Optimum design of downhole chokes with high sulfur content and large pressure difference

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Abstract: Natural gas resources are abundant in southwest China, but the exploitation environment with high pressure and sulfur always affects the working performance of downhole chokes, which in turn restricts the output of natural gas. In this paper, a high sulfur resistance fixed downhole choke is designed for high temperature (120°C), high production rate and high pressure difference (105MPa) sand-producing Wells. Through the nozzle discharge model to simulate the flow of the fluid through the nozzle, with Bono Maleev method to predict the hydrate formation conditions of downhole choke for the design of the structure. According to the failure forms of different parts, the materials were optimized, and the high sulfur resistant 3YC51 alloy, hard alloy and wear and corrosion resistant sulfur resistant rubber were selected through the test to improve the service life of the choke in the high sulfur high-pressure gas well and ensure the reliability of the tool. The results of numerical analysis on the tool holder and the pressure test of the Laboratory seal show that the choke designed has a good sealing and pressurization performance in the high temperature and high pressure difference environment of 120°C and 105MPa, and it can realize the function of lowering the pressure at the bottom of the well under this working condition, meeting the feasibility requirements. Through this design, the design and improvement of high sulfur gas well tool and new choke has guiding significance.

1. Introduction
High sulfur gas reservoir resources are abundant in China, and 90% of high sulfur gas reservoir are concentrated in the Sichuan basin [1]. The discovery of Gaoshiti-Moxi sour gas reservoir represented that the sulfurous gas proved reserves in our country has entered a new period of rapid growth. At present, the proved reserves of high sulfur natural gas in Sichuan basin are about 920 billion cubic meters, accounting for 1/9 of the proven reserves of natural gas in China. However, China's currently used reserves of natural gas with high sulfur content are about 140.25 billion cubic meters, only accounting for 15% of the proven reserves of natural gas with high sulfur content, so the exploitation potential is huge [2,3,4].
In gas Wells, the pressure and temperature of natural gas at the bottom of the well are higher. As the gas rises, the pressure and temperature gradually decrease. Under the condition of critically low temperature and high pressure, natural gas is easy to form hydrate, which will block the pipeline and affect the production. In the process of natural gas production, the formation of hydrate must be inhibited, so it is necessary to control the pressure and temperature of natural gas. At present, there are two main approaches to control the temperature and pressure of natural gas, wellbore throttling and downhole throttling.

Wellbore choking relies on water jacket furnace and other assistance equipment for multi-stage pressure reduction and temperature rise measures. The equipment covers a large area. Wang Weilin estimated that the cost of water jacket equipment in 245 wells of Sichuan and Chongqing from 2006 to 2010 exceeded 21 million dollars [5]. Downhole throttling is installing throttling chokes(stationary, activity type downhole throttling tools) on the appropriate placement of the tubing to reduce expenditure, and at the same time, make full use of ground temperature to heat natural gas after throttling to make higher temperature of gas than that of hydrate formation, which reduces the ground line pressure and prevents hydrate formation [6].

The content of hydrogen sulfide in high sulfur gas reservoirs in Sichuan basin is 30~200g/m³, the buried depth is 2000~7000m, the original strata stress is 20~70MPa, the strata temperature is 85~150°C, the production of gas wells is 20~100×10⁴m³/d, with the superior difficulty of technology and the high requirements grade of material, and complex reservoir environment also leads to a significant increase in cost [7] and frequent accidents [8].

At present, the original strata stress of Heba well 1 in production is 111.1MPa, and the strata temperature is 151°C. Due to immature extraction natural gas technology in high pressure gas well and inadequate facilities, this well has been closed abnormally for 4 times in the early stage of trial production [9]. At present, there are no reports about chokes applied in high-pressure gas wells. The maximum working pressure difference of JL 59-35-H8 mobile chokes developed by PetroChina Southwest Oil & Gas Field Company is 35MPa, and that of the two fixed chokes is only 70MPa. The technical design parameters of sulfur resistance of the chokes meet the content of H2S of 5~30g/m³[5]. In addition, the maximum working pressure difference of CX632 is 50MPa [6], that of HJQ-3 is 45MPa[10], and that of HY-4 is 35MPa[11]. The test of the collar relocating downhole choke newly applied in the Sugeli gas field is only 35MPa [12], and there are few studies on high-pressure gas Wells. To consider safety production and benefit development and meet the throttling needs of high-pressure gas Wells, the research and development objectives of downhole throttling tools are determined according to the production needs of high-sulfur gas wells as follows:

1. Throttling pressure difference of 105MPa, temperature resistance of 150°C;
2. Wells with hydrogen sulfide content of 30 ~ 225 g/m³ and carbon dioxide content of less than 150 g/m³;
3. A large yield, up to 80 ~ 100×10⁴ m³ production capacity;
4. Suitable for 2³/₈", 2⁵/₈", 3¹/₂ " completion string;

2. Structure design and material selection of choke

2.1 Structure design
The components of the choke designed in this paper mainly include the seat short section, sand control structure, slip, combined seal and integral choke.

The minimum inner diameter of the seat short section is 71mm, the maximum outer diameter is 114mm, and the length is 431mm. Sand drainage holes should be designed at the salvaging neck position and the upper part of the seal to prevent sand to bury the salvage head and the phenomenon of stuck. Fitting design the contact area and the degree of fitting between the slip tooth and the holder of the working cylinder, strengthening the strength of the pressure difference, improving the success rate and stability of clamping and salvaging, and adding anti-jamming rotation measures between the slip holder and the holder. The sealing part adopts "V" type sealing part, which overcomes the defects of rubber
materials that are easy to wear and expand and difficult to salvage. In view of the phenomenon of oil nozzles being eroded by conventional downhole chokes, the whole thermal installation structure of nozzle and muzzle is adopted to solve the problem of failure caused by erosion of nozzles and muzzles in gas wells with high production and large pressure difference.

Natural gas is mainly throttled at the throttling nozzle, and the flow state of fluid through the throttling nozzle refers to the flow model of the nozzle, which thinks gas and water pass through the throttling nozzle at a stable flow rate respectively. After derivation and simplification, the empirical formula of the critical flow condition of gas-liquid two-phase mixed fluid crossing the throttling nozzle at the bottom of the well is finally obtained [13,14]. The formula is represented as:

\[
d' = 0.3325 \times \frac{Q_w}{\sqrt{1.75 p}} + 6.67 \times 10^{-1} \frac{Q_g}{p}
\]

Where, \( Q_w \) is water production per day, m\(^3\)/d; \( Q_g \) is gas production per day, 10\(^4\) m\(^3\)/d; \( d \) is the diameter of throttle nozzle, mm; \( P \) is pressure of upstream, MPa.

According to the gas well limit flow formula [15], when the actual gas production is higher than the theoretical production, the gas flows at high speed in the pipe string, and the liquid in the wellbore can be completely carried by gas. Minimum gas velocity of carrying fluid in gas well:

\[
V_g = 2.5 \times \sqrt{\frac{(\rho_l - \rho_g) \sigma}{\rho_g}}
\]

Theoretical gas production:

\[
Q_g = \frac{2.5 \times 10^4 APV_z}{ZT}
\]

Where, \( V_g \) is Minimum gas velocity of carrying fluid in gas well, m/s; \( \rho_l \) and \( \rho_g \) are density of liquid and natural gas respectively, kg/m\(^3\); \( \sigma \) is Gas-liquid surface tension, N/m; \( A \) is Cross sectional area of oil tube, m\(^2\); \( P \) is pressure of gas, MPa; \( T \) is temperature of gas, K; \( Z \) is gas deviation factor at \( P \) and \( T \); \( Q_{sc} \) is theoretical production, m\(^3\)/d.

When the temperature in the wellbore is lower than the critical temperature of hydrate formation, hydrate will be generated. In addition, the content of water in natural gas also has a certain influence on hydrate generation [16]. When the installation of downhole choke is completed and the gas pressure is reduced after throttled, then the critical temperature of hydrate production is reduced and the conditions for hydrate production are improved. The formation of hydrate is predicted by Bono Maleev method [17]:

\[
\log P = -1.0055 + 0.0541(14.76 + T - 273)
\]

Where, the parameters are the same as above.

The falling depth of the choke is determined by the wellbore temperature. The critical falling depth is as follows:

\[
H_{min} \geq M (T_s + 273) / \beta k^{2/3} \theta^{2/3} \theta - 273 - T
\]

Where, \( H \) is the falling depth of the choke, m; \( M \) is low temperature gradient, m/°C; \( T_s \) is the wellbore temperature at the falling depth of the choke, °C.

The structure design diagram of the stationary downhole choke is shown in Fig.1.
2.2 Selection of material

The selection of tool materials should first meet the industrial standards, mainly meeting ISO 15156/NACE MR0175 hydrogen sulfide environment used in oil and natural gas production [18,19,20,21]. These materials also meet certain corrosion conditions: \(T=150^\circ\text{C}, P=50\text{MPa}\); \(P_{H_2S} = 7.5\text{MPa}, P_{CO_2} = 5\text{MPa} ; M_{Cl^-} = 170000\text{mg/l}\). In addition, factors such as material production conditions and production cost should be considered.

According to the above requirements, 3YC51 alloy was selected as the material of the choke work cylinder and the body of the throttle tool with high sulfur resistance; hard alloy was selected as the material of the throttle nozzle; ”V” type seal was adopted as the sealing element, and alternative combination of sulfur resistance rubber and four fluorine rubber was selected as the material.

2.3 Result of material test

2.3.1 Test of sulfur corrosion resistance of 3YC51 alloy. Based on NACE TM0177-2005 H\(_2\)S stress corrosion resistance standard, test samples were prepared [22], and carried out experiments. As can be seen from Fig.2, after the test, 3YC51 alloy test piece has no obvious crack on the surface, so 3YC51 alloy meet sulfur corrosion resistance requirement.

2.3.2 Electrochemical corrosion test of 3YC51 alloy. Electrochemical corrosion test was carried out on the metal material alloy 3YC51. JB/T7901-2001 uniform corrosion full immersion test method [23,24] was as the evaluation standard. Relevant parameters of the test are shown in the following Table1.

| Material | Temperature (°C) | Mass of untested sample(g) | Mass of tested sample(g) | Loss of mass(g) | Corrosion velocity (mm/a) | The test environment |
|----------|-----------------|---------------------------|--------------------------|----------------|--------------------------|---------------------|
|          | 90              | 10.1110                   | 10.1106                  | 0.0004         | 0.0065                   |                     |
| 3YC51 alloy | 10.0494             | 10.0492                   | 10.0095                  | 0.0009         |                         |                     |
|          | 10.1092         | 10.1080                   | 10.0566                  | 0.0005         | 0.0083                   |                     |
|          | 10.1793         | 10.1791                   | 0.0002                   | 0.0083         |                         |                     |

Fig.2 Untested and tested of alloy 3YC51 (left before the test and right after the test)
Test result showed that alloy 3YCY51 was 0.0065 mm/a at 90°C and 0.0083 mm/a at 150°C, respectively, and the corrosion rate was less than 0.01 mm/a, so it reached the design standard and passed the electrochemical corrosion test.

2.3.3 Sulfur corrosion resistance test of seal material. The sulfur corrosion resistance test was carried out on different sealing materials to select more suitable sealing materials. The test conditions were consistent with the 3YCY51 alloy. After 72 hours of test, the specimen was taken out.

| Materials of samples | TS(MPa) | Eb (%) | H (%) |
|----------------------|---------|--------|-------|
| KE-2 (un-soaked)     | 23.52   | 244.09 | 9.36  |
| KE-2 (soaked)        | 8.56    | 105.63 | 5.63  |
| KE-3 (un-soaked)     | 14.3    | 260    | 8.42  |
| KE-3 (soaked)        | 11.5    | 188    | 8.0   |
| KLZ-1 (un-soaked)    | 19.4    | 120    | 8.64  |
| KLZ-1 (soaked)       | 16.3    | 112    | 8.64  |
| KLZ-2 (un-soaked)    | 16.6    | 92     | 4.80  |
| KLZ-2 (soaked)       | 15.7    | 85     | 3.25  |

According to GB/T 528-1998 testing of vulcanized rubber or thermoplastic rubber tensile stress and strain properties, the selected material treated according to the requirements, KLZ-1 specimen has a bright surface, more reasonable relevant indexes, and meets the design requirements.

2.3.4 Sulfur resistance test of choke nozzle material. Hard alloy is selected as material of the choke nozzle. In 24±3°C and H₂S medium under normal pressure, no any hydrogen bubble phenomenon exist in the surface of the hard alloy. And no sulfide stress cracking occurs when subjected to 30MPa, 50MPa and 80MPa tensile and compressive stress respectively. In 200°C, under experimental conditions of \( P_{H₂S} = 7.5 \text{MPa}, \ P_{CO₂} = 5 \text{MPa} \), the cemented carbide under 80MPa tension and pressure also did not occur stress corrosion cracking.

According to the test results, the carbide material used in the throttle nozzle has no corrosion cracking under the relevant conditions, which meets the design requirements.

3. Numerical analysis of structural stress of three fixture blocks

The structure of three fixture blocks is the positioning mechanism of the choke. When the choke reaches the set position, the structure is stressed and radially opened. The tool is stuck in the groove of the oil nipple. During the fishing, the fishing head is subjected to upward lift-force, the spring will push the blocks into the body and tool will be away from the seat short section of oil nipple. The three fixture blocks are the key structure to ensure the normal operation of the choke. The high pressure of bottom hole leads to the large contact stress of the blocks, and the unreasonable structure will lead to the failure of the block or even serious accidents. The stress analysis of the block structure will be carried out below. The three fixture blocks are installed in three circumferentially distributed holes on the body. The body withstands axial pressure \( P_o=105 \text{MPa} \) from the bottom hole of the adjacent structures. The material of three fixture blocks is 718 steel with Elastic modulus \( E=2.5\times10^5 \), Poisson's ratio \( \mu=0.3 \) and Yield strength =980MPa.
As can be seen from Fig. 4, when bearing axial load \( P_0 = 105 \text{MPa} \), stress concentration will be generated at the positions where the blocks contact the body. The maximum equivalent stress of the blocks is 299.3 MPa, and the maximum supporting reaction force at the back end of the blocks is 122 kN. It can be seen from the above that the structure of three fixture blocks is safe and can work normally under this working condition.

4. Laboratory tests

According to the design parameters to complete the tool parts processing and assembly, seal pressure test. In this experiment, nitrogen and water were respectively used as test media, and the bench pressure was slowly pressurized to 105 MPa to explore whether the design tool could have good sealing performance under the target pressure. Under the same experimental conditions, the temperature was raised to 120°C to test the sealing performance of the tool under high pressure and high temperature. The following three experiments were conducted.

4.1 Tests of sealing

4.1.1 Pressure test of water seal at room temperature and 105MPa. The pressure was gradually pressurized to 105 MPa and stabilized for 15 min by step test. After the pressure test is finished, the choke is taken out directly through the vibrator. Fig. 5 shows the throttling working cylinder and fixture undergoing pressure test of water seal at room temperature 105 MPa.

Fig. 5 Water seal test at room temperature and 105 MPa

4.1.2 Pressure test of 105 MPa water seal at high temperature. The test water pressure was 5 MPa, then the temperature was raised to 120°C, the temperature was maintained, the pressure was gradually pressed, and finally the pressure was boosted to 105 MPa and the pressure was stabilized for 15 min. After the pressure test is finished, the choke is taken out directly through the vibrator. Fig. 6 illustrates the temperature control instrument and the pressure control curve in the test.

Fig. 6 Water seal test at 120°C and 105 MPa
4.1.3 Pressure test of N2 seal at room temperature and 105MPa. Step pressure test, boost to 105MPa, stabilize the pressure for 15min; After the pressure test is finished, the choke is taken out directly through the vibrator. The ongoing pressure test of nitrogen seal at room temperature and 105MPa is presented in Fig.7.

4.2 Results of sealing test
The test results are shown in Table 3.

| Serial number | Test media | Temperature     | Pressure  | Pressure holding time | Results                       |
|---------------|------------|-----------------|-----------|-----------------------|------------------------------|
| 1             | water      | Room temperature| 105MPa    | 15min                 | No leakage, choke in good condition |
| 2             | water      | 120℃            | 105MPa    | 15min                 | No leakage, choke in good condition |
| 3             | N₂         | Room temperature| 105MPa    | 15min                 | No leakage, choke in good condition |

There is no leakage of the chokes in the above three groups of tests after maintaining the pressure for 15min, and the tool structure is intact. It indicates that the designed choke meets the design requirements and can withstand the working pressure difference of 105MPa at 120℃.

5. Conclusion
Based on the previous chokes, 3YC51 alloy with high sulfur resistance, hard alloy and anti-sulfur rubber material with wear and corrosion resistance were selected to improve the service life of the chokes in high-pressure gas Wells with high sulfur content and ensure the reliability of the tools.

Numerical analysis of structural stress and the laboratory test shows that the choke designed in this paper has good sealing and pressurization performance in the high temperature and high pressure difference environment of 120℃ and 105MPa, which meets the application in this condition.

The innovation of throttling tool designed in this paper mainly lies in the following: firstly, it is suitable for the reservoir with high sulfur acidity (partial pressure of hydrogen sulfide: $P_{H_2S} = 7.5$MPa, $P_{CO_2} = 5$MPa), temperature range $\leq 120$℃, throttling pressure difference $\leq 105$MPa. The fixed downhole throttling tool can meet the requirements of high gas production ($80$-$100 \times 10^4$ m$^3$/d).

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Reference
[1] Chang Honggang, Xiong Gang. Technologies for safe production and sulfur recovery in giant high-sulfur gas fields[J]. Natural Gas Industry, 2012, 32(12): 85-91.
[2] Gang Qinlin. Some Understanding of the Basic Law of Gas Field Developmen[J]. Natural Gas Industry. 1997(3): 30-35.
[3] Dai Jinxing. Distribution, classification and origin of natural gas containing hydrogen sulfide in China[J]. Acta sedimentologica sinica. 1985, 3(4): 109-120.
[4] Zhang Zishu. Hydrogen sulfide in Sichuan carbonate gas field[J]. Petroleum Geology & Expemento. 1983(4): 67-70.
[5] WANG Weilin, HE Yiguo, YE Changqing. Application of underground choke process in Chuanyu area[J]. Energy Conservation in Petroleum & Petrochemical Industry. 2012,2(12):25-27+52.
[6] HU Dan, HOU Zhimin, TENG Wenjiang, et al. Development and application of a new mobile-type downhole choke[J]. Oil Drilling & Production Technology. 2014(3): 123-125.
[7] Li Luguang. Progress in and developing orientation of technologies for the recovery and production of high-sulfur gas[J]. Natural Gas Industry. 2013, 33(1): 18-24.
[8] WANG Ping, LI Wenfei, ZHANG Rui, et al. Risk analysis method for drilling trouble in Northeast Sichuan[J]. Oil Drilling & Production Technology. 2012, 34 (02):29-32.
[9] LIU Qilin, TANG Yu, LUO Zhaqian, et al. The surface gathering and transportation technology suitable for ultrahigh pressure sulfur gas wells in the northwestern Sichuan Basin[J]. Natural Gas Industry. 2017, 37(07):101-107.
[10] YU Chenggang, ZHANG Huali, DENG Youchao. DEVELOPMENT AND APPLICATION OF NEW DOWNHOLE CHOKE[J]. Drilling & Production Technology. 2008(04):91-93+2.
[11] XIAO Shuqin, WEI Yaming, YANG Xudong, et al. Collar seating type downhole throttling device[J]. Oil Drilling & Production Technology. 2019, 41(3) : 314-317.
[12] GU Chengyi, FENG Pengxing, SONG Hanhua. Application of HY-4 down-hole choke in Sulige gas field[J]. Oil Drilling & Production Technology. 2010,32(04):120-122.
[13] Omama R, Houssiere C, Brown K, et al. Multiphase Flow Through Chokes[J]. Fall Meeting of the Society of Petroleum Engineers of Aime. 1969, 21.
[14] Elgibaly A A M, Nashawi I S. New Correlations For Critical And Subcritical Two-phase Flow Through Wellhead Chokes[J]. Journal of Canadian Petroleum Technology. 1998, 37(6): 36-43.
[15] LI Yuansheng, TENG Sainan, YANG Zhixing, et al. Critical liquid carrying flow rate model with consideration of interfacial tension and droplet deformation[J]. Oil Drilling & Production Technology. 2013, 33(1): 18-24.
[16] LI Xiaoping. Several methods of distinguishing gas well bottom hole fluid[J]. Drilling & Production Technology. 1992(2): 41-44.
[17] CAO Fang-ling. WANG Ting-fang, CAO Li-ying, et al. Formation Conditions of Forecasting Natural Gas Hydrate with Numerical Calculation Method[J]. Guangzhou Chemical Industry. 2013, 41(5): 82-83.
[18] GE Youyan, DU Qiang. Standard method of material selection for hydrogen sulfide environment oil and gas field development—Application synopsis of NACE MR0175 / ISO 15156[J]. Chemical Engineering of Oil & Gas. 2008, 37(5): 410-415.
[19] WANG Yan. Analysis of corrosion and protection of petrochemical equipment in wet hydrogen sulfide environment [J]. Chemical Enterprise Management. 2017(1): 159.
[20] LUO Wenshan. Analysis of corrosion and protection of petrochemical equipment in wet hydrogen sulfide environment[J]. Heilongjiang Science and Technology Information. 2016(3): 21.
[21] LIU Kaiming. Study on stress corrosion of mechanical equipment in wet hydrogen sulfide environment and its prevention measures[D]. Lanzhou University of Technology.2005
[22] WANG Wenming, PENG Cunling. Study on wet hydrogen sulfide corrosion mechanism of mechanical equipment[J]. Chinese Hi-tech Enterprises. 2009(17): 195-196.
[23] ZHANG Wanzhen. Corrosion of metal materials in wet H2S environment [J]. Corrosion & Protection in Petrochemical Industry. 2006, 23(3): 22-25.
[24] DAI Haiqian. Evaluation of measurement uncertainty of uniform corrosion full immersion test in metal materials laboratory [J]. Natural Gas and Oil. 2006, 24(4): 51-53.