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Research and Practice of Intelligent Separate Injection Technology in Shengli Oilfield

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Abstract: After years of technical optimization and iteration, Shengli Oilfield has developed cabled measurement and control separate injection technology. Downhole intelligent water distributors collect data such as zonal flow rate, temperature, and pressure, which are transmitted to the surface via cables. After analysis and judgment by staff, remote control commands are sent to adjust the intelligent water distributors until the injection allocation requirements are met. Anchored measurement and control separate injection strings and small-diameter measurement and control separate injection strings have been formed to meet different reservoir and well condition types. The cabled measurement and control separate injection technology has been promoted and applied in more than 150 well times in Shengli Oilfield, with 4 injection-production coupling demonstration areas established. Applications such as real-time monitoring of production data, pressure build-up testing, and injection-production linkage regulation have been carried out. The average daily oil increase per well group is 1.8 tons, which reduces on-site testing and deployment workload and improves deployment efficiency. The application of this technology is of great significance for the efficient development of water-flooded reservoirs and the construction of smart oilfields.

Keywords: Intelligent Separate Injection; Cabled Measurement and Control; Injection-production Coupling; Intelligent Oilfield.

1. Introduction

To meet the needs of complex reservoir development and improve water-flooding development effects, the separate injection technology in Shengli Oilfield has experienced three development stages: fixed type, movable type, and integrated measurement and regulation type. The supporting standardized separate water injection process strings and downhole tools have formed the third-generation separate water injection technology [1]. As the oilfield development enters the medium-high water cut stage, the reservoir dynamic changes are complex. The integrated measurement and regulation separate injection technology can only obtain data when the testing instrument is run into the well, and cannot realize real-time monitoring and regulation, which is difficult to meet the needs of precise development. To solve the limitations of the measurement and regulation separate water injection technology and further improve oilfield development efficiency, recovery factor, and intelligence level, Shengli Oilfield began to tackle the key problems of cabled measurement and control separate injection technology in 2014. Key tools such as integrated intelligent water distributors integrating flowmeters, pressure sensors, temperature sensors, and water nozzle adjustment mechanisms have been developed. Through real-time data transmission via cables and remote control from the surface, precise regulation of downhole separate water injection is realized [2-3].

2. Principle of Cabled Measurement and Control Separate Injection Technology

The cabled measurement and control separate injection system is mainly composed of downhole intelligent water distributors, cable communication systems, through-cable packers, and surface control centers. Its core goal is to realize real-time monitoring and remote regulation of downhole separate water injection through cables, as shown in Figure 1. The intelligent water distributor integrates flowmeters, pressure sensors, temperature sensors, and adjustable water nozzles, which can real-time monitor zonal water injection parameters and adjust zonal water injection rates. The through-cable packer is a specially designed downhole packing tool that can maintain the smoothness of the cable channel after setting. The cable communication system adopts armored single-core cables, which can realize high-speed data transmission between the surface and downhole water distributors.

Downhole injection allocation tools are run into the well with the string. The cable connects the intelligent water distributor, through-cable packer, and intelligent control assembly in sequence from outside the pipe. During the running-in process, the tool status must be monitored in real-time to ensure that the cable and the string are lowered synchronously to avoid cable winding or damage. After well completion, the intelligent water distributor real-time collects zonal flow rate, temperature, pressure, and other data, which are transmitted to the surface control cabinet via the cable through DC carrier communication for analysis, and then the data are transmitted to the safety production command center through wireless communication for technical personnel to obtain analysis results. According to the reservoir dynamic requirements (such as water absorption profile and injection-production ratio), the safety production command center sends remote control commands to adjust the water nozzle opening to optimize the injection allocation amount, forming a closed-loop management of "monitoring-optimization-execution".

As the core tool of the separate water injection system, the structure of the intelligent water distributor mainly includes a main control circuit module, a data acquisition module, a flow regulation module, and a power supply module. The main control module, as the "brain" of the water distributor, is

responsible for receiving commands, processing data, communicating and transmitting, and coordinating the operation of each module. It real-time compares the actual flow rate with the target value through a preset algorithm and drives the regulation module to adjust the water nozzle opening of multiple key components. The data acquisition module includes temperature and pressure sensors and a differential pressure flowmeter.

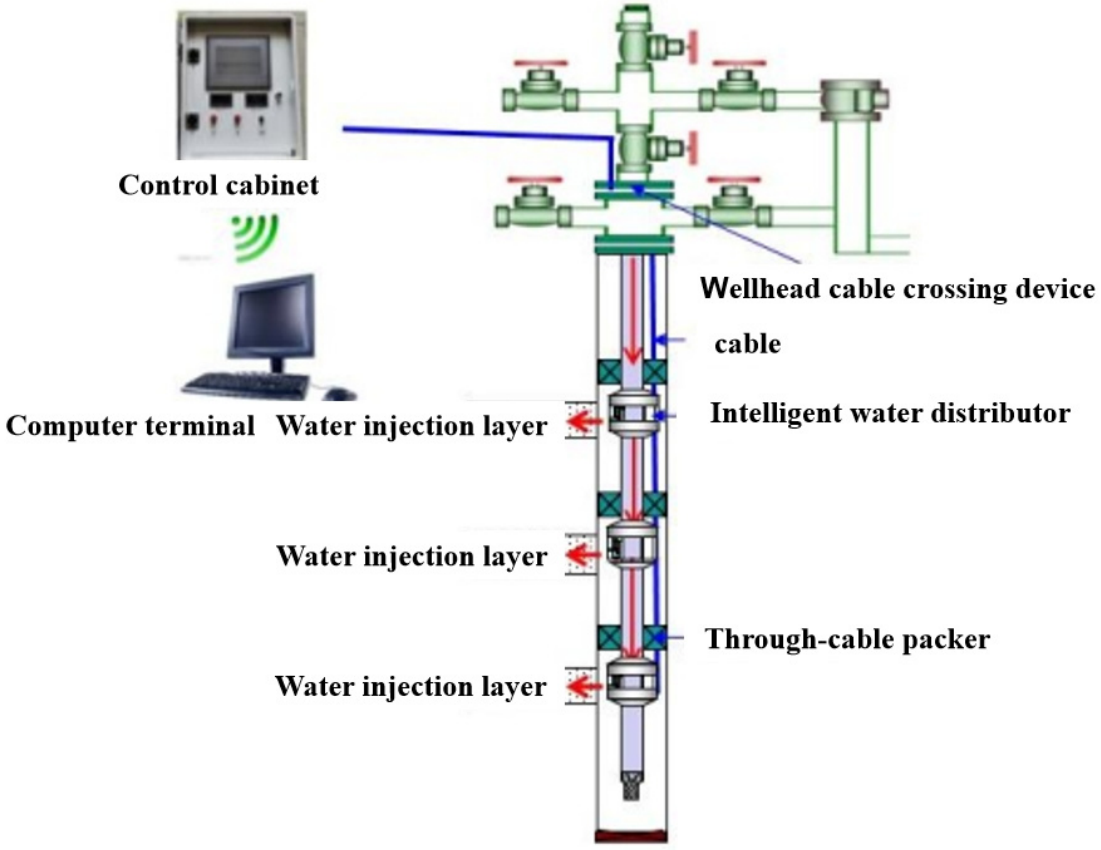


Fig 1. Schematic diagram of cabled measurement and control separate injection technology

The flow regulation module includes a DC gear motor, a lead screw, and a regulating valve, which adjusts the flow area by changing the spool position to achieve precise flow control. The power supply module includes a voltage stabilizing circuit and a high-temperature lithium battery, mainly used for 24VDC power supply. The core components of the intelligent water distributor are shown in Figure 2.

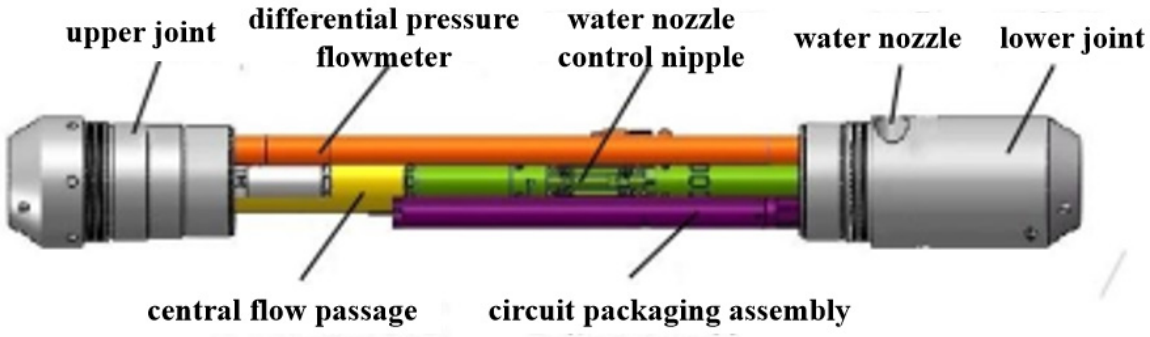


Fig 2. Cabled intelligent water distributor

3. Technical Optimization and Improvement

The development process of the cabled measurement and control separate injection technology in Shengli Oilfield can be divided into three important stages: technical research and test period, optimization and improvement application period, and mature promotion and improvement period. Through systematic research on core technologies such as data acquisition technology, zonal regulation methods, and standardized string design, the performance and reliability of the intelligent water distributor have been significantly improved, and finally, a measurement and control separate injection technology system with accurate data acquisition, flexible regulation, strong adaptability, and stable operation has been formed.

3.1. Research on Graded Flow Rate Accurate Measurement Technology

Comprehensively considering the fluid properties of water injection wells and the requirements for flow measurement accuracy, the adaptability analysis and evaluation of

commonly used downhole flowmeters were carried out. Combined with field tests, the differential pressure flowmeter was selected as the downhole measurement method. Its main advantages are low cost, simple structure, and strong applicability [4]. The measurement structure principle of the differential pressure flowmeter is shown in Figure 3.

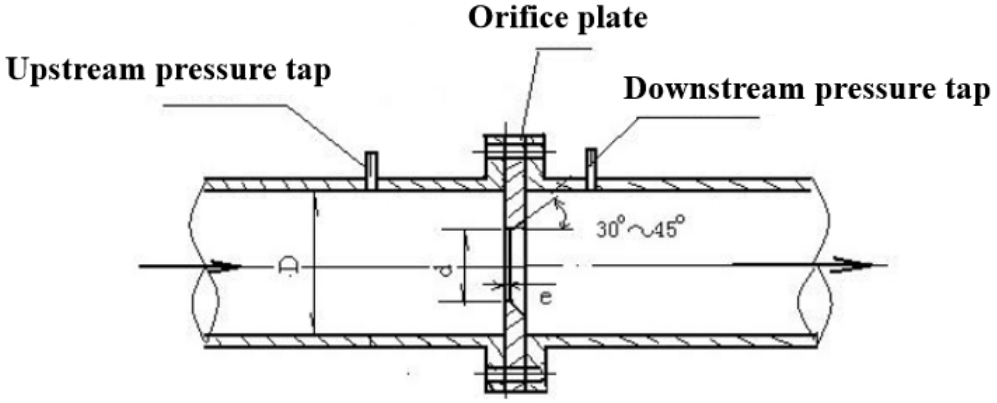


Fig 3. Measurement principle of differential pressure flowmeter

The measurement accuracy of the differential pressure flowmeter is proportional to the generated differential pressure. When the flow rate is small, if the orifice diameter is too large, the generated differential pressure will be too small, making it difficult to achieve accurate measurement. By reducing the orifice diameter, the flow velocity can be increased, and sufficient differential pressure can be obtained, thereby improving the resolution and accuracy of flow measurement. On the contrary, for large flow rate measurement, selecting an appropriately larger orifice diameter can avoid damage to the structure caused by excessive differential pressure. Therefore, it is necessary to optimize the orifice diameter for different downhole working conditions, determine the optimal orifice diameter under different working conditions, which can obtain the maximum differential pressure under the same flow rate, thereby improving the resolution and accuracy of flow measurement. According to the injection allocation range of separate injection wells in Shengli Oilfield, graded design is adopted. The orifice plate structure of the flowmeter was simulated and optimized in three flow rate ranges: 5-50m³/d, 15-150m³/d and 30-300m³/d, and the corresponding pressure loss values under different flow rates were obtained. The optimized orifice diameters for the three flow rate ranges are 5mm, 7.5mm, and 9.5mm respectively.

3.2. Research on Zonal Flow Rate Regulation Algorithm

In separate water injection production, the operating time of downhole moving parts (high-temperature motors, water nozzle adjustment mechanisms) is an important factor affecting their reliability and service life. In the early field applications, it was found that the flow control method often had problems of long adjustment time and large overshoot. To solve the above problems, Shengli Oilfield proposed a control algorithm based on the fusion of a separate water injection prediction model and a time threshold. This algorithm combines open-loop control of zonal flow rate and closed-loop control of single-layer flow rate, which greatly reduces the operating time of downhole moving parts and realizes precise, rapid, and long-term zonal flow rate regulation. The flow regulation algorithm is shown in Figure 4.

The algorithm is divided into two parts: rough flow regulation and fine flow regulation. After determining the target water injection flow rate, the water distributor opening is predicted by the zonal flow rate prediction model based on pipe string mechanics. The opening is directly adjusted to the predicted opening through rough flow regulation, which greatly shortens the motor operating time. After rough regulation, the current pressure before and after the water nozzle, injection flow rate, and wellhead pressure are detected by downhole pressure sensors and flowmeters, and the model parameters of the flow prediction model are updated in real-time. At the same time, automatic fine adjustment is performed based on the flow difference between the measured injection flow rate and the target injection allocation amount. On the basis of downhole closed-loop flow control, the closed-loop control based on the time threshold realizes zero overshoot in the adjustment process, improves the stability of flow control, and thus can greatly reduce the motor working time and invalid adjustment of the water nozzle.

3.3. Research on String Standardization

After many technical iterations and upgrades, Shengli Oilfield currently has two series of intelligent water distributors (95 and 114) and supporting downhole tools. Anchored measurement and control separate injection strings and small-diameter measurement and control separate injection strings have been developed, realizing technical coverage for separate injection wells with casing inner diameter ≥101.6mm, reservoir temperature ≤125℃, and injection pressure ≤35MPa. The string structure is shown in Figure 5.

The anchored compensation measurement and control separate injection string is mainly composed of through-cable compensators, drillable bidirectional tubing anchors, intelligent water distributors, through-cable drillable packers, well flushing valves, etc. The drillable bidirectional tubing anchor can fix the string, reduce string creep caused by working condition conversion and pressure fluctuation during water injection, maintain effective separate layer of packers, and extend the service life of the measurement and control string. It is suitable for conventional separate injection wells with casing inner diameter ≥121.36mm and well depth ≤2800m. The small-diameter measurement and control separate injection string is mainly used for small casing wells and offshore separate sand control and separate water injection wells. The offshore small-diameter measurement

and control separate injection string is mainly composed of through-cable packers, small-diameter intelligent water distributors, well flushing valves, and outer sand control tools. The outer sand control tools are supported by tubing anchors.

The measurement and control separate injection string is run into the sand control string, which can avoid the impact of sand production on the string.

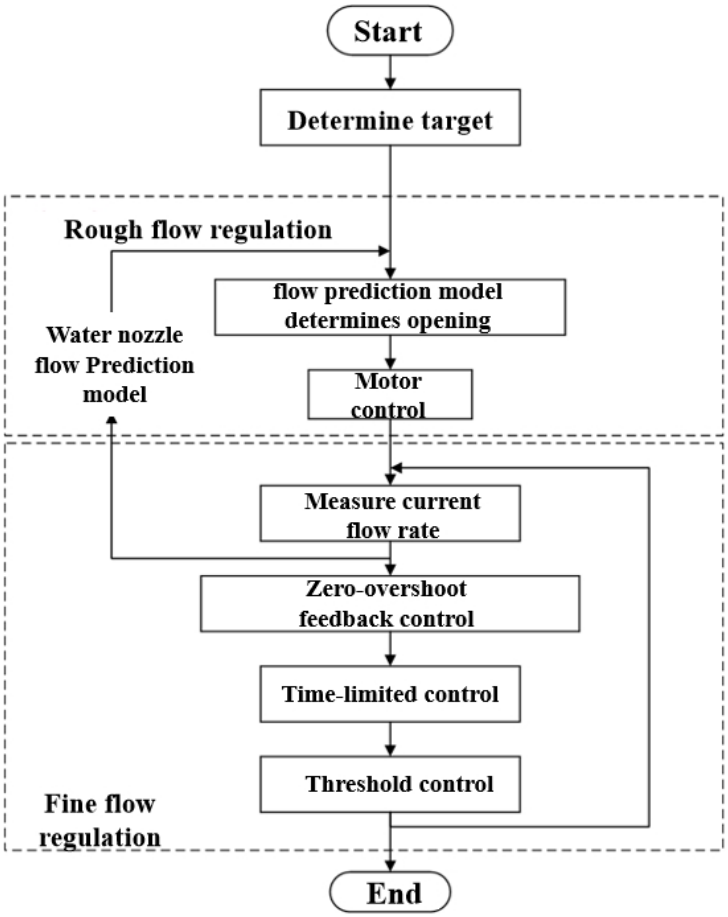


Fig 4. Flow chart of flow regulation algorithm

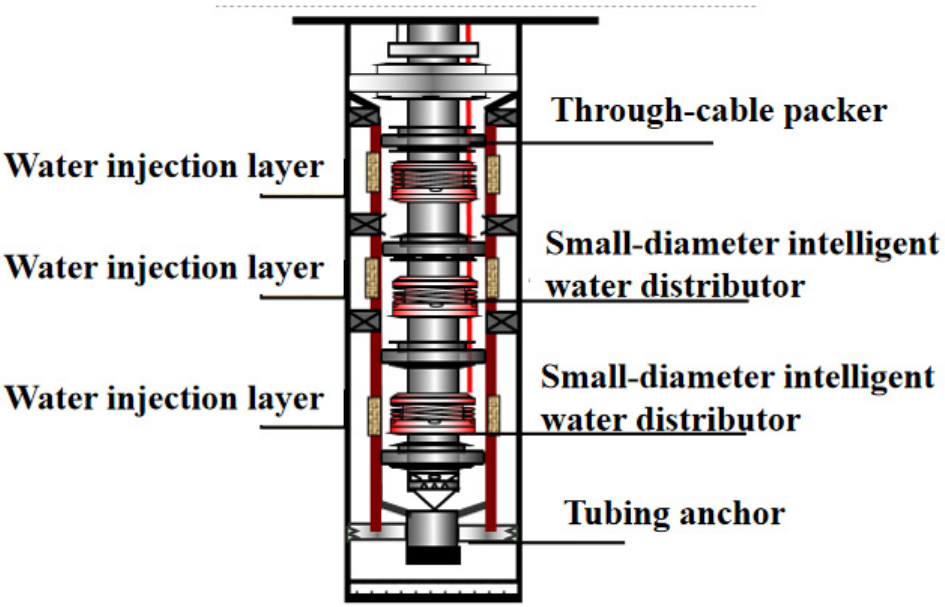


Fig 5. Standardized string structure diagram

4. Field Application and Effect Evaluation

The field practice of intelligent injection-production technology has gone through three stages: single well test, application in intelligent water injection demonstration areas, and construction of injection-production coupling demonstration areas. It has achieved the development from technical verification feasibility, reliability improvement to promotion demonstration. It has been applied in more than 150 well times in the field. Through the SCADA system, real-time monitoring and regulation of the injection situation of each downhole layer have been realized. The layer qualification rate is 89%, and the effective period is more than 3 years, which is higher than the average level of the oilfield.

4.1. Single Well Application Effect Evaluation

Taking advantage of external pressure data monitoring, zonal static pressure build-up tests were carried out to understand the zonal reservoir energy retention status and guide the optimization of injection allocation. The pressure detection data of Well 203 in a certain block are shown in Figure 6: the pressure of the first layer dropped from 25.42MPa to 14.39MPa and stabilized at 13.88MPa; the pressure of the second layer dropped from 25.89MPa to 14.58MPa and stabilized at 14.0MPa; the pressure of the third layer dropped from 26.1MPa to 14.97MPa and stabilized at 14.2MPa. The formation pressure decreased. By analyzing the test data, the zonal injection allocation was adjusted up to 10/10/10m³/day, which effectively supplemented the formation energy.

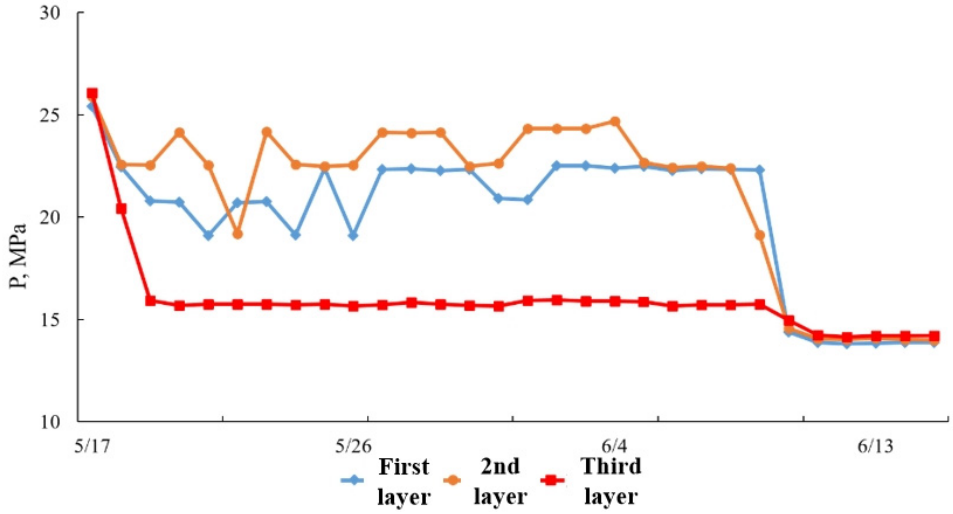


Fig 6. Static pressure build-up test curve

4.2. Injection-Production Coupling Regulation Experiment

Injection-production coupling regulation can combine the static data of the reservoir and the dynamic data tested by the downhole intelligent injection-production measurement and control system. Using scientific analysis methods, reasonable reservoir injection-production development policies are obtained to solve the plane and interlayer injection-production contradictions of water-flooded reservoirs and realize balanced displacement and vector injection-production [5-7]. A certain block has 11 oil wells and 7 water wells. In the early stage, integrated measurement and regulation separate injection for water wells and commingled production for oil wells were implemented. Streamline adjustment mainly relied on water well deployment + oil well parameter adjustment, which was difficult and inefficient. At present, it is in the stage of medium water cut, medium recovery degree, and low oil production rate. The overall injection-production coupling of intelligent injection-production technology is applied. Vertically, the energy supplement of low-permeability layers is strengthened to realize balanced interlayer production. Horizontally, the advancement of main streamlines is controlled, and the sweep of weak streamlines is expanded to realize balanced streamline distribution. 7 wells with intelligent separate injection and 10 wells with zonal oil production have been deployed. Since the implementation for 20 months, there have been 62 water well deployments and 19 oil well layer changes, with a cumulative oil increase of 4156t and a recovery factor increase of 0.7%.

5. Conclusion

With the advantages of improved data monitoring, efficient testing, and regulation, the intelligent separate water injection technology in Shengli Oilfield provides important technical support for the control of production and development status, re-understanding of reservoir dynamics, and rapid regulation of injection-production parameters. The zonal injection-production regulation mode with "block" as the unit shows the key technical means of vertical precise energy supplement, strengthening weak layers while controlling strong layers, and horizontal injection-production coupling and flow field regulation.

In the next step, it is necessary to continue to improve the technical system, carry out research on long-term life extension technology of intelligent injection-production technology, research on cost reduction and efficiency improvement technology of intelligent injection-production technology, expand the application scale, strengthen intelligent injection-production collaborative autonomous decision-making, and explore the construction of block-level intelligent oilfields.

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