Present Statue and Development Trend of full-Scale Simulator for Drilling and Producing

Lv Zhenhu1,a, Wei Yafang2, Xiang Yingjie3, Liu Jingtian1, Chen Lu1, Yu Weichu4

1Engineering Research Institute, PetroChina Xinjiang Oilfield Company, Karamay, Xinjiang, 834000, China
2No. 1 Oil Production Plant, PetroChina Xinjiang Oilfield Company, Karamay, Xinjiang, 834000, China
3Institute of Geophysics, PetroChina Xinjiang Oilfield Company, Urumqi, Xinjiang, 830000, China
4Yangtze University, Jing Zhou, Hubei, 434000, China
alaizhenhu2016@petrochina.com.cn

Abstract: Because it provides favorite ancillary support in terms of technology research and tools test, full-scale simulator for Drilling and Producing is still the focus for overseas researches. The test capability for full-scale simulator represents the level of development for national petroleum exploration and development. That the increasing efforts on unconventional oil & gas and deep water exploration brings new challenges to theory and technology for oil-gas exploration, so the full-scale simulator provides an intermediate bridge for theory and technology innovation. Following the tracks of the development of full-scale simulator, the overseas and domestic classify and development of full-scale simulator was analyzed, and identifying the main technical bottlenecks faced during it establish. This paper describes the development of key technologies for wellhead loading system, wellbore simulation technology and test monitoring system. On this basis, the research prospect for the full-scale simulator was forecasted.

1. Introduction

Full-scale simulator for drilling and producing is applied to put the drilling and producing working conditions of oilfield into simulation in laboratory, for technology research, tool test, research and development by means of test simulation. The overseas research and production of full-scale simulator for drilling and producing had begun since 1950s. After more than half a center of application and development, most research achievements had been directly transferred to actual productivity[1], which laid solid foundation for the development of drilling and producing tools and technology. The forward development of drilling theory and technology drew attention from various domestic oilfield colleges and universities. Since the mid-term of 1970s, China started to study the test simulation well with independent intellectual property right. As time goes on, the development of test simulation well in China has gone through the following three transitional period: (1) its dimension developed from small-scale simulator for drilling and producing to full-scale simulator; (2) analysis and research capacity developed from single performance test to comprehensive performance test; (3) wellbore structure developed from straight well to inclined well, horizontal well and comprehensive test well bore. Establishment of test simulation well not only solved the problem of on-site test cannot analyze the
effect and mechanism of single factor, but also controlled the risk brought by on-site test, provided important research approaches\cite{2} for quantitative and predicted engineering science from the perspective of qualitative development of drilling and production engineering. The increased difficulty and complexity of oil-gas exploration has brought about new challenge to drilling theory and technology. Before popularization and application, the new technology and new energy including percussive drilling, deep well drilling, pressure control drilling, shale gas and combustible ice should be subject to sufficient experimental demonstration in laboratory. The test simulation well may play a significant role in the future oil exploration and development in view of the above-mentioned reasons, this paper discusses the classification, development status, technical bottle neck and future development direction of test simulation well.

2. Classification and Development Status of Full-Scale Simulator for Drilling and Producing

2.1. Classification of Full-Scale Simulator for Drilling and Producing

According to the development process of oil-gas field, intermediate testing is provided for different stages of oil-gas field development. Based on the functions, the full-scale simulator for drilling and producing can be presently divided into three types as follow:

(1) Tool test well

Tool test well, such as drilling tool test well in Dagang Oilfield\cite{3}, is a testing platform established to perfect the intermediate testing conditions for down-hole tools for drilling, well completion, well testing and oil production. It is required to run the tools down into corresponding positions in simulative well bore under true down hole environment and practical working conditions. By using the wellhead device to apply tension, pressure and torque to the downhole tool, the mechanical and functional performance of the downhole tool is tested and analyzed.

(2) Process test well

Process test well is a testing platform established to study new technology for drilling and well completion as well as oil production technology, having relatively higher requirements on the pressure-bearing capacity and mechanical property of testing equipment. The simulation environment in test well bore should be consistent with the practical drilling environment. At present, process test well in China mainly includes full-scale experimental simulative well and small-scale similar simulation experimental device, such as well control simulation test well of Sichuan Authority of Petroleum\cite{4} and full-scale oil production technology test well of Zhongyuan Oilfield\cite{5}. Studying and analyzing objective laws of drilling and producing technology through process test well can optimize the drilling technology and provide conditions for popularization and application of drilling technology.

(3) Comprehensive test well

Comprehensive test well, such as drilling and well completion test center of U.S. Terra Tek\cite{6}, is a comprehensive test platform established for tool property analysis and process test research. With the development of mechanical technology, computer technology, test technology and well bore simulation technology, the scale and integrity of test simulation well are growing with each passing day.

2.2. Overseas Development Status

Studying the influencing mechanism of drilling technology, increasing the development level of oil-gas drilling and production, optimizing drilling technology and reducing development cost have always been the ambitions of oil industry in various countries. The overseas research on test well simulation technology started from 1950s and the first full-scale simulator for drilling and producing was developed in 1970s. Since 1990s, the U.S. Schlumberger, Terra Tek, Technische Universität Clausthal, Japan's MITI Resources Research Institution and Russian Research Institution of Drilling Technology developed different simulators for drilling and producing in various sizes and functions. The main design parameters of simulation test well in different research unit are shown in Table (1). The establishment of simulation test platform has shortened the development cycle of new drilling technology and tools and played a significant role in promoting the updating of basic drilling theory and
engineering technology. The overseas research and development of simulation test well can be divided into three phases:

| Unit | Parameters | Well depth (m) | Overburden pressure stress (MPa) | Lithostatic stress (MPa) | Pore pressure (MPa) | Bottom fluid pressure (MPa) | Simulated temperature (°C) |
|------|------------|----------------|-------------------------------|-------------------------|-------------------|---------------------------|----------------------------|
| Terra Tek Drilling Laboratory | 9,000 | 207 | 138 | 27.6 | 103.5 | Atmospheric temperature |
| Schlumberger SCR Research Center | 5,000 | 1379 | 103.5 | 69 | 69 | 200 |
| Japan's MITI Resources Research Institution | 5,000 | 135 | 100 | 50 | 50 | 150 |
| Japanese National Oil Corp (JNOC) Research Institution of Technology Development | 5,000 | 119.8 | 100 | 70 | 68 | 200 |
| Russian Research Institution of Drilling Technology | 20,000 | 500 | 350 | 400 | 500 | 400 |

(1) Phase I (1956-1970): development phase of micro-drilling test.
Micro-drilling test is a testing method for micro drill bit, mainly applied to study the interaction effect between drilling parameters as well as working mechanism of rock breaker. In 1956, Ekei conducted drilling test on rock under different pressure with a small drilling machine to study the influence of pressure on drilling rate and drilling resistance of rock as well as working mechanism of rock breaker. In the same year, Cunninghom and his partners also conducted micro-drilling test to study the influence of formation pressure and bottom hole pressure on drilling rate. In the following two decades, many scholars studied the relationship between drill bit parameters and rock breaking by micro-drilling test. Although micro-drilling test provided simple and effective approaches for studying working mechanism of rock breaker, it is generally considered that the test has a certain restrictions on field applications, its down hole simulation environment (temperature and pressure) is different to practical environment, which created conditions for the development of full-scale simulator for drilling and producing.

(2) Phase II (1970-2000): development phase of full-scale test simulation well
Because of shortcomings of micro-drilling test, scientific and technological workers tried to find more real and effective test simulation means. In the middle and later periods of 1970s, the U.S. Terra Tek Company developed the first full-scale simulator for drilling in the works, as shown in Fig. 1, this simulator is mainly composed of well bore simulation device, circulation system, down hole tool testing system, hoisting system, etc. This success provided new train of thought for the study of drilling theory and technology. Later, the University of Tulsa established a full-scale simulation well bore with variable inclination in 1979, mainly used for test research on bore hole cleaning and artificial lift. In 1992, the U.S. Schlumberger established a full-scale simulator for drilling and producing in the Cambridge Research Center, which realized the drilling in a 10 m long core. Japanese oil company established a full-scale simulator with the well bore and rock pattern replaceable. The U.S. Texaco Company established a full-scale high-temperature and high-pressure multi-functional test well, to simulate the multi-phase flow exploration of oil and gas by taking real oil and natural gas as the test medium. The University of the State of Louisiana established a well-control simulation test well to
simulate the on-shore and off-shore well control test. The full-scale simulator of Russia\[^{[16]}\] is a set of testing platform which can simulate the rock properties under 20,000 m deep into the well and real high temperature and high pressure environment of formation, with the main features of realizing the mechanical enclosure. In order to fit the development of off-shore oil and gas fields, University of Rio de Janeiro\[^{[17]}\] developed an oceanic deep water simulator, provided with the maximum water pressure of 10 MPa and the maximum simulated water depth of 1,000 m. According to the self-requirements, oil companies have established unique full-scale testing platforms in succession, realized the transition from small scale to full scale, from single performance test to multiple performance test and from straight well to variable inclination simulation well.

(3) Phase III (1990 till now): further application of testing platform

In the first two phases, the main purpose of establishing simulator for drilling and producing is to study the basic theory of drilling and production, provide intermediate simulator for research and development of drilling and producing technology and tools, so as to solve practical problems. Making science and technology researches with test simulator and transferring the scientific research achievements to practical productivity has become the new development stage. Over the past three decades, Terra Tek Laboratory\[^{[18-19]}\] played a positive role in drilling technology development, drill bit design and drilling fluid performance optimization. The testing platform of the University of Tulsa\[^{[20]}\] made breakthrough progress in aspects of large displacement, rock debris removing mechanism in high-inclination well and bore hole cleaning optimization. The full-scale simulators\[^{[21, 22]}\] of Japan oil company and Russia have a certain guiding significance in oil and gas exploitation in deep well, high temperature and high pressure wells.

2.3. Domestic Development Status

Compared to overseas development, the domestic development of full-scale simulator for drilling and producing started a little later. The research on micro-drilling test was started since 1970s, and full-scale simulator development began to take shape in early 1980s. From 1990s till now, the development of domestic test simulator is the most vigorous. In this stage, the Beijing Petroleum Exploration and Production Research Institute, Daqing Oilfield, Dagang Oilfield and CNOOC research institute took turns to establish their unique simulators according to self-characteristics. The domestic test simulation started relatively late, but develops fast. In conclusion, the domestic development of simulator can be divided into following three phases:

(1) Phase I (1970-1980): development of micro-drilling test

With the support of the original Ministry of Petroleum Industry, Southwest Petroleum University\[^{[23-25]}\] established a laboratory for drill bit research. Through years of hard work, an advanced integrated
system has taken shape in terms of basic working theory, design analysis technology and test technology of oil and gas well drill bit. The achievement has been put into successful application in many domestic important bit manufacturers like Chengdu General Petroleum Machinery Factory of Sichuan Petroleum Administration Bureau and Jianghan Petroleum Drill Co., Ltd., making great contributions to the technical progress of China petroleum drill bit and drilling engineering.

(2) Phase II (1980-1990): preliminary development phase of full-scale simulation well

In the following 10 years, domestic scientific research institutes and colleges like Shengli Oilfield, Sichuan Authority of Petroleum and Zhongyuan Oilfield[26-30] developed the full-scale simulator based on the original drilling machine by learning from foreign countries. In that period, the simulator is simple with single function. For example, the full-scale simulator developed by the Sichuan Authority of Petroleum based on the original drilling machine in 1987 is about 1,000 m deep, with the simulated pressure gradient of 0.0196 MPa/m. It is possible to fill compressed air into the well. This simulation well has made great contribution to the well control technology training and "Seventh Five-Year Plan" science and technology key project. Later, Zhongyuan Oilfield developed four full-scale simulation test wells including straight well, directional well, gas storage well and instrument shallow well based on the original drilling machine in 1988, which provided necessary research means for research and development of various oil production technology and down hole tools.

(3) Phase III (1990 till now): fast development phase of full-scale simulation test well

In this period, the domestic development of testing platform was the most active. The PetroChina Exploration & Development Research Institute[30] established the first testing platform (ZM-35) able to simulate the pressure environment of 3,500 m deep in well, laid foundation for the development of real wellbore simulation. In 1994, Daqing Oilfield[31-35] developed a testing platform which can simulate the pressure environment of 6,000 m deep in well, which was rated as one of the ten great technologies of China National Petroleum Corporation in the year of 1995. With strong comprehensive functions, it is a large mechanics-electronics-hydraulic integrated test device for comprehensive simulation, able to simulate down hole working conditions of drilling tools and test dynamic parameters of drilling. It is of unique characteristics in vibration simulation and dynamic test and reaches advanced level in general terms. However, the simulator cannot simulate the down hole temperature and cannot realize the real simulation of high-temperature, high-pressure deep well. In order to improve the drilling and production process level, Dagang Oilfield[35-39] established a full-scale simulation test well for drilling and producing in 2009, which was the most advanced in that time and the first one for test of drilling and producing tools in vertical and horizontal wells in China. It can simulate the temperature and pressure environment of 20MPa and 180℃ respectively in vertical section and pressure environment at maximum of 20 MPa in horizontal section. But for technical limits, temperature rise can be realized in part of horizontal section, instead of whole section. Moreover, the bottom hole resistance torque simulator is developed to make the simulation of dynamic resistance torque possible, making the simulated working conditions much more practical. To adapt to the deep water oil and gas exploration, China University of Petroleum developed the first deep water petroleum engineering simulator in China with China National Offshore Oil Cooperation Research Institutes at the end of 2010. This simulator is capable to provide the working pressure of 35 MPa and simulate the water depth of 3,500 m. It provided a sound simulation test platform for our "Eleventh Five-Year Plan" deep water oil and gas major special research and its achievement obtained good effect in the deep water oil and gas exploration in South China Sea. To study the pressure control drilling technology and equipment, CNPC Drilling Research Institute developed a full-scale pressure control drilling test detector in 2012, which has passed over 1,000 times of field failure-free safe operation and able to simulate the working conditions of proper drilling, overflow and well kick.

2.4. Comparative Analysis on Research Status

Compared with development status of drilling and producing test platform abroad, it is not difficult to know that the current development level at home is relatively lower. The development of China test simulation well started late but fast, mainly represented in the following aspects:
Relevant research on test simulation well technology began relatively late in China. The research had been conceptualized in overseas countries since 1956, a full-scale simulator had been established in 1970s. While China started the micro-drilling test research in the beginning of 1970s. The overseas high-temperature, high-pressure test simulation well bore had been realized as early as 1970s, about 20 years earlier than China;

Foreign countries have established the simulator with the simulated well depth of 20,000 m, overburden pressure of 500 MPa and maximum temperature of 400 ℃. However, the deepest simulation well in China is the 6,000 m test simulation well of Daqing Oilfield, which cannot simulate the bottom temperature yet. In addition to some high-temperature simulators for special use, the simulated temperature of existing full-scale simulator cannot be higher than 180 ℃. It can be seen that the limited material performance and technology resulted in the lower simulation parameters of domestic test simulators and had hindered the progress of oil and gas exploration of high-temperature, high-pressure and extra-deep well in China;

Test simulation well had been applied abroad in a long time ago and remarkable achievement had been made in terms of drilling technology and theory. For example, the drilling and well completion test center of U.S. Terra Tek completed plenty of simulation tests in over 30 years and the test results played an active role in promotion of percussion drilling and deep-well drilling. But China still stays in the small-scale simulator for percussion drilling. In addition, the Terra Tek test platform has provided conditions for the researches on shale gas development technology and well wall stability, but nothing has been done in this field in China;

Domestic research on test simulation well started late but developed fast. Through a dozen years since mid-1970s to late 1980s, a full-scale simulator had been developed. But the simulator in initial period was simple with single function as most of them were developed upon original drilling machine, which limited the testing function of test simulation well. For example, the full-scale simulation test well of Sichuan Petroleum Administration is a 1,000 m-deep well control technology test well developed upon original drilling machine.

3. Key Technology of Drilling Test Platform

Establishing a drilling simulator involves many disciplines including drilling technology, computer control theory, instrument science and technology, sensor technology, mechanical design theory and structural mechanics, generally facing great developing difficulties and high technical contents. The development of well head loading device, simulation well bore technology and test monitoring system decides the development level of full-scale simulator.

3.1. Well Head Loading System

The loading system of simulation test well can not only simulate the functions and parameters of real drilling machine, but also simulate the strained condition of simulation test tool in the well. High pressure liquid test can be conducted while measuring the mechanical properties of tools including tensile force, stress and torque. According to the existing statistics, the current full-scale simulator lading system mainly includes original drilling rig derrick, simulated loading beam and multi-functional testing machine. Since most of the preliminary full-scale simulators were developed on the original drilling machine, the mechanical performance of the drilling machine was retained. The original full-scale simulator was large but stable, costing a lot to build and maintain. For example, the full-scale simulators of Zhongyuan Oilfield and the Sichuan Petroleum Administration. To overcome the shortcomings above on the premise of maintaining the original functions and mechanical properties, Daqing Petroleum Administration designed a simulation loading beam structure with three beams and four columns, which is composed of movable loading platform, movable unit platform, upgrading centralizer platform and four box-type vertical columns. Loading platform is driven by hydraulic cylinders on top and bottom to realize tensile force and stress loading. Turn plate on the unit platform is driven by motor to provide torque for system. Simulation loading beam costs less and easy to be maintained, but it can move only in vertical direction, cannot be used in horizontal section. For the
above-mentioned reasons, Dagang Oilfield designed the multi-functional simulator loading system based on self-requirements by learning from the domestic existing simulators. The multi-functional simulator is mainly composed of traveling positioning mechanism and executing mechanism. In the meanwhile of drawing the multi-functional simulator to slide on the rail, the traveling positioning mechanism driven by the motor can make the test rack incline by 0~90° to realize well head positioning. The executing mechanism is mainly made of portal, main beam, bi-directional power swivel and main hydraulic cylinder. Under the hydraulic pressure of the bi-directional hydraulic cylinder, the portal provides tensile and compressive load for tools, with the maximum lifting displacement of 1.5 m and the maximum tensile load and compressive load of 100 t. The bi-directional power swivel driven by hydraulic motor rotates and twists with the maximum torque load of 7.2kN·m. In the future, the loading system will be more reliable and flexible and easier to be maintained.

3.2. Well Bore Simulation Technology

Well bore simulation technology is developed for the well bore of oil and gas well. Well bore is an important medium between ground and oil and gas reservoir, playing a significant role in practical oil drilling and exploration. So it is also main part of test well. Its degree of simulation directly decides the test effect of simulator. At present, the most commonly used simulation well bore has the following 6 functions, mainly including mechanical property test of tool, instrument calibration and inspection, multi-phase flow kinetic characteristics research for well bore, mechanism research for down hole complex accidents, high-temperature, high pressure characteristic study and interaction mechanism study for formation and bore hole. The development of tool mechanical property test is the most mature. Almost all simulators of scientific research institutions at home and abroad have this function, to study the dynamic property and ultimate state of various drilling tools under tensile and compression torque and hydraulic pressure. This function made it possible to test in various wells. It greatly reduced the research cost and test risks. Instrument calibration and inspection function is applied to calibrate and check the working parameter of downhole instruments. For example, the down hole production well test instrument calibration simulator of Atlas Company and Changqing Oilfield. The multi-phase flow kinetic characteristic research is carried out to study the complex law of motion of interaction between solid, liquid and gas during drilling. For example, the simulation well bore with variable inclination established by the University of Tulsa made great contribution to the research on motion law of rock debris in greatly-displaced wells; The mechanism research for down hole complex accidents can simulate the down hole complex accidents like overflow, leak, blowout and jamming, having important reference value for studying trigger mechanism of down hole accidents and countermeasures. For example, the full-scale simulator for pressure control drilling established by CNPC Research Institute of Engineering Technology for study of pressure control drilling technology and equipment test, which can simulate pump starting, tripping, making connection, overflow, leak and well kick. The high-temperature, high pressure characteristic study is a simulation scheme put forward for drilling work in high-temperature and high-pressure formation, which promoted the development of high-temperature and high-pressure deep wells. For example, the simulator of Japan oil company, which can simulate the bottom environment at the temperature of 200°C; The interaction mechanism study for formation and bore hole is the hardest to achieve as it requires high similarity of well bore and formation for the convenience of studying the oil and gas leakage mechanism in formation. Controllability of working parameters of simulation well bore promoted the scientific and quantitative research on drilling technology. In the future, people will set higher requirements on the properties of simulation well bore for the development of special drilling technology, deep-water drilling technology and frozen earth oil and gas production technology and indoor research on combustible ice production.

3.3. Research and Development of Test Monitoring System

Test monitoring system integrated with sensor technology, communication technology and computer technology is applied to test the physical quantity of measured objects and acquire corresponding data. In simulator, the test monitoring system can realize the sensor measurement of test signals of drilling
tools or technology, and also make a record, analysis, process and display the results. Testing requirements of simulation well bore decides the monitoring parameters of test monitoring system. According to main parameter monitoring functions, the existing simulation well bores can be divided into drilling and producing test mechanics parameter monitoring, fluid motion state parameter monitoring, high temperature and high pressure characteristics parameter monitoring and down hole complex working conditions dynamic visualization monitoring. The four types of parameter dynamic monitoring above provided necessary conditions for quantitative analysis of drilling and production process.

To sum up, the main purpose of establishing a simulator is to analyze and process the test results. Therefore, test monitoring system plays an important role in simulator. But the shortcomings including long axial distance of test bore hole, short transverse distance and bad down hole environment bring great difficulties for the design and installation of measurement system. In addition, limitation of the test precision, long-term stability and signal transmission capacity of sensor greatly restricts the development of simulator. Actually, it is crucial to develop a high-precision signal sensor and scientific design and installation technology.

4. Development Trend of Full-Scale Simulator for Drilling and Producing

In the over 20 years of application research, the full-scale simulator for drilling and producing kept being improved and perfected. In the future, it is expected to make great progress in tackling key problems in the following aspects:

1. Apply high-precision sensor and allocate measuring point positions in a scientific and effective way to simplify the down hole line structure, deepen the weak signal testing and research of processing technology, further broaden the measurement range of test parameters;

2. Optimize the well structure of simulation well bore, improve the vraisemblance of simulation well bore, especially the simulation in high-temperature, high-pressure soft shale formation. In addition, deepen the research of formation dynamic simulation of simulation well bore to make the theoretical research on drilling and producing in complicated geological conditions much easier;

3. Optimize the structure of simulator well head loading system, further improve the stability and flexibility of system to better adapt to the tool test and technology test;

4. Strengthen the effort of research on simulators for drilling and producing of marine oil and gas as well as unconventional oil and gas, develop a suitable simulator to improve our core competitiveness.

In conclusion, the research, development and application of the full-scale simulator for drilling and producing has made great progress, but still needs to be perfected. The technical difficulties in special process drilling, offshore deep water oil and gas exploration as well as exploration of shale gas, combustible ice and unconventional oil and gas provide favorable change and developing space for establishment of simulator. With application research of the full-scale simulator for drilling and producing going on, the result will gradually translate into practical productivity and become an important method for the future research on petroleum engineering.

5. Conclusions

The research and development of full-scale simulator for drilling and producing has high technology content, deserving high investment and high return. Its development represents the comprehensive capacity of a country in petroleum industry, playing a crucial role in popularizing new theory, new technology and new tools. Compared with the international full-scale simulators for drilling and producing, we still fall far behind in this aspect. How to establish a suitable simulator according to the difficulties in exploration technology development is a big problem in the future. To accelerate the domestic development of simulator, it is required to strengthen the efforts in simulator research and talents cultivation, summarize and accumulate experience to establish a "multi-functional, all-aspect and multi-dimensional" simulator which will provide effective method for the research of oil and gas exploration.
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