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Progress and Development Direction of "Three-High" Oil and Gas Well Testing Technology

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Abstract

By reviewing the development of "three-high" oil and gas well testing technology of Sinopec in recent years, this paper systematically summarizes the application of "three-high" oil and gas well testing technology of Sinopec in engineering optimization design technology, and high temperature and high pressure testing technology, high pressure and high temperature transformation completion integration technology. Major progress has been made in seven aspects: plug removal and re-production technology of production wells in high acid gas fields; wellbore preparation technology of ultra-deep, high-pressure, and high-temperature oil and gas wells; surface metering technology; and supporting tool development technology. This paper comprehensively analyzes the challenges faced by the "three-high" oil and gas well production testing technology in four aspects: downhole tools, production testing technology, safe production testing, and the development of low-cost production test tools. Four development directions are put forward: 1) Improve ultra-deep oil and gas testing technology and strengthen integrated geological engineering research. 2) Deepen oil and gas well integrity evaluation technology to ensure the life cycle of oil and gas wells. 3) Carry out high-end, customized, and intelligent research on oil test tools to promote the low-cost and efficient development of ultra deep reservoirs. 4) Promote the fully automatic control of the surface metering process to realize the safe development of "three-high" reservoirs.

Keywords

"Three-High" Oil and Gas Wells, Oil Test, Geological Engineering Integration, Intelligent Downhole Tools

1. Introduction

In recent years, as Sinopec has made strategic breakthroughs in the exploration of deep and ultra-deep reservoirs in the Tarim Basin and Sichuan Basin, deep and ultra-deep high pressure and high temperature reservoirs and complex lithologic low permeability reservoir fields have gradually become important fields of oil and gas exploration [1]. Taking the "three-high" oil and gas reservoirs in the Shunbei block of the Tarim Basin and the Yuanba Block of the Sichuan Basin as examples, have burial depths of 7000 - 8600 m, high formation pressure (over 140 MPa), high bottomhole temperature (167˚C - 190˚C), multiple stratigraphic sequences, strong heterogeneity, are easy to spray, leak, and collapse, and contain H_2S and CO_2. Oil testing technology and downhole tool performance are challenging to execute safely.

We summarized the main progress of "three-high" oil and gas well testing technology systematically, analyzed the challenges of "three-high" oil and gas well testing technology comprehensively, and proposed the development direction of "three-high" oil well testing technology in this paper by reviewing the development process of "three-high" oil and gas well testing technology in Sinopec over the last ten years.

2. Main Progress of "Three-High" Oil and Gas Well Testing Technology

Since Sinopec introduced Halliburton high temperature and high pressure oil test technology, through continuous absorption, exploration and innovation, oil testing technology has progressed through four stages: quasi high pressure stage, high pressure stage, high pressure and high temperature stage, and ultra-deep and ultra-high pressure and high temperature stage. In the "three-highs" of oil and gas well testing, test engineering optimization design technology, testing technology of high pressure and high temperature, high pressure and high temperature transformation-well completion integration technology, broken down and production recovery technology of high acid gas field production wells, wellbore preparation technology for ultra-deep high-pressure and high-temperature oil and gas wells, surface measurement technology, and supporting tool development technology of ultra-deep high pressure and high temperature oil and gas wells made important progress.

2.1. Engineering Optimization Design Technology

Operating risks for the "three-high" reservoirs of Sinopec include severe casing wear, high wellhead pressure during oil testing or shut-in, a complex downhole environment prone to annular pressure, complex pipe string stress under various extreme conditions, and difficult downhole packer performance indexes to meet operational requirements. To address the aforementioned issues, this technology has developed an engineering design technology that includes well integrity evaluation, string checking, casing residual strength evaluation, well control design, material selection, and buckle selection, as well as design specifications for oil testing and completion engineering of high-pressure and high-temperature oil and gas wells, such as ultra-deep wells, ultra-high pressure wells, high-pressure and high-temperature wells, and wells containing H_2S. The application of this program can effectively improve the success rate of oil testing and construction in "three-high" oil and gas wells and key exploration and evaluation wells, as well as ensure the safety of oil testing string, greatly improve the integrity of wellbore, and meet the requirements of efficient and safe site construction.

2.2. High-Pressure and High-Temperature Testing Technology

2.2.1. Complex Well Testing Technology for Ultra-Deep, High-Pressure, and High-Temperature

Deep burial, complex lithology in the top section, complex wellbore structure, and well completion with 139.7 mm casing are all the characteristics of the "three-high" reservoir. The testing technology of ultra-deep, high-pressure, and high-temperature complex wells is formed, which includes the "three valves and one packer" testing technology suitable for reconnaissance tests and improving test aging, which is based on the principle of "reducing operation risk, high efficiency, and simple process", through the study of three-axis checking of string, optimization of test string combination, and anti-corrosion of complex corrosion environment, aiming at different test purposes. The "four valves and one packer" testing technology is suitable for negative pressure channeling tests to ensure well control safety. The "five valves and one packer" testing technology is suitable for conventional formation testing of high-pressure and high-temperature complex wells, and meets productivity, temperature and pressure data admission, and other requirements (**Figure 1**).

The above testing techniques have been widely applied in the "three-high" reservoirs of the Tarim Basin, meeting the testing requirements of oil and gas wells with a well depth of 8000 meters, a formation pressure of 140 MPa, and a temperature of 232˚C. The success rate of the one-time test of "three-high" oil and gas wells in the Tarim Basin has remained above 92% during the "13th Five-Year Plan" era.

2.2.2. Characteristic Technology of APR Testing Collaboration

Aiming at solve the problem of difficult test joint operation technology implementation in ultra-deep reservoirs, based on generalized Hooke's law and theoretical mechanics, combined with the characteristics of ultra-deep and highly deviated wells, through the axial deformation calculation of the string, the multi-directional stress decomposition. To ensure the effective sealing of the test string and form the seating technology of ultra-deep and highly deviated wells, friction is eliminated and the seating tonnage is controlled within the reasonable load range of the rubber cylinder. To solve the problems of fluid replacement and tool stab prevention in the high pressure layer of ultra-deep wells, the damage relationship of high specific gravity mud and the displacement of fluid

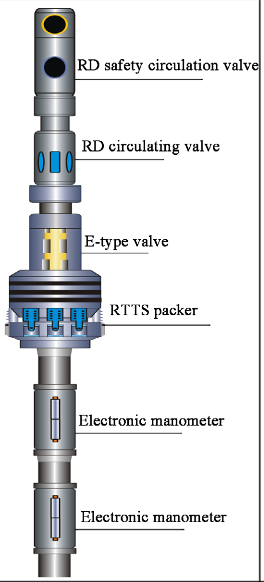
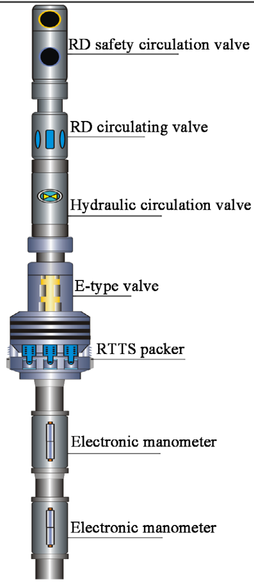
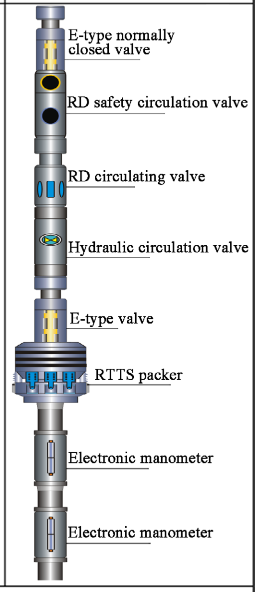
Craft series	Three valves and one packer	Four valves and one packer	Five valves and one packer
String figure			
Applicability	Set first and then submersible (high temperature mud precipitation, easy to cause circulation valve can not open)	E-type normally closed valve as RD safety circulation valve standby valve, add standby valve, improve test establishment	

Figure 1. Testing technology of ultra-deep, high-pressure, and high temperature complex wells.

replacement on downhole tools is studied. By optimizing liquid performance, refining the slurry replacement program, and quantifying operation parameters, a graded slurry replacement and stab prevention technology was established based on the mechanical effect of the string. The payload was controlled by optimizing the string design, tool combination, and precise pressure management to ensure efficient sealing of the test string under dynamic conditions of perforation, acid pressure, jetting, testing, and recovery.

2.3. Integration of High-Pressure and High-Temperature Transformation-Well Completion Technologies

2.3.1. Multi-Functional acid Salt Integrated Completion Technology

To solve the problems of deep carbonate reservoirs, such as multiple types, easy to spray and leak, and high sulfur content. The reservoir physical properties, well structure, downhole tool performance, and completion tubing size are combined to optimize the completion string structure to achieve all geological objectives in one run, based on full consideration of construction safety and well control blowout prevention measures, through continuous technical exploration, taking "meeting the safety requirements of reservoir reconstruction, blowout, and other working conditions" as the core. The main points of this technology are: 1) Adopted the test-retrofit completion multi-function string of "recoverable completion packer + telescopic pipe + tubing plug valve" for wells with average oil and gas display, which require reservoir modification and can be taken out normally. 2) The plugging - testing - transformation - production - completion multi-functional string of "POP valve (secondary plugging valve) + completion packer can be removed and inserted back" is used for the system of drilling directly into the hole, which is easy to spray and leak. 3) Integrated innovation has produced a multi-functional string of "test - transformation - plugging-production" for multi-layer oil test selected completion and wells with high safety risks of easy blowout and leakage; 4) For oil and gas wells with long open-hole section and water layer or easy collapse layer on the upper part of open-hole section, which are not suitable for general transformation and a centralized transformation string is constructed in an innovative formed. 5) If drilling meets multiple reservoirs and requires layered transformation to completion, the multi-functional string of "telescopic pipe + retriefable completion packer + release device + open hole packer" of "test - transformation - completion" shall be adopted. 6) The heavy oil - transformation - completion multi-functional string of "telescopic tube + dilute valve + retrievable completion packer" is used since the production fluid of oil well is heavy oil.

Under the parameters of an 8000 m well depth, a 70 MPa packer pressure differential, and a 177˚C temperature, the multi-functional integrated completion technology of acid salt can meet various operations. Well test and completion operations that meet the requirements for easy blowout and leakage wells can work in a variety of media, including acid fracturing fluid, well killing fluid, salt water, crude oil, natural gas, and H_2S. The field application of more than 2000 wells, a 99% success rate, and a single well average test cycle shortened to 18 days.

2.3.2. Technology for Completing Ultra-Deep Wells and Ultra-High-Pressure Gas Wells

Without adjustment, the deep, high-pressure, and high-temperature sandstone reservoir cannot obtain industrial productivity. For ultra-deep wells, three reservoir modification modes are determined based on the development of reservoir fractures, and a completion string structure that meets the requirements of reservoir reconstruction construction and production is proposed, the fracture prediction and reservoir evaluation of ultra-deep wells (Table 1).

2.3.3. Segmented Reconstruction Completion Technology for Open Hole Horizontal Wells

To solve the problems of deep buried carbonate reservoirs, strong heterogeneity, and the need to be fixed-point transformed. The open-hole layered acidification (fracturing) process is based on the technology of "accurate fixed-point separation transformation and completion" in Halliburton. Through the study of string stress analysis, tool structure optimization, reservoir physical properties, and other aspects, it is formed to use the "tail pipe hanger + sliding sleeve + outer pipe packer + pump-out plug" to achieve one-trip string entry and multiple

Table 1. Integrated string for ultra-deep and ultra-high-pressure gas well testing and transformation.

String name	Completion string for pickling or acidifying	Completion string for acid pressure	Sand fracturing completion string
Transforming displacement	Meet the requirements of transformation displacement within 3.0 m^3/min	Meet the requirements of 5 - 7 m^3/min transformation displacement	Meet the requirements of 8 - 10 m^3/min transformation displacement
Sphere of application	Small pickling or acidification in reservoirs with established fractures can result in wells with industrial output potential [2] [3].	Large hydraulic fracturing in reservoirs with highly developed fractures produces wells with industrial production capacity more.	Sand fracturing in reservoirs with less developed fractures is the only way to get wells with industrial output potential.

purposes, such as accurate transformation, layered completion, and temporary plugging. This technology is very suitable for the needs of well completion and layering transformation of large leakage wells caused by drilling fluid in large fracture hole systems. More than 50 wells have been promoted, and the success rate is 100%.

2.4. Plugging and Production Recovery Technology of Producing Wells in High Acid Gas Fields

To solve the problems of deep burial, high pressure, high yield, and difficulty in plugging removal of small-diameter wells in high-acid gas fields, they studied the influence of the wellbore temperature field and pressure field on the formation of bound hydrate [4] and established a high-precision hydrate formation prediction method (**Figure 2**). The studied the influence of downhole natural gas composition, temperature, pressure, and other conditions on sulfide precipitation, and the experimental results show that the amount of sulfide precipitation increases with the deepening of well depth (**Figure 3**). The researchers looked at various well structure and sulfide deposition and migration rules to develop a sulfide blockage prediction method. The researchers investigated the mechanism of hydrate plugging and developed an effiective hydrate blocking agent. The researchers studied the environmental protection sulfur dissolving working fluid and low corrosion compound organic acid and carried out the optimization of key parameters for plugging by spraying acid, and the development of a jet acid flushing tool, formed the development of a rapid plugging removal technology for complex plugging materials.

In more than 30 ultra-deep sulfur gas wells of Sinopec, the hydrate formation prediction error is less than 3%, and the sulfur deposition prediction error is less than 5%.

2.5. Wellbore Preparation Technology for Ultra-Deep, High-Pressure, and High-Temperature Oil and Gas Wells

In ultra-deep, high-pressure and high-temperature oil and gas reservoirs, the problems of ultra-deep burial, slim holes, complex wellbore trajectory, benches in casing combinations with different sizes, deformation in some casings, long

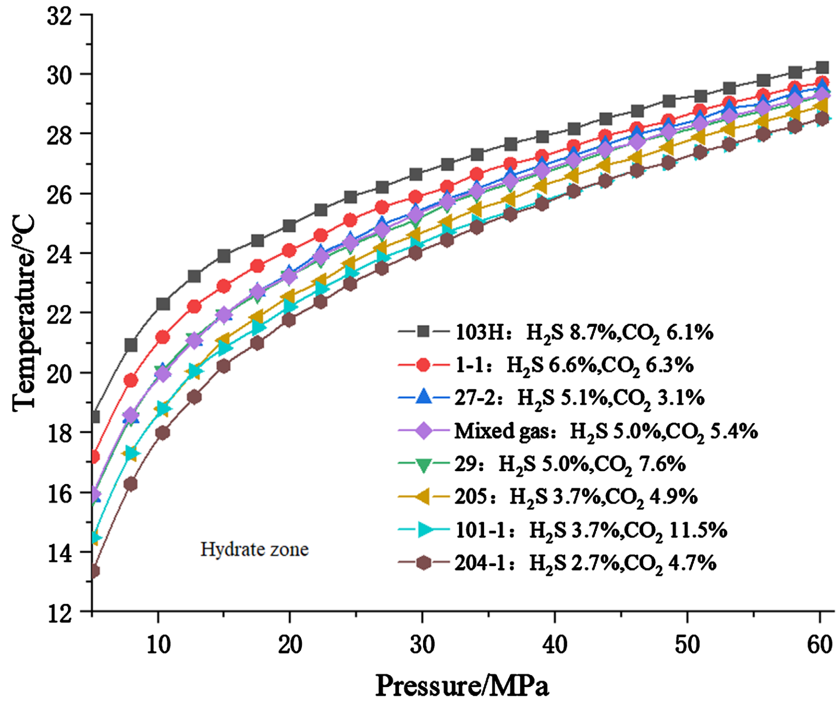


Figure 2. Effect of temperature and pressure on hydrate formation.

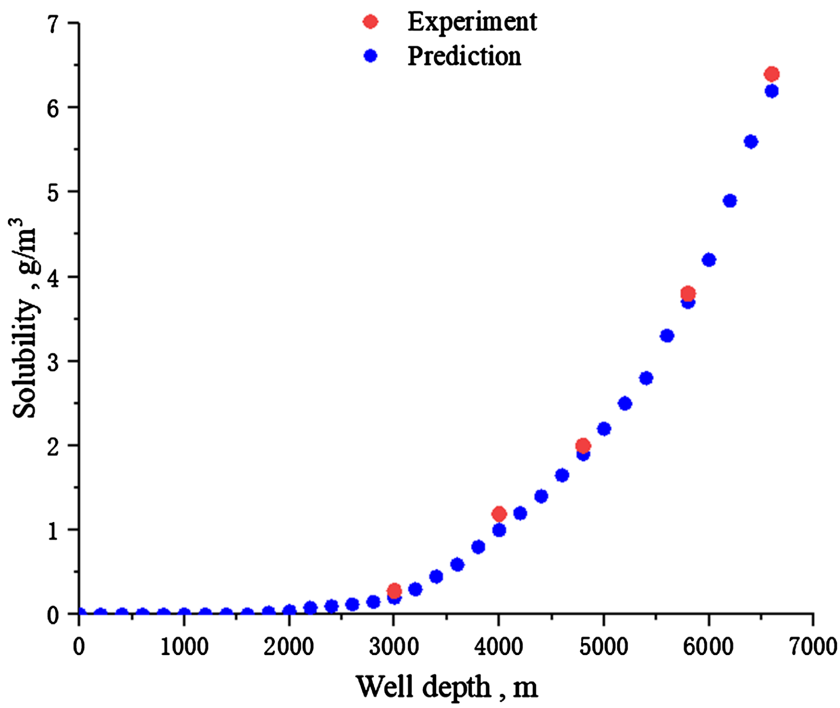


Figure 3. Comparison of theoretical predicted value and experimental results of sulfur solubility.

wellbore preparation cycle, low efficiency, and high cost were addressed. The passability of simulation tests and completion strings in wellbore was investigated in this paper. Non-destructive testing techniques such as multi-arm diameter and electromagnetic flaw detection were used to detect changes in wall thickness and inner diameter of wellbore casing. Combined with impression and MWD wireless directional detection instrument, determined the direction of casing wear, and realized the efficient treatment of complex wellbore; The research results showed that a multi-functional integrated wellbore preparation tool was developed and the research results achieved the completion of drilling-scraper-milling-fishing and other processes in a single trip, reducing the operation cycle in ultra-deep wells by an average of 48 hours (**Figure 4**).

The multi-functional integrated wellbore preparation technology has been applied to 100 wells per year with a success rate of 100%, which promotes the efficient completion of the block in the Shunbei Block of the Tarim Basin.

2.6. Ground Metering Technology

Conventional equipment finds it difficult to meet the test requirements for "three-high" oil and gas reservoirs, such as high wellhead pressure, high production, sand contained in formation produced fluid, mud solid particles, and other impurities, causing great erosion damage to surface equipment. A 140 MPa remote control high anti-erosion throttle valve and a 140 MPa anti-sulfur swirl desander have been developed. A 140 MPa remote control nozzle manifold is matched to build a 140 MPa high pressure remote control ground process with eight functions, including sand removal, sewage discharge, heating, separation, measurement and on-line monitoring of sand production. The ground process bears 140 MPa high pressure; sulfur, acid, and gas treatment capacity of 1.7 million square/day. The liquid treatment capacity is 2067/day, which is suitable for

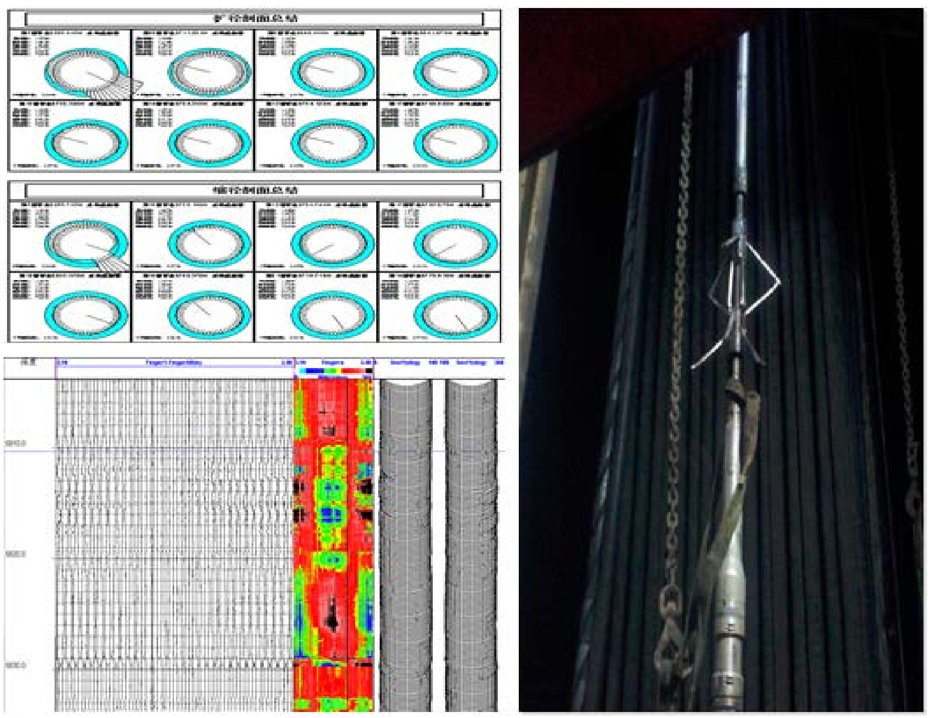


Figure 4. Wellbore detection and evaluation technology for ultra deep and highly deviated wells.

wellhead shut-in pressure of 105 - 140 MPa. The technology has been applied to 168 wells, and the success rate is 100%.

2.7. Development Technology of Supporting Tools

The packer setting tool has become the key tool for "three-high" oil and gas reservoir testing, and the packer is the main sealing tool for "three-high" oil and gas well testing, with a 95% application proportion. According to oil testing requirements, packers are classified into three groups: redeemable, semi-permanent, and permanent. The RH redeployable hydraulic packers and the SAB-3 permanent hydraulic packers, introduced from abroad at a great cost, were utilized in Sinopec's "three-high" oil and gas reservoir tests. Sinopec has developed mechanical packers, removable hydraulic packers, semi-permanent hydraulic packers, and permanent hydraulic packers after years of research. These packers have realized localization and large-scale application, providing a new means for improving the efficiency of isolation and operation. The developed packers can accommodate a wide range of specifications, including 5"7-7/8" casing construction and some of the tools have reached to an international advanced level. The developed redeemable packer has a performance index of 204˚C and 70 MPa V3 level, which meets the completion requirements of an 8000 m well depth, 177˚C well temperature, and 70 MPa packer pressure difference. A permanent packer with a 204˚C and 105 MPa V0 level has been developed to meet the completion requirements of ultra-deep, high-pressure, and high-temperature gas wells. A complete set of oil testing tools has been developed, with performance indexes up to 204˚C and 105 MPa, which can be applied to all types of "three-high" reservoir oil testing requirements and improve Sinopec's the core competitiveness of "three-high" well oil testing technology.

3. Challenges Faced by "Three-High" Oil and Gas Well Testing Technology

In general, the oil and gas well testing technology of Sinopec's "three-high" oil and gas wells is currently in the technical benchmarking stage and the development of oil fields in northwest and southwest China is relatively quick. Ultra-deep high pressure and high temperature oil and gas resources have become an important field of exploration and development due to the expending reserves and the production of major oil field companies [1] [5]. The Shunbei block in the northwest working region has reserves of 1.7 billion tons of oil equivalent [6], the quasi-Central block has reserves of 130.8 million tons [7], and the Yuanba block in the southwest working area has reserves of 200 billion cubic meters [8]. The drilling depth of the above blocks has increased to above 7000 m, and the formation temperature and pressure have surpassed 200˚C and 160 MPa, respectively. There is no mature experience in deep oil testing technology at home or abroad [9]. The writer believes that there are four main challenges.

3.1. The Reservoirs of "Three-High" Oil and Gas Wells Have High Temperature and Pressure, Oil Testing Tools Face Challenges

Deep burial, strong heterogeneity, poor connectivity, and high reservoir temperature and pressure coefficient define "three-high" reservoirs in China. At present, the exploration and development depth of Yuanba and Shunbei blocks of Sinopec has reached more than 7000 m. At present, the APR test tool and RTTS are used to test the packer [10]. Problems with RD valve/RDS valve closing not precisely or action failure frequently during construction, particularly in conditions of high temperature and high specific gravity mud. The wellhead oil pressure management is challenging in the test operation with high pump pressure or high pressure and limited permeability in the reconstruction construction. The pressure difference of a 70 MPa packer is prone to high internal and external pressure differences, and the pressure of the packer is more than the specified pressure value, resulting in packer seal failure.

3.2. The Integrity of the "Three-High" Oil and Gas Wells Is Difficult to Guarantee, and the Testing Technology Is Facing Challenges

The protracted drilling cycle of ultra-deep, high-pressure, and high-temperature wells reduces casing wear strength, increases drilling leakage, and makes cementing quality in the slim hole reservoir difficult to guarantee. Complex stress in the oil casing string, casing deformation during production, wellhead uplift, leakage of the oil pipe string, improper pressure control pipe string being crushed or broken, formation cuttings and sand entering the wellbore during the blowout period, buried card string, and other factors make selecting the test process difficult.

3.3. The Downhole Medium of "Three-High" Oil and Gas Wells is Complex, and the Safety Test is Challenging

High temperature, high pressure and sulfur content all have an impact on the stability and reliability of the test string. Hydrogen sulfide seriously corrodes downhole tools and tubing [11], making them prone to H_2S stress hydrogen embrittlement. Tool seals are prone to failure, and packers are prone to sealing failure. Instability of test tubing, sub quality and sealing resistance. Tubing threads are prone to slipping at high pressure, resulting in test failure. The tensile strength of sub is insufficient, and it breaks. Due to high pressure and high gas production during the gas test of "three-high wells", particularly those with high H_2S content, there are risks such as pipeline blockage, high-pressure gas leakage, and toxic gas leakage, which cause substantial risks to the safety of ground equipment and personnel [12]. Safety testing is especially crucial in the contemporary circumstances of safety and environmental protection.

3.4. "Three-High" Oil and Gas Well Downhole Tools, as Well as Low-Cost Testing Tools, Are Facing Challenges

Because small size 51/2" and 5" casings are frequently employed for completion in the bottom oil layers of ultra-deep wells due to drilling geological conditions, developed downhole test tools with large diameter, high pressure and high temperature is problematic. The developed packer is designed to testing perforation in ultra-deep well and to withstand high temperatures, large pressure differences, and high strength tests under complex working conditions. The majority of China's recoverable completion packers are V3 grade, and developing completion packers with 105 MPa, 204˚C and above V2 grade is still a major challenge. Technical problems in developing low-cost downhole switch valves operated by ground pressure wave or electronic signal have emerged as a consequence of the development of intelligent downhole tools.

4. Development Direction of "Three-High" Oil and Gas Well Testing Technology

4.1. Improve Ultra-Deep Oil and Gas Testing Technology and Integrate Geology and Engineering Studies

Strengthen research on string stress in extreme working conditions, perforation detonation force, casing residual strength, pipe corrosion and scale prevention in 8000 m deep oil tests, clarify the geological and engineering difficulties, establish a comprehensive reservoir evaluation and process method of dynamic data in the entire oil and gas test process, carry out fine reservoir evaluation during operation, and improve wellbore cleaning technology, ultra-deep slim hole perforation-test joint operation technology, and ultra-deep high pressure and high temperature gas well clean completion technology. Improve reservoir quality, reduce the operation cycle, and realize the economic and efficient reservoir exploitation.

4.2. Improve Oil and Gas Well Integrity Evaluation Technologies to Ensure the Life Cycle of Oil and Gas Wells

Conduct well integrity technology research, improve the integrity of oil and gas wells throughout their entire life cycle of through scientific engineering design and strict construction control, and ensure the integrity of well barrier components during oil and gas testing, to ensure the safe and reliable service of the through outs its entire life cycle and maximize well benefit [13].

4.3. Conduct High-End, Customized, and Intelligent Research on Oil Testing Tools to Boost Low-Cost and Efficient Development of Ultra-Deep Reservoirs

4.3.1. High-End Development of Oil Testing Tools

Strengthen oil testing tools and equipment research and development, conduct research and development of high-end downhole tools such as V0 grade packer and 140 MPa downhole safety valve, establish a quality control system for downhole tools, improve test and detection ability, further improve tool stability and maturity, break the monopoly of foreign high-end tools, eliminate the risk of "neck sticking", and reduce oil testing costs by 30%.

4.3.2. Intelligent Development of Oil Testing Tools

At present, oil and gas testing technology is in its infancy. Water exploration, water plugging, flow regulation, and production distribution are challenging to meet with current testing technology, which is limited to well completion, fracturing, oil test, production and other operations. Therefore, conduct research on intelligent flow control oil and gas testing technology to meet the needs of injection and production in different types of reservoirs, such as stratification, segmentation, and branches, and implement intelligent and refined flow control management at each stage of well completion, transformation, oil production, and stimulation.

4.4. Promote the Automatic Control of Surface Metering Process to Realize the Safe Development of "Three-High" Reservoirs

Develop ground metering process automatic control technology, build standardized and automated high-pressure and ultra-high-pressure ground processes, realize automatic control and automatic metering of high-pressure area manifold-real-time and online monitoring of fluid properties, automatic recording and automatic control of oil and gas separator and heat exchanger, unattended on site. Promote ground testing technologies to go in the direction of automation and intelligence. Promote the development of ground testing technology, particularly in the areas of automation and intelligence.

5. Conclusion

After 10 years of development, Sinopec's "three-high" oil and gas well testing technology has advanced significantly in seven areas: engineering optimization design technology, high pressure and high temperature testing technology, high pressure and high temperature transformation and completion integration technology, high acid gas field production well plug removal and reproduction technology, ultra-deep high pressure and high temperature oil and gas well wellbore attaching technology, ground measurement technology, and supporting tool development technology, which effectively supports the production capacity construction of "three-high" oil and gas reservoirs in northwest, including the Yuanba and Puguang oilfields. Overall, Sinopec's "three-high" oil and gas well testing technology is competing with other companies, but in the case of long-term low oil prices in the case of hovering, greater challenges, increasing demand for testing technology, and higher technical difficulties are required to achieve economic benefits. We will promote geological engineering integration research, oil and gas well integrity evaluation technology, testing research, high-end, intelligent test tools, fully automated ground measurement process, exploration of inductive is suitable for different blocks and reservoir characteristics of the "three-highs" system of oil and gas well testing, testing technology, and efforts to achieve super deep reservoir scale development, ultra-deep reservoirs as a new strategic growth point and ensure national energy security.

Fund Project

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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