducted on chemical injection valves, including rupture disc rupture test, bottomhole flow pressure injection test, and 2000 m injection pipeline flow friction test. Finally, the research results will reduce unsafe incidents such as wax deposition in wellbores and column blockages, and improve the efficiency of condensate gas reservoir exploitation.

2. DEVELOPMENT PLAN FOR INJECTION VALVES

2.1 Characteristics of the Bozi condensate gas field

The Bozi gas field is located in the Tarim Basin in western China and is a typical tight sandstone condensate gas reservoir. It is currently the deepest (7084 m) onshore condensate gas field in China. The basic reservoir properties and characteristics are as follows: formation temperature and pressure system; measured formation pressure of 120.9 MPa, pressure coefficient of 1.76, formation temperature of 122℃, and average temperature gradient of 1.75℃/100 m. Gas reservoir characteristics: the depth of the gas reservoir is 7128.22 m, and it is a normally pressured high-pressure gas reservoir with a water edge. Fluid characteristics: methane averages 89.33%, nitrogen averages 1.13%, an average carbon dioxide content of 0.24%, a relative density of natural gas of 0.63 g/cm^3, an average wax content of approximately 7.8%, a condensate density of 0.788 g/cm^3, and formation water density of 1.03-1.13 g/cm^3. The production data of 23 wells in the Bozi gas field are shown in Figure 1.

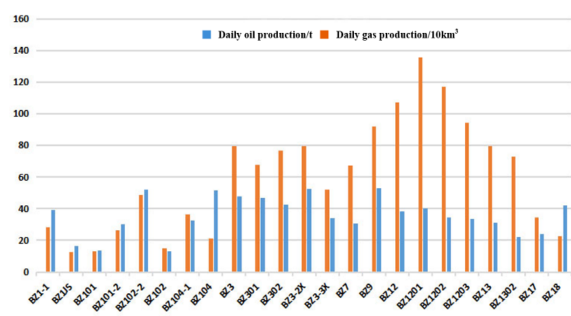


Figure 1. Distribution of dynamic oil and gas production from 23 wells in Bozhi gas field.

2.2 The applicability analysis of wax removal technology in the Bozi gas field

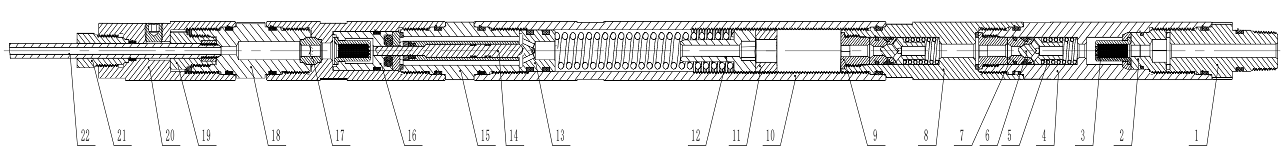
Combining the production characteristics of the Bozi gas field, it can be determined that it belongs to a deep condensate gas reservoir. The well depth exceeds 6000 m, there is a large production pressure difference, and the wellhead pressure is high. The gas wells in the block have an oil pressure higher than 60 MPa. In the development process, if conventional wax cleaning methods are used, there may be safety or environmental issues. It is believed that effective wax prevention measures can be mainly divided into two categories: wax prevention method, which uses chemical wax inhibitors to suppress the aggregation and growth of wax molecules in the condensate oil system; and electric heating method, which increases the wellbore temperature to prevent wax deposition. The advantages and disadvantages of different wax prevention methods are compared in Table 1.

Table 1. Comparison of advantages and disadvantages of different clearing and wax prevention methods.

Clear wax method	Principle	Advantages	Disadvantages	Risks
Electric heating method	The production tubing column is lowered into the continuous tubing cable, and the wellbore temperature is raised by heating to ensure that the wellbore temperature is above the waxing point.	(1) No need for major repairs to the start-up and completion tubular columns; (2) Simple production management.	(1) Inability to conduct test operations; (2) The main valve of the gas extraction tree failed.	(1) The wellhead is electrically charged and under pressure; (2) The continuous tubing cable may break off during long-term service in the well.
Chemical method	An injection valve is tripping in the appropriate position through the completion tubing string to prevent wax deposition by injecting a clearing and anti-wax agent.	(1) It can guarantee the tubing string through-hole without affecting the testing operation; (2) There is no well control risk for wellhead operations.	(1) Complex tubular column and implementation of old wells requiring major repair operations. (2) Limited pumping rate and high requirements for surface pumping system.	Higher cost, once the tubing string is fixed installation, the dosing depth cannot be adjusted.
Mechanical method	A wax cleaning tool attached to the wire rope is lowered into the well by an electric winch to scrape the wax from the tubing wall and bring the wax to the surface by liquid flow.	(1) Easy to manage and simple to operate; (2) No pollution of oil layer and no impact on production	(1) Only for wells with less severe wax formation; (2) Only for low pressure wells.	The tool breaks off the well, causing a complex downhole.

2.3 Development of injection valve technology scheme

The injection valve is a key component for injecting chemical agents into oil well underground. It needs to stay in the well for a long time. On one hand, it is required to smoothly inject chemical agents from the wellhead into the tubing. On the other hand, when not injecting, it needs to effectively and reliably seal off the one-way check valve mechanism to prevent gas and liquid from flowing back into the wellbore. The key technology of this tool lies in its ability to repeatedly open in the forward direction and seal in the reverse direction under high temperature and high-pressure conditions at the bottom of the well. Brief description of the injection valve working principle: agents enter the valve body through capillary tubes. When the pressure reaches the specified burst pressure of the upper burst valve, the upper burst valve opens and the chemical agents enter the back pressure valve. When the pressure reaches the set opening pressure of the back pressure valve, the agents enter the upper drug chamber of the first-stage check valve, and under pressure, the first-stage and second-stage check valves open in sequence. The pressure continues to increase until it is greater than the lower burst disk, allowing the agents to enter the injection sleeve and then into the wellbore for agent injection (as shown in Figure 2). The basic parameters of the injection valve design are shown in Table 2.



1-Lower connector, 2-Lower rupture disc, 3-Sealing cone sleeve; 4-Valve core I, 5-Spring, 6-Secondary check valve core, 7-Check valve seat, 8-Valve core II, 9-Valve core plug, 10-Spring cylinder body, 11-Back tightening screw plug, 12-Back pressure spring, 13-Spring seat, 14-Back pressure valve core, 15-Valve core joint, 16-Back pressure valve seat, 17-Upper rupturedisc, 18-Upper connector, 19-Ferrule joint, 20-Pressure test joint, 21-Pipeline plug, 22-Capillary.

Figure 2. Schematic of injection valve design options.

Table 2. Technical parameters for injection valve program design.

Parameter	Numerical value	Parameter	Numerical value
Outer Diameter	25.4 mm	Temperature Resistance	-46℃-180℃
Minimum diameter	4 mm	Pressure valve opening pressure	0.87-27.5 MPa
Material	718	Check valve opening pressure	1.75 MPa
Steel grade	125000 psi	Injection volume	0.045-0.765 L/min
Pressure resistance	105 MPa	Overall length	670 mm/425 mm
Connection buckle type between injection valve and cartridge	3/8”Sealing threads	Connection buckle type between line and injection valve	1/4”Sealing threads

3. PERFORMANCE ASSESSMENT OF INJECTION VALVE

3.1 Material performance analysis of injection valve

Based on the requirements for high temperature and high-pressure resistance, corrosion resistance, and the research on materials for injection valves, the material selected for the injection valve is Inconel 718 nickel-based alloy. After heat treatment, its mechanical properties can reach: tensile strength≥965 MPa; yield strength≥785 MPa; elongation≥30%; hardness HB363. Considering that the injection valve will be working underground for a long time, a triangular thread with good self-locking characteristics is selected as the connection thread between the helical pairs of the injection valve, and the connection thread is M20×1.5. The strength verification of the connection thread of the injection valve is conducted from the following five aspects: resistance to compression, resistance to shear, resistance to bending, self-locking, and thread tensile strength.

Resistance to compression refers to the requirement that the compressive stress between the male and female threads should not exceed the allowable compressive stress, otherwise it will lead to compressive failure. When the thread teeth are straightened, it is equivalent to a cantilever beam. Assuming the axial force is *F* and the number of engaged thread turns is *z*, the calculation formula is:

$$\sigma_p = \frac{F}{A} = \frac{F}{\pi d_2 h z} \le [\sigma_p] \tag{1}$$

where, σ_p is compressive stress, MPa; $[\sigma_p]$ is allowable compressive stress, MPa; F is axial force, N; d_2 is the major diameter of the external thread, mm; h is the thread working height, mm; z is the number of engaged threads, which is generally chosen to be less than 10. After calculation, the allowable compressive stress is $[\sigma_p]$=367 MPa; and the compressive stress is σ_p=122 MPa; it is determined that the selected helical pair has sufficient resistance to compression.

For the shear strength of the male thread, it should satisfy $\tau = \frac{F}{\pi d_1 b z} \le [\tau]$; For the shear strength of the female thread, it should satisfy $\tau = \frac{F}{\pi D b z} \le [\tau]$.

where, F is the axial force, N; d_1 is the calculated minor diameter of the male thread, mm; D is the calculated major diameter of the female thread, mm; b is the thread root width, mm; $[\tau]$ is the allowable shear stress, MPa. $[\sigma]$ is the allowable tensile stress of the material. The allowable shear stress is $[\tau]$=110 MPa. The male thread is $[\tau]$=91 MPa, and the female thread is τ=83.6 MPa. Therefore, both the male and female threads satisfy the requirement of $\tau < [\tau]$, indicating that the selected threads have sufficient shear strength.

For the male thread, it should satisfy $\sigma_b = \frac{(F/z)\cdot(d-d_2/2)}{(\pi d_1 b^2/6)} = \frac{3Fh}{\pi d_1 b^2 z} \le [\sigma_b]$; For the female thread, it should satisfy $\frac{3Fh}{\pi D b^2 z} \le [\sigma_b]$.

where, D is the diameter of the female thread, mm, d is the diameter of the male thread, mm, L is the bending lever arm, mm, $L = \frac{d-d_2}{2}$, $M = \frac{F}{z}L = \frac{F}{z}\frac{d-d_2}{2} = \frac{F}{2z}(d-d_2)$; $W = \frac{\pi d_1 b^2}{6}$; σ_b is the bending stress, MPa; b is the thread root width, mm; p is the pitch, mm; F is the axial force, N; h is the thread working height, mm; p is the pitch, mm, and z is the number of engaged threads, which is equal to 7. After calculated, $[\sigma]$=367 MPa, and actual bending stress is σ_b=196 MPa, the thread meets the bending strength requirement.

When the material of the female thread is the same as that of the male thread, the strength of the male thread needs to lower than that of the female thread. Therefore, it is necessary to check the strength of the male thread for injection valves. The equation is as follows:

$$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi}{4}d_c^{\ 2}} = \frac{F}{\frac{\pi}{4}\left(d_1 - \frac{H}{6}\right)^2} \le [\sigma] \tag{2}$$

where, F is the axial force, N, d_c is an empirical value, the empirical calculation formula is σ_b; H is the original triangle height, mm, for ordinary threads: $H = \sqrt{3}\cdot p/2$; d_1 is the calculated minor diameter of the thread, mm. $[\sigma]$ is the allowable tensile stress of the material, MPa. The calculated values for allowable tensile stress are $[\sigma]$=183 MPa, and thread tensile strength is σ=160.2 MPa. The thread strength check is deemed satisfactory.

When the Bozi gas field requires a maximum rated injection pressure of 105 MPa, the maximum axial thrust generated internally in the injection valve can be calculated using the equation $F = PS$, resulting in F_{push}=34656.7 N. The critical section of the entire injection valve occurs at the back-off groove of the female thread (inner diameter 20.5 mm, outer diameter 25.4 mm). The strength check of the workpiece or specimen mainly refers to the maximum force (F_b) that the workpiece can withstand during the yield stage. This force decreases significantly with the cross-sectional dimensions during the yield stage and strengthening stage, and is divided by the original cross-sectional area (S_0) of the workpiece to obtain the stress (σ), which is the ultimate tensile strength (σ_b) in N/mm² (MPa). It represents the maximum resistance of the metal material to failure under tensile stress. The specific calculation formula for the strength check is as follows:

Tensile strength calibration formula: $\sigma = \frac{F_b}{S_0} \le [\sigma_b]$. Torsional section factor: $W_t = \frac{\pi d^3}{16}(1-\beta^4) \le [W_t]$

According to the calculation, the maximum axial force generated inside the injection valve at an injection pressure of 105 MPa is F_{push}=34656.7 N, which is less than the allowable tensile strength $[\sigma_b]$=64769.2 N of the critical section. The ultimate torsional strength $[W_T]$=680 N·m is greater than the maximum tightening torque of the connection threads of the injection valve. Therefore, the strength check of the critical section is qualified and meets the requirements.

Based on the formula $F = PS$, the opening force F of the check spring is calculated. The dimensions of the spring for the structural design of the injection valve can determine the design dimensions of the spring as d=2.8 mm, D=14 mm. The material used is 50 CrSi. The stiffness of the spring is calculated using the formula found in the material manual.

$$P' = \frac{Gd^4 F_n}{8P_n D^3} = \frac{GDF}{8P_n C^4} = 22\text{N/mm} \tag{3}$$

With a spring set preload value of 5~10 mm, the preload force of the spring is $F = 110 \sim 220\text{N}$. The diameter of the back pressure piston rod is d=4 mm. The thrust force generated by the back pressure valve piston under unit pressure is $F_0 = PS = 12.56\text{N}$. Therefore, the opening pressure of the back pressure piston is calculated as $P_{\text{start}} \geq 0.87 \sim 17.5\text{MPa}$.

The dimensions of the check valve spring are: d =1.6 mm, D =10 mm. The stiffness of the spring is calculated as P' =5.2 N/mm. With a preload of 5 mm for the check valve, the preload force of the spring is F =55 N. The diameter of the check valve core is d = 4 mm. The thrust force generated under unit pressure is F_0 =12.56 N. Therefore, the opening pressure of the check valve core is calculated as P_Q ≥4.37 MPa. Based on the design of the barrel structure, it is easy to see that the dimensions of the weak point are an outer diameter of 25.4 mm and an inner diameter of 21 mm. The calculation can be based on a pipe structure with an outer diameter of 25.4 mm and an inner diameter of 21 mm, using the formula.

$$P = \frac{2 \times \sigma / s \times \delta}{d} \tag{4}$$

where, P is the pressure borne by the pipe, MPa; σ is the tensile strength of the pipe material, MPa; δ is the wall thickness of pipe, mm; d is the inner diameter of pipe, mm; and s is the safety factor.

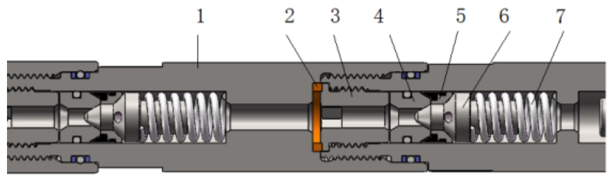
Based on the above formula combined with the mechanical properties of the material, the ultimate compressive strength of the spring barrel can be calculated as P =134.7 MPa, which is greater than the usage requirement of 105 MPa in the Bozi block. Therefore, the overall pressure resistance of the injection valve at the weak point can meet the usage requirement. Based on the comprehensive analysis above, the tensile and torsional strength of the various connection components of the injection valve meet the usage requirements, and the metal seals at various locations can meet the temperature and pressure usage requirements of the Bozi block. The overall pressure resistance of the weak point of the valve is calculated to be 134.7 MPa, which is higher than the rated usage pressure of 105 MPa in the well. Therefore, it can be concluded that the injection valve designed based on the material selection of 718 can meet the high temperature and high-pressure usage requirements of the Bozi gas field. The comparison results of the material properties of the chemical injection valve are shown in Table 3.

Table 3. Technical parameters for injection valve program design.

Parameter	Conditional allowable value	Actual value	Parameter	Conditional allowable value	Actual value
Compressive stress of thread	367 MPa	122 MPa	Bending stress of thread	367 MPa	196 MPa
Shear stress of thread	110 MPa	91/83.6 MPa	Tensile stress of thread	183 MPa	160.2 MPa
Tensile strength of thread	64769.2 N	34656.7 N	Compressive strength of the spring barrel	134.7 MPa	105 MPa

3.2 Feasibility analysis of sealing technology for injection valve

As shown in Figure 3, the valve inlet is on the left, and the outlet is on the right. The structure mainly consists of the valve body where the valve core is installed, the metal seal between the valve bodies, the plug where the valve core is installed, the hard seat, the soft seat, the valve core, and the compression spring. The inlet valve body and the outlet valve body achieve sealing through the plastic deformation of the metal sealing ring, which can adapt to higher pressure and provide more reliable sealing. The hard seat and the valve core are sealed with metal-to-metal contact on an inclined surface, and the valve core undergoes plastic deformation to achieve sealing when subjected to reverse high pressure. The front end of the soft seat is equipped with a sulfurized rubber ring, and the rubber is vulcanized with high-temperature resistant fluoro rubber, with a hardness of 80-90 Shore, and a maximum temperature resistance of 180°C. The soft seat can achieve sealing by extruding the rubber ring against the conical surface of the inlet valve body when the pressure difference before and after the valve core is low, thereby avoiding liquid backflow. Under the action of the pressure difference, the valve core can slide freely within the valve body. When the inlet pressure is lower than the opening pressure, the valve core achieves reverse sealing under the action of the spring. When the inlet pressure increases, the valve core overcomes the spring force under the pressure difference, thereby achieving the function of one-way valve opening.



1-Valve body, 2-Metal seal, 3-Valve core plug, 4-Hard valve seat, 5-Soft valve seat, 6-Spool, 7-Compression spring

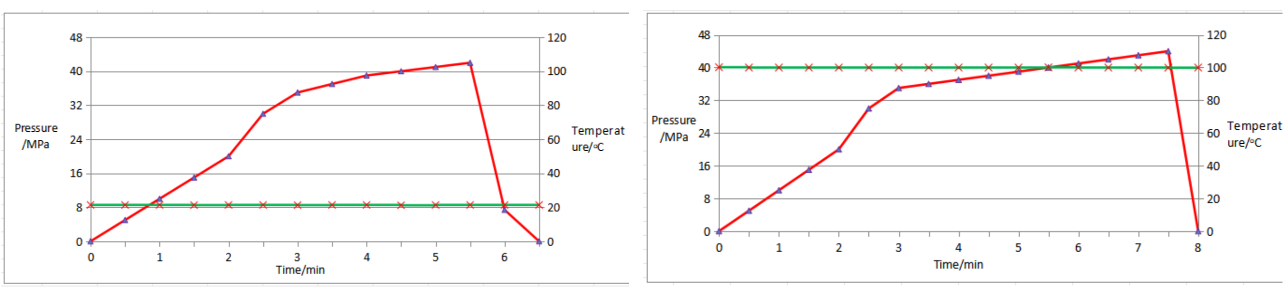
Figure 3. Block valve spool structure.

3.3 Injection valve ground experimental testing

(1) Rupture disc rupture and impurity prevention test

Room temperature test: Firstly, it fills the hole cavity of the injection valve and rupture disc with an oil-liquid mixture, and install the rupture disc and injection valve according to the design assembly drawing. The injection valve is connected to the test pump as a pressure inlet. Then the test pump is pressurized with 5 MPa, 10 MPa, 15 MPa, 20 MPa, 30 MPa, 35 MPa, 37 MPa, 39 MPa, 40 MPa, and 41 MPa respectively, and the pressure is stabilized for 30 seconds each time. There is no liquid returning from the outlet of the injection valve. Further increase the pressure to 42 MPa, and a large number of liquid returns from the injection valve outlet. The pressure drops sharply to 7.4 MPa, and the measured rupture pressure of the rupture disc is 42 MPa. It is determined that the anti-impurity test of the rupture disc is qualified. The development of its curve is shown in Figure 4a. After completing the previous step, the injection pump continues to step pressurize every 5 MPa to 90 MPa as the flow test pressure value. Then, a 1-hour constant pressure injection test is carried out, and the liquid discharged is collected by the outlet of the injection valve through a measuring bucket. After 1.1 hours of pressure, the total liquid discharged is 76.4 L. The injection rate per unit time is calculated to be 1.157 L/min, which is 0.045-0.76 L/min higher than the minimum flow requirement. It is determined that the anti-impurity test of the rupture disc is qualified.

Test at 100℃: Firstly, it fills the injection valve and the inner hole of the rupture disc with an oil-liquid mixture. The rupture valve and injection valve are installed according to the design assembly diagram. The outer cylinder was heated to 100℃. The injection valve is connected to the test pump as a pressure inlet. The test pump is pressurized with 5 MPa, 10 MPa, 15 MPa, 20 MPa, 30 MPa, 35 MPa, 36 MPa, 37 MPa, 38 MPa, 39 MPa, 40 MPa, 41 MPa, 42 MPa, and 43 MPa respectively, and the pressure is stabilized for 30 seconds each time. There is no liquid returning from the outlet of the injection valve; Further increase the pressure to 44 MPa, and a large number of liquid returns from the injection valve outlet. The pressure drops sharply to 7.4 MPa, and the measured rupture pressure of the rupture disc is 44 MPa (shown in Figure 4b).



(a) Room temperature test (b) Test at 100℃

Figure 4. Pressure variation curve inside the ruptured disk.

(2) Injection valve injection speed test

Firstly, the injection valve is installed according to the general assembly drawing, and connect it to the testing frame. Then, it repeats the pressure of 60 MPa, and release the pressure and air. Finally, it releases the pressure after the oil is discharged from the tail of the injection valve. Then, it connects the tail end of the injection valve to the oil pipe, and put the other end into a 20 L volumetric cylinder to calculate the displacement. It set the injection pump pressure to 105 MPa and temperature to 180℃. It record the start time, end time, daily displacement, cumulative displacement, and duration every day, as shown in Table 4. From the table, it can be seen that the injection valve is fully open and fault free for injection for ≥200 h, and the injection flow rate is between 0.87 and 1.40 L/min, which is greater than the maximum injection rate of 0.76 L/min designed for the injection valve, meeting the design requirements.

Table 4. Injection valve injection speed test data.

No.	Start time	End time	Cumulative time (h)	Daily output volume (L)	Daily injection rate (L/min)
1-2	2023/9/1 08:30	10:37	3	227.7	1.27
3-7	2023/9/2 8:10	17:04	8	574.3	1.20
7-11	2023/9/3 8:10	17:07	9	755.1	1.40
12-19	2023/9/4 8:10	9/5 8:09	24	1256.7	0.87
20-26	2023/9/5 8:09	9/6 8:16	24	1686.8	1.17
27-34	2023/9/6 8:16	9/7 10:00	26	1842.4	1.18
35-42	2023/9/7 10:00	9/8 7:42	22	1509.2	1.14
43-49	2023/9/8 7:42	9/9 7:05	24	1622.1	1.13
50-56	2023/9/10 7:42	9/11 7:05	24	1627.9	1.13
57-63	2023/9/11 7:42	9/12 7:05	24	1631	1.13
64-65	2023/9/12 7:42	19:26	12	777.6	1.08

(3) 2000 m injection pipeline flow friction test

The injection port of the injection lever is connected to the pressure gauge through a 1/4" injection pipeline, and the other end of the pressure gauge is connected to a 2000 m pipeline. It continuously pressurizes at 5 MPa, 6 MPa, 7 MPa, 10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, 70 MPa, 80 MPa, 90 MPa, 100 MPa, 110 MPa, 120 MPa, 130 MPa, 140 MPa, 150 MPa, 160 MPa, 170 MPa, and 180 MPa, respectively, and record the liquid volume and pressure readings at the pipeline outlet, as shown in Table 5. Under the maximum injection flow rate of 0.76 L/min designed for the injection valve, the frictional resistance of the 2000 m pipeline is approximately 67 MPa (with 0 # diesel as the injection medium). The maximum downhole flow pressure at the injection point is calculated at 90 MPa; The opening pressure of the injection valve is 10-15 MPa. The maximum injection pressure is 172 MPa, and the 2000 m pipeline can meet the on-site injection requirements.

Table 5. Injection valve injection speed test data.

No.	Injection pressure (MPa)	Pipeline frictional pressure (MPa)	Stable injection time (min)	Discharge liquid (L)	Injection rate (L/min)	No.	Injection pressure (MPa)	Pipeline frictional pressure (MPa)	Stable injection time (min)	Discharge liquid (L)	Injection rate (L/min)
1	5	3	10	0.44	0.044	12	90	60	5	3.36	0.672
2	6	3.8	10	0.62	0.062	13	100	64	5	3.48	0.696
3	7	4	10	0.81	0.081	14	110	65	5	3.61	0.722
4	10	7	10	1.91	0.119	15	120	67	5	3.78	0.756
5	20	12	10	2.5	0.25	16	130	71	5	3.95	0.79
6	30	20	11	3.77	0.34	17	140	77	5	4.02	0.804
7	40	26	5	2.07	0.414	18	150	64	5	3.59	0.718
8	50	28	5	2.39	0.478	19	160	63	5	3.61	0.722
9	60	40	5	2.63	0.528	20	170	62	5	3.68	0.736
10	70	48	5	2.92	0.584	21	180	63	5	3.61	0.722
11	80	51	5	3.18	0.636						

4 CONCLUSIONS

(1) Based on the principles of reliability and rationality of the technical solution, a structural design scheme for the injection valve was proposed, considering the characteristics of HPHT in the Bozi block, as well as the usage cycle. The structure principle is similar to that of a one-way globe valve, with the addition of a burst valve on the basis of the one-way valve. The work analyzed the mechanical structure of the valve, the risk points of sealing failure, and the corresponding measures. It also provided measures to deal with the valve being mistakenly opened during actual operation, further verifying the feasibility of the injection valve in high temperature and high-pressure deep condensate gas reservoirs.

(2) The work conducted strength verification, connection strength calculation, and pressure resistance calculation under high pressure. Then, through theoretical calculations, the mechanical properties of the key structure of the injection valve were obtained, including the compressive stress of thread (122 MPa), bending stress of thread (196 MPa), shear stress of thread (91/83.6 MPa), tensile stress of thread (160.2 MPa), tensile strength of thread (34656.7 N) and compressive strength of the spring barrel (105 MPa), which verified that the material properties of the designed chemical injection valve can meet the operational requirements.

(3) Finally, laboratory experiments were conducted on chemical injection valves, including rupture disc rupture test, bottomhole flow pressure injection test, and 2000 m injection pipeline flow friction test. It was found that, firstly, under normal temperature conditions, the rupture disc rupture pressure was 42 MPa. Under the working condition of 100°C, the rupture pressure of the rupture disc is 44 MPa, which is greater than the design pressure of the rupture disc (40 MPa) and can meet the requirements of underground operations. Secondly, under different pressures, a large amount of liquid flows out of the outlet end of the relief valve and the injection valve opens, indicating that the test is qualified. Thirdly, Under the maximum injection flow rate of 0.76 L/min designed for the injection valve, the frictional resistance of the 2000 m pipeline is approximately 67 MPa. The maximum downhole flow pressure at the injection point is calculated at 90 MPa. The opening pressure of the injection valve is 10-15 MPa, and the 2000 m pipeline can meet the on-site injection requirements.

REFERENCES

[1] Akbarzadeh, K., Ratulowski, J., Eskin, D., et al., "The importance of wax-deposition measurements in the simulation and design of subsea pipelines," SPE Projects Facilities & Construction 5(2), 49-57 (2010).

[2] Rahimzadeh, A., Bazargan, M., Darvishi R. and Mohammadi A. H., "Condensate blockage study in gas condensate reservoir," Journal of Natural Gas Science and Engineering 33, 634-643 (2016).

[3] Labed, I., Oyeneyin, B. and Oluyemi, G., "Gas-condensate flow modelling for shale reservoirs," Journal of Natural Gas Science and Engineering 59, 156-167 (2018).

[4] Xue, S. J., "Waxing mechanism of oil wells and application of wax cleaning and preventing technology," Inner Mongolia Pero Industry 36(20), 112-114 (2010).

[5] Khanaposhtani, M. M., Bahramian, A., Pourafshary, P., Aminshahidy, B. and Fazelabdolabadi, B., "Effect of disjoining pressure on the onset of condensate blockage in gas condensate reservoirs," Journal of Natural Gas Science and Engineering 9, 160-165 (2012).

[6] Nasiri Ghiri, M., Nasriani, H. R., Sinaei, M., Najibi, S. H., Nasriani, E. and Parchami, H., "Gas injection for enhancement of condensate recovery in a gas condensate reservoir," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 37(8), 799-806 (2015).

[7] Lapidus, A. L., Zhagfarov, F. G., Grigor'eva, N. A., Khudyakov, D. S. and Kozlovn, A. M., "Processing of natural gas and gas condensate," Chemistry and Technology of Fuels and Oils 46, 141-147 (2010).

[8] Sun, Y., Zhu, W. Y., Li, B. Z., Xia, J., Jiao, Y. W. and Huang, K., "Numerical simulation of dry gas migration in condensate gas reservoir," Bulletin of the Institute of Heat Engineering 98(2), 212-219 (2018).

[9] Xu, W. H., Lei, G.L. and Xue, Y., "Research on the mechanism of microbial antifouling action," Journal of Southwest Petroleum University (Science & Technology Edition) 27(6), 68-72 (2005).

[10] Severianoa, J. A., Silvaa, A. S., Sussushib, E. M., Mércia, V. S. S., Cunhac, M. A., Bergmannc, C. P. and Griza S., "Corrosion damages of flow regulation valves for water injection in oil fields," Engineering Failure Analysis 96, 362-373 (2019).

[11] Ejaz, M., Mahmoud, E. R. I. and Khan, S. Z., "The investigation of the fatigue failure of nickel-based superalloy 718 choke valve stems used in offshore subsea water injection service," Engineering Failure Analysis 110, 104434 (2020).

[12] Luo, G. F., Economides, C. E. and Nikolaou, M., "Advantage of miscible fluid injection and tight oil production through a single-well alternating production-injection procedure over other single-well EOR methods," Journal of Petroleum Science and Engineering 199, 108091 (2021).
[13] Sun, Q., An, W. Z., Wu, L., Zuo, X., Xu S. J. and Yue, Y. L., "Flow measurement method for underwater chemical injection based on dual-rate fusion," Control and Instruments in Chemical Industry 50(2), 175-180 (2023).
[14] Hoseinpour, S. A., Madhi, M., Norouzi, H., Soulgani, B. S. and Mohammadi A. H., "Condensate blockage alleviation around gas-condensate producing wells using wettability alteration," Journal of Natural Gas Science and Engineering 62, 214-223 (2019).
[15] Farhoodi, S., Sadeghnejad, S. and Dehaghani, A. H. S., "Simultaneous effect of geological heterogeneity and condensate blockage on well test response of gas condensate reservoirs," Journal of Natural Gas Science and Engineering 66, 192-206 (2019).
[16] Wang, W. Y., Zhu, W. and Li, M. Z., "Gas–liquid flow behavior in condensate gas wells under different development stages," Energies 16(2), 950 (2023).
[17] Smallwood, T. J., Robey, N. M., Liu, Y. L., Bowden, J. A., Tolaymat, T. M. and Solo-Gabriele H. M., Townsend T.G., "Per- and polyfluoroalkyl substances (PFAS) distribution in landfill gas collection systems: leachate and gas condensate partitioning," Journal of Hazardous Materials 448, 130926 (2023).
[18] Chen, Y. T., Zhang, H. K., Liu, Y. L., Bowden, J. A., Tolaymat, T. M., Townsend, T. G. and Solo-Gabriele, H. M., "Evaluation of per- and polyfluoroalkyl substances (PFAS) in leachate, gas condensate, stormwater and groundwater at landfills," Chemosphere 318, 137903 (2023).
[19] Liu, W. C., Yang, Y. J., Qiao, C. C., Liu, Chen, Lian, B. Y. and Yuan, Q. W., "Progress of seepage law and development technologies for shale condensate gas reservoirs," Energies 16(5), 2446 (2023).
[20] Hussain, W., Ehsan, M., Pan, L., Wang, X., Muhammad, A., Shahab, U. D., Hussain, H., Jawad, A., Chen, S. Y., Liang, H. G. and Liang, L. X., "Prospect Evaluation of the Cretaceous Yageliemu Clastic Reservoir Based on Geophysical Log Data: A Case Study from the Yakela Gas Condensate Field, Tarim Basin, China," Energies 16(6), 2721 (2023).