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Research Progress and Prospects of Intelligent Well Completion Technology

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Abstract

Intelligent well completion technology, as a key means to enhance the efficiency of oil and gas field development, has evolved from its early exploratory phase into a mainstream solution encompassing three major technical types: hydraulic control, electric control, and electro-hydraulic composite control. The core of this technological system lies in the integration of key elements such as downhole monitoring, downhole control, data transmission, and the surface control center. Through its large-scale application in numerous oil fields worldwide, it has significantly improved oil and gas recovery rates and extraction efficiency. In recent years, research has focused on improving the system's long-term operational stability, control precision, and the integration of data acquisition systems. However, the field still faces key challenges, including the long-term reliability of hydraulic systems, bottlenecks in electric flow control technology, and optimization of complex electro-hydraulic composite control systems. This review aims to systematically outline the development trajectory of intelligent well completion technology from its initial exploration to the current multi-type approach, analyze its application outcomes and frontier trends, and deeply examine the practical challenges it faces, with the goal of providing industry decision-makers with a comprehensive technical evolution map, clarifying future development trends, and identifying potential technological breakthroughs.

Keywords

Intelligent Well Completion Technology; Hydraulic-Controlled Intelligent Well Completion; Electric-Controlled Intelligent Well Completion; Electro-Hydraulic Composite Intelligent Well Completion; Current Status of Technology.

1. Introduction

As oil and gas development extends into deeper formations and offshore fields, the application of horizontal and multilateral wells has increased, leading to higher extraction challenges. Key issues include high-cost, high-risk operations in deep wells, inter-layer interference in complex wells, and a lack of efficient control measures. Intelligent well completion (IWC) systems, integrating real-time monitoring and control, are crucial for optimizing efficiency and enhancing recovery. These systems are available in hydraulic, electric, and electro-hydraulic drive modes, with hydraulic systems dominant offshore. After 30 years of innovation, foreign IWC technologies are mature, with major companies like Baker Hughes and Weatherford deploying advanced systems. This paper compares foreign and domestic IWC technologies, identifying key advantages for integration into domestic systems and addressing current research bottlenecks.

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2. The Research Progress of Fully Electric-Controlled Intelligent Well Completion Technology

Fully electric-controlled intelligent well completion technology is a comprehensive integrated system that combines cutting-edge technologies from multiple fields, including downhole electric power disconnectors, electric-controlled flow control valves, data transmission systems, and surface control systems. Internationally, this technology has been successfully applied for nearly 20 years, resulting in significant economic and social benefits[1]. However, in China, fully electric-controlled intelligent well completion technology is still in its early stages. There is a need to learn from the mature experiences abroad, particularly the advanced achievements in key technologies by companies such as Baker Hughes and Schlumberger.

Domestic researchers are actively engaged in exploration and development, aiming to gain a deeper understanding of the operating principles and characteristics of fully electric-controlled intelligent well completion technology[2]. They are also working to overcome the technical challenges encountered in the development of downhole wireless electric power disconnectors and electric-controlled flow control valves. By thoroughly analyzing the technologies of leading international companies, valuable insights can be provided to support the development of this field in China, identifying the necessary conditions for successful R&D and the critical issues that need to be addressed, thereby promoting the advancement of domestic fully electric-controlled intelligent well completion technology to a higher level.

2.1. Analysis of Key Technologies for Fully Electric-Controlled Intelligent Well Completion Abroad

2.1.1. InCharge™ Fully Electric-Controlled Intelligent Well Completion Technology

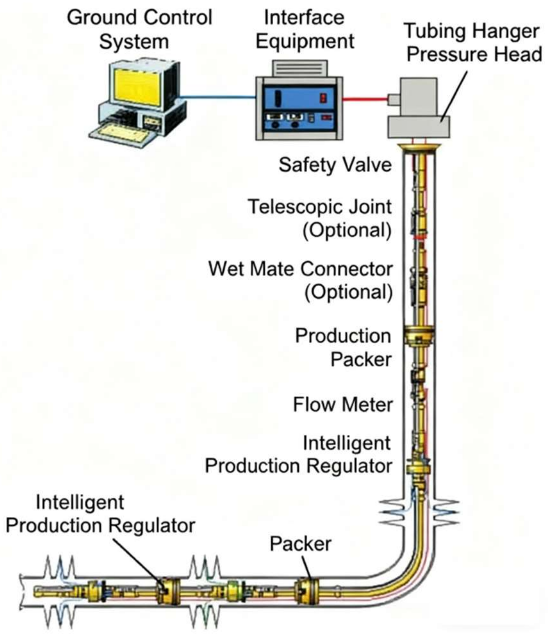

Fig. 1 Schematic Diagram of the InCharge™ Fully Electric-Controlled Intelligent Completion String

Baker Hughes' InCharge™ technology is the world's first fully electric-controlled intelligent well completion system, specifically designed for 244.48 mm casing, with the goal of achieving complete electrification and remote control of oil well production. The core component of the system is the downhole Intelligent Production Regulator (IPR), which is equipped with an integrated motor and sensors, enabling continuous flow regulation and real-time monitoring of critical parameters such as pressure, temperature, and flow rate[3]. The InCharge™ system is

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suitable for various well types and complex environments, and all control and data transmission are carried out through a single 6.35 mm TEC cable, greatly simplifying the installation process. Additionally, the system allows for individual addressing and precise adjustment for each layer, optimizing the production process and significantly improving reservoir management efficiency.

The InCharge™ Intelligent Oilfield System consists of a surface control unit and downhole fluid regulation devices, offering significant zonal control capabilities. The horizontal well section can be independently addressed up to 12 zones, while vertical control extends to a depth of up to 12 layers. The Intelligent Production Regulator is the key downhole component of the system, designed with an eccentric structure. Each regulator is equipped with a motor-driven choke valve capable of delivering a driving torque of up to 4536 kg, making it suitable for complex downhole environments. The independent addressing function of the regulator allows each unit to precisely control the production of any target zone within the designated well, based on specific commands[4].

2.1.2. Intelligent ICV (Inflow Control Valve) Technology

The Intelligent ICV (Inflow Control Valve) is an advanced downhole control device, designed with an eccentric structure and composed of an electric-controlled ICV and an in-well information monitoring system. The electric-controlled ICV utilizes a micro motor to drive a sliding sleeve, enabling continuous adjustment of the choke opening from 0% to 100%, with an accuracy of up to 1%. The in-well information monitoring system is equipped with high-precision pressure and temperature sensors, which are installed at key positions in the Venturi tube. These sensors calculate the fluid volumetric flow rate based on Bernoulli's equation. Additionally, capacitive sensors measure water cut using the Bruggeman model, while displacement sensors ensure precise control of the valve opening.

The Intelligent ICV transmits production and diagnostic data to the surface through a 6.35 mm multi-core cable. This design reduces the number of downhole pipelines and connection points, simplifying the installation process and enhancing system reliability. This integrated technology not only improves the precision of downhole control but also reduces the need for manual intervention, enhancing both the efficiency and safety of the entire oilfield development process[5].

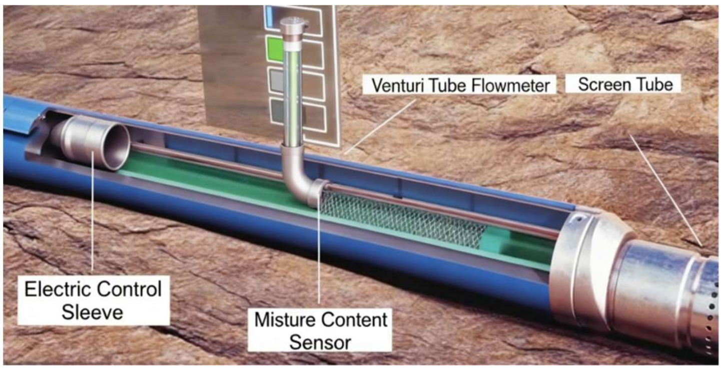

Fig. 2 Schematic Diagram of the Intelligent ICV Structure

3. Research Progress on Hydraulic-Controlled Intelligent Completion Technology

Hydraulic-controlled intelligent completion technology began to develop in the mid-1990s. In 1994, Norway's Saga Petroleum Company first implemented it in the Snorre field, marking a pioneering attempt for this technology. Since the turn of the 21st century, the technology has advanced rapidly. Major international oilfield service companies such as Schlumberger and

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Baker Hughes have continuously optimized system performance, launching the TRFC-II and Hydraulic DV systems, which use hydraulic pulse technology to simplify pipeline design. Well Dynamics has stood out in the industry with its Smart Well and MultiBore systems, which integrate multiple hydraulic control valves in a single completion string, enabling independent and precise control of multiple reservoir zones.

3.1. Current Development and Technical Analysis of Hydraulic-Controlled Intelligent Completion Technology Abroad

Compared to traditional completion methods, foreign intelligent completion technologies have significantly improved the production capacity of single wells, with production increases typically ranging from 20% to 300%. Additionally, these technologies can stabilize the liquid production water cut in the wellbore to below 10%. The application of this technology has not only multiplied the net present value (NPV) of projects but also increased crude oil recovery by more than 10 percentage points. It has helped avoid costly well intervention measures, effectively mitigated the risk of reservoir water breakthrough, and achieved the goal of efficient development and production optimization[6].

Currently, intelligent completion technology is mainly divided into two categories: hydraulic control and fully electric control. Hydraulic-controlled intelligent completion technology relies on downhole hydraulic control devices, with a basic structure typically consisting of at least two 6.35 mm diameter hydraulic control lines and an optical or electrical cable, capable of controlling up to 12 independent production zones. On the international market, leading companies such as Schlumberger and Halliburton have developed various hydraulic-controlled intelligent completion systems, including direct hydraulic drive, numerical control hydraulic drive, and electro-hydraulic hybrid drive solutions. Each of these technologies has its own advantages, meeting the needs of various completion applications.

3.1.1. N+1 Type Direct Hydraulic System

The N+1 Type Direct Hydraulic Control System developed by Halliburton is an early hydraulic-controlled intelligent completion technology solution, specifically designed to regulate three independent production zones or branches in oil and gas wells. The core components of the system include a surface hydraulic pump station, pressure regulating devices, hydraulic control line bundles, pipeline connection assemblies, and downhole flow control valves. Its operational logic is based on the "N+1" strategy, which uses N+1 hydraulic control lines to precisely regulate N Independent Control Valves (ICVs). The system establishes a drive path through three hydraulic lines to directly drive the two target ICV actuators point-to-point, with the topology shown in Figure 9. This design provides an efficient and direct control method for intelligent completion technology[7].

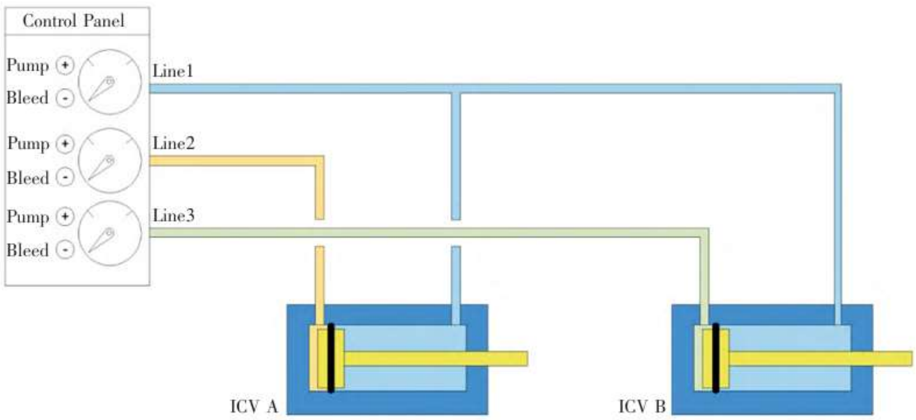

Fig. 3 Schematic Diagram of the Topology of the Direct Hydraulic Control System

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3.1.2. Digital Hydraulic Control System

The Digital Hydraulic Control System is a multi-node collaborative control system based on fully hydraulic pulse encoding technology. Its core components include a surface hydraulic power unit, pressure modulation devices, hydraulic signal transmission pipelines, joint connection hydraulic control lines, downhole intelligent flow control valves, and associated hydraulic decoding units. The system encodes control commands into hydraulic pulse signals in a specific format and transmits them to the downhole, where the hydraulic decoding unit receives and decodes them. Upon recognizing the preset commands, the decoding unit drives the corresponding target ICV actuators. Each ICV is equipped with a dedicated decoder with a unique address, and according to the address-matching principle, it will only respond when the hydraulic pulse signal matches its specific address. The system uses three hydraulic control lines to independently address and control up to six downhole ICVs, and it can operate stably in extreme high-temperature environments of up to 180°C. This demonstrates its excellent control performance and environmental adaptability in intelligent completion applications[8].

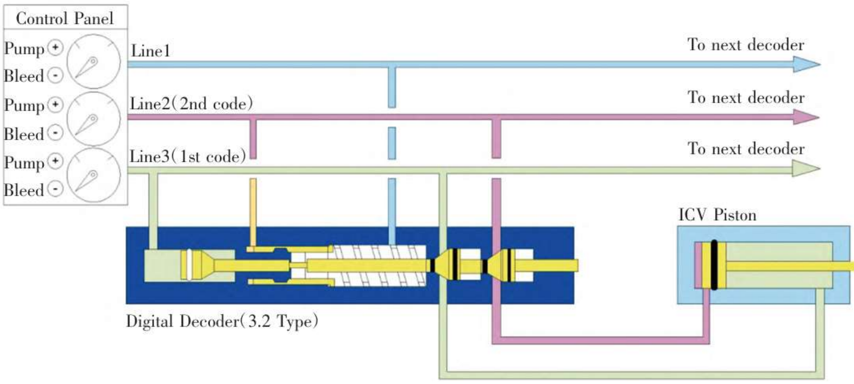

Fig. 4 Schematic Diagram of the Topology of the Digital Hydraulic Control System

4. Research Progress in Electro-Hydraulic Composite Intelligent Completion Technology

4.1. Analysis of Key Technologies in Electric-Hydraulic Intelligent Completion Abroad

The electro-hydraulic drive control system integrates an electronic control module to achieve millisecond-level rapid response. The surface control equipment uses composite pipelines to simultaneously transmit high-precision electrical command signals and high-pressure hydraulic power to the downhole, precisely driving the electro-hydraulic actuators to adjust the opening of the intelligent flow control valve. This enables dynamic regulation of the fluid volume in the oil field reservoir. This technology overcomes the traditional hydraulic system's delay bottleneck of 2–5 minutes, reducing the response time for single valve operation to ≤8 seconds, thereby providing key technological support for real-time water control in high-water-cut reservoirs[9-11].

4.1.1. Multiple-Zone System

The Multiple-Zone system is an advanced electro-hydraulic composite control valve intelligent well completion system. It achieves precise flow control and remote management of different reservoir zones in oil and gas wells through various sensors and equipment integrated underground. The system includes downhole flow control valves that adjust the flow rate according to production needs. Sensors monitor critical data such as downhole temperature, pressure, and flow rate. The data transmission system is responsible for sending this information back to the surface, where the central control system processes it, allowing

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operators to remotely control and make decisions, thereby optimizing reservoir production and management. The system adopts a modular design for easy installation, maintenance, and upgrades, and combines the advantages of both electric and hydraulic drives to enhance system reliability and flexibility[12].

4.1.2. Weatherford's Fiber Optic Technology

Optical Fiber Monitoring Technology provides comprehensive real-time data, surpassing the limitations of traditional single-point monitoring. As temperature changes, the laser pulse in the optical fiber undergoes backward scattering, accurately revealing the downhole temperature and depth distribution. Weatherford's downhole optical fiber sensors achieve continuous temperature monitoring along the entire well at intervals of every 0.5 meters[13-14]. This technology significantly outperforms traditional electronic sensors in terms of temperature resistance, corrosion resistance, and electromagnetic interference resistance, ensuring the reliability of the monitoring system.By combining optical fiber sensor technology with electric-hydraulic control systems, Weatherford has achieved a full well three-dimensional real-time monitoring system, enabling faster and more precise adjustments for multi-reservoir exploitation downhole.

4.1.3. Analysis of Key Technologies in Domestic Electric-Hydraulic Controlled Intelligent Well Completion

Research on domestic intelligent well completion systems is showing a positive development trend, especially in the context of oilfield development gradually shifting towards deeper and more complex reservoirs. The importance of intelligent well completion technology is becoming increasingly evident. Many researchers and engineers in China are focused on developing systems with independent intellectual property rights to improve production efficiency, reduce operational costs, and achieve refined oil and gas well management.

The IC-Riped electro-hydraulic integrated intelligent well completion system developed by the China Petroleum Group Science and Technology Research Institute has been successfully applied in several domestic oilfields. This system combines the fast response characteristics of electric control with the high reliability of hydraulic drive, enabling precise control of the 7-stage non-equal spacing opening of the hydraulic multi-stage flow control valve. The core components of the system can operate stably under extreme pressures of up to 70 MPa and temperatures as high as 150°C. By utilizing a dynamic model of hydraulic pipeline pressure loss and flow rate, the pressure prediction error is reduced to less than 3.5%, providing theoretical and technical support for precise closed-loop control of downhole valve positions.

Domestic research on intelligent well completion technology has formed an interdisciplinary integrated system that includes high-performance downhole tools, full lifecycle data chains, and cloud-based collaborative decision-making systems. This system not only improves the efficiency of oil and gas extraction and operational safety but also effectively reduces the energy consumption of ineffective injection and production by 41%, significantly lowers water resource consumption and carbon emission intensity, and promotes the transition of unconventional oil and gas resources toward a green and sustainable development model.

Although domestic progress has been made in the field of intelligent well completion technology, there is still a gap compared to international advanced levels. In the future, research needs to achieve further breakthroughs in technological maturity, system integration capabilities, and practical application effects to drive comprehensive technological advancement and rapid industrial development. With the continued evolution of digitalization and automation technologies, electro-hydraulic composite intelligent well completion technology is expected to play an increasingly important role in the future development of the oil and gas industry.

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5. Summary

(1) Research indicates that current electric-driven flow control technologies still heavily rely on the ground control system for motor drive and data acquisition. To promote the engineering application and intelligent upgrade of this technology, three critical systems must be addressed simultaneously: the real-time multi-parameter downhole data acquisition and encoding transmission system, the dynamic monitoring and feedback system, and the simulation test equipment for high temperature and high-pressure environments. These systems need to be developed in coordination, as they are key prerequisites for the practical implementation of the technology.

(2) The hydraulic-controlled intelligent well completion system is a multidisciplinary system engineering project that requires the integration of standardized technical equipment, real-time monitoring and data analysis, communication control, technological innovation, integration platform management, pilot testing and validation, as well as comprehensive technical specifications and processes. This approach ensures efficient coordination among subsystems and guarantees the high efficiency and reliability of the overall system.

(3) As oil and gas exploration and development advance into deeper and more complex formations, high-temperature and high-pressure environments have become the norm. Currently, the domestic electric-hydraulic composite intelligent well completion equipment used under high-temperature and high-pressure conditions is not yet mature. There is a need for enhanced innovation and breakthroughs in areas such as basic materials, data transmission, energy supply, and corrosion resistance technologies, in order to develop a new generation of intelligent well completion systems that are suitable for these harsh conditions.

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