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RESEARCH ARTICLE

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Practice and understanding of developing new technologies and equipment for green and low-carbon production of oilfields

Abstract The core of China's low-carbon development includes optimization of industrial structure, clean energy technologies, emission reduction technologies, and innovation of relevant systems and institutions. China National Petroleum Corporation (CNPC) has always been a proactive participant in developing low-carbon economy, shouldering the responsibilities of safeguarding oil and gas supply, conserving energy, and reducing emission. Therefore, CNPC fulfills those responsibilities as a substantial part of its overall strategy. Guided by low carbon and driven by innovation, petroleum corporations have taken constant innovation of low-carbon technologies, especially the development of green and low-carbon petroleum engineering technologies and equipment, as major measures for energy conservation and emission reduction. Large-scale development mode of unconventional resource anhydrous fracturing should be innovated. And supercritical CO_2 should be used to replace water for fracturing operation, in order to achieve multiple objectives of CO_2 burying, conserve water resource, improve single well production and ultimate recovery, realizing reduced emission and efficient utilization of CO_2 resources. Artificial lifting energy-saving and efficiency-increasing technologies and injection-production technology in the same well should also be innovated. Energy consumption of high water-cut wells is reduced to support the new low-carbon operation mode of high water-cut oilfields and realize energy saving and efficiency improvement during oil production by developing the operation efficiency of the lifting system and reducing the ineffective lifting of formation water. These technologies have been widely recognized by local and international experts and have greatly enhanced CNPC's international influence. This study expounds the key technologies and equipment with regard to the development of green and low-carbon petroleum engineering and provide relevant suggestions.

Keywords low carbon, energy conservation and emission reduction, petroleum engineering technology, petroleum equipment

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1 Introduction

Low-carbon economy refers to an economic development model characterized by low energy consumption, low pollution, and low emission (Wang, 2009; Jin et al., 2010; Wang et al., 2017). Its essence is energy-efficient utilization, clean energy development, and pursuit of economic green growth. The basic approach to achieve this goal is to develop clean energy and new technologies for energy conservation and emission reduction. The global major economies take low-carbon economy as an important direction for their future development and even as an important link for adjusting economic structure and stimulating economic recovery. They provide great support for low-carbon technologies and management mechanism innovation (Yin and Huo, 2010; Shan, 2011; Shi, 2015; Shi, 2016); seize the commanding height of future competition; and make unprecedented efforts for promoting low-carbon economy, which has become a focus for a new round of global economic competition.

Low carbon is the trend of the world's economic and social development, and China is becoming involved in low-carbon development with unprecedented depth and breadth. The "13th Five-Year Plan" clearly stated that by 2020, the energy consumption per 10000 yuan of GDP (Gross Domestic Product) will fall by 15% compared with 2015, and the total energy consumption will be controlled within 5 billion tons of standard coal (National Development and Reform Commission, Ministry of Environmental Protection, 2017). As a state-owned enterprise (SOE) in the energy industry, China National Petroleum Corporation (CNPC) shoulders the responsibilities of safeguarding oil and gas supply, conserving energy, and reducing emission in the context of developing low-carbon economy, taking low carbon as an important link for fulfilling its social responsibilities and strategic development. The responsibilities has become a considerable part of its development strategy (Du, 2010; Yang et al., 2010).

CNPC places great importance on top-level design for its low-carbon development. Through the integration of design, organization, and implementation, it can effectively integrate the superior upstream, medium-stream, and downstream technical resources to jointly address the aforementioned problems. Guided by low carbon and driven by innovation, CNPC will establish and improve a long-term mechanism of scientific emission reduction, energy conservation, and consumption reduction and keep innovating low-carbon technology (Gu and Wang, 2015). To make innovations and develop green low-carbon petroleum engineering technology and equipment have become important measures for oil enterprises in implementing energy conservation and emission reduction. Such engineering technologies as CO_2 waterless fracturing, artificial lift for energy conservation and efficiency improvement, and injection-production in the same well have received extensive local and international attention.

2 Innovation and establishment of a new model of waterless fracturing with unconventional resources for improving emission reduction efficiency

During CO_2 waterless fracturing, liquid or supercritical CO_2 instead of water is used as a fracturing medium to fracture crude oil reservoir. This process can improve reservoir seepage conditions, complement stratum energy, and achieve water conservation and CO_2 reduction (Liu et al., 2014; Wang et al., 2016).

After technical breakthrough and on-site practice for three years, CNPC has formed waterless fracturing construction process flow, supporting equipment, liquid system, and management system with independent intellectual property rights (Meng et al., 2018; Zheng et al., 2018). The main equipment includes storage tank, booster pump, closed blender, fracturing pump, and low- and high-pressure pipelines (Fig. 1). During fracturing construction and in the pre-pad fluid phase, CO_2 in the storage tank is initially sucked into the main manifold via a booster pump, and the high-discharge injection is then conducted to open the reservoir through the fracturing pump truck. In the sand-carrying fluid phase, the sand butterfly valve under the sand mixing tank is opened to mix proppant and CO_2 evenly in the main manifold; then, it is pumped into the reservoir to support the crack and thus form an oil and gas seepage channel with high flow conductivity.

The monitoring data of the fracturing site show that CO_2 is in a supercritical state for a long time in waterless fracturing construction, soaking, and blowout (Meng et al., 2016). At this moment, the density of CO_2 is close to that of liquid, and its migration capacity is similar to that of gas. It diffuses easily in the reservoir, and its capability to dissolve in the formation fluid becomes strong. This condition is advantageous for storage (Ye and Ye, 2012). Hong 87 block of Jilin Oilfield is selected as a research object, and a geological model is established. CO_2 extraction is simulated after waterless fracturing is conducted for Hong 87-11-4, Hong 87-5-3, and Hong 87-7-7. The results show that the average CO_2 storage rate reaches 76.46% after three wells are conducted with waterless fracturing, and the storage rate is increased by nearly 30% compared with that using CO_2 driving technology (Bachu, 2008).

As CO_2 is stored, the application potential of production increasing and water saving gradually becomes evident. By comparing the production of Hong 87 block with CO_2 waterless fracturing for 8 wells and that of Rang 11 block

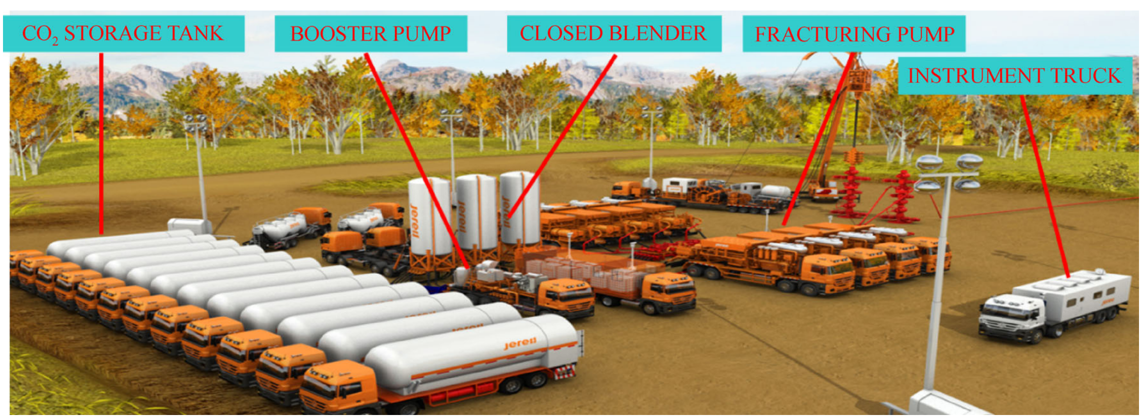

Fig. 1 Schematic of ground equipment for CO_2 waterless fracturing.

with conventional water-based fracturing for 23 wells, the oil production per unit volume of CO_2 fracturing fluid is equivalent to that of 2.4 unit volume of water-based fracturing fluid (Table 1). As a result, if the average CO_2 injection of waterless fracturing wells is 630 m^3, a single well can save 1512 m^3 of water.

3 Innovation and development of new technologies of low-carbon operation for high water-cut oilfield for saving energy, improving efficiency, and reducing cost

At present, most domestic oilfields would be in the high water-cut phase at their later stage of development. By the end of 2018, CNPC had about 54548 oil wells with a water-cut rate over 95% and 33439 oil wells with a water-cut rate over 97%. The emergence of numerous high water-cut wells increases the energy consumption for lifting, gathering, transportation, and sewage treatment dramatically. The total power consumption for oil and gas production in 2018 was nearly 26 billion kWh. Energy conservation and efficiency improvement are crucial in reducing the production cost of oilfields. Currently, the main oil production method for oilfields is mechanical oil production. In the power consumption of oil and gas production, the energy consumption of the machine production system was the highest, which accounted for 42.41% of the total energy consumption in 2018. In this context, CNPC has made innovations of artificial lift for energy conservation and efficiency improvement, and injection-production technology in the same well. The energy consumption for oil production of the high water-cut wells is reduced considerably by improving the operation efficiency of the lifting system and reducing the ineffective lifting of the formation water. A new model of low-carbon operation for high water-cut oilfields is initially formed.

3.1 Artificial lift energy conservation and efficiency improvement technology

(1) Optimization of energy conservation technology via pumping unit

The proportion of pumping units in the equipment used in oil production exceeds 90%. Old high water-cut oilfields and low-permeability development oilfields use the pumping unit production systems with low efficiency and high energy consumption (Wang et al., 2010; Zhang, 2017). To address the current situation where the water-cut rate of the oilfield is increasing year by year, a new optimization design method for pumping unit selection is established, and the selection basis is determined through research on the change law of oil production volume. A calculation method for new pumping unit load and a dynamic control optimization method are determined for large loading period variations of conventional pumping unit and low utilization of motor power. The pumping unit dynamic control device and the corresponding optimization software are developed. The efficiency of the optimized pumping unit system is enhanced from 27% to 30%.

(2) Energy conservation technology for ground-driven progressive cavity pump

The ground-driven progressive cavity pump is a new energy-saving lifting device (Liu et al., 2015). By optimizing the motor structure, the motor loading rate is controlled between 70% and 80% to solve motor heating effectively, and the ground transmission efficiency exceeds 80%. For the uneven swelling of the rubber of conventional progressive cavity pump, reduced matching accuracy of molded line, and insufficient lifting capacity, a new progressive cavity pump with iso-wall thickness stator is investigated, and the parameter optimization design method is established. Machining process is finalized and improved, and mass production is realized. The iso-wall thickness progressive cavity pump enhances the average pump efficiency of the ground-driven progressive cavity pump by 14.7%, reduces the torque by 15.1%, and improves the system efficiency from 29% to 33%.

(3) Rodless lifting technology

Most of the work done by the rod pump lift is applied to the sucker rod, which consumes considerable energy but produces low system efficiency. To overcome the shortcomings of the rod lift, rodless lifting technology is developed, including submersible reciprocating pump and submersible progressive cavity pump (Liu et al., 2015; Zhu et al., 2016; 2017; 2018) (Fig. 2).

Submersible reciprocating pumps are used for 251 wells in Daqing Oilfield. The average daily liquid production is 3.28 t, the average pump efficiency is 53.1%, and the average daily power consumption is 50.1 kWh. In comparison with the rod pump lift with the same displacement, the power saving rate is 53.8%. The submerged reciprocating pump demonstration area has 78 wells, the daily power consumption of a single well decreases from 133.4 to 72.5 kWh, and the power saving rate is 45.7%. The system efficiency is enhanced from

Table 1 Comparison of operation scale and oil production between CO_2 waterless fracturing and conventional water-based fracturing

Fracturing technology	Number of wells	Average amount of fracturing fluid (m^3)	Average daily oil production after fracturing (m^3)	Average daily oil production /1000 m^3 of fracturing fluid (m^3)
CO_2 waterless fracturing	8	630	2.4	3.81
Conventional water-based fracturing	23	380	0.6	1.58

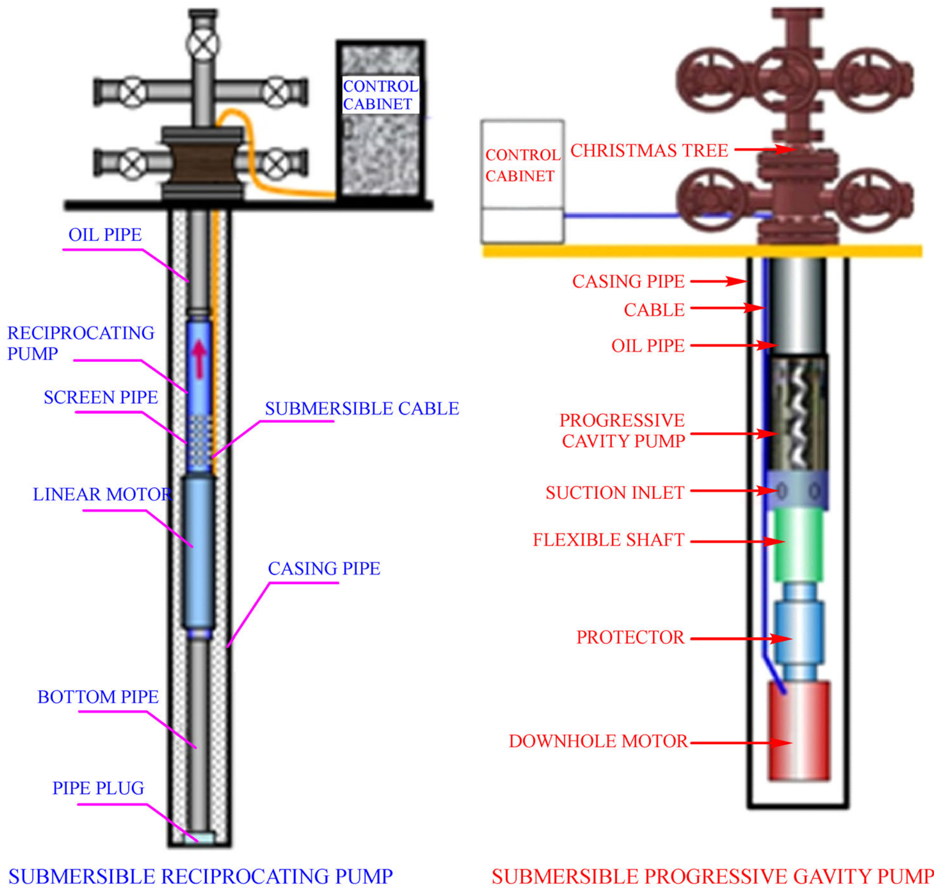

Fig. 2 Submersible reciprocating pump and progressive cavity pump driven by permanent magnet synchronous motor.

7.3% to 11.7%. The single well saves a power cost of 14000 yuan. On the basis of the conversion of the energy consumption for a single well, it can indirectly reduce CO_2 emission by 17.5 t per year, so that the demonstration area can reduce carbon emission by approximately 1300 t per year.

Submersible progressive cavity pumps are used for 39 wells in Daqing Oilfield, including 31 vertical wells and 8 directional wells. The pump is hung for 1164 m at average and 1802 m maximally. The average daily production of liquid is 35.4 t, the average pump efficiency is 74.6%, and the average daily power consumption is 83.6 kWh. In comparison with the ground-driven progressive cavity pump with the same displacement, the power saving rate is 39.2%. The submersible progressive cavity pump can save power by 60 kWh per day at average and power charge by 13600 yuan per year. It can reduce carbon emission by 17.1 t per year. According to the test, the rodless lifting technology can reduce the risk of environmental pollution, prolong the pump inspection cycle of the oil well, improve the production efficiency of the oilfield, and reduce the energy consumption for lifting compared with the traditional walking beam pumping unit. This technology is expected to be applied in scale.

3.2 Injection-production technology in the same well

The ineffective energy consumption for lifting, gathering, transportation, and treatment in old high water-cut oilfields is extremely high. It results in annual increase of production cost and poor benefits, for which numerous oil wells are to be closed. Thus, the injection-production technology in the same well is developed. The oil-water mixture in the wellbore is directly separated under the well by an oil-water separator. The separated water is directly injected back into the underground waste layer or the water injection layer, while the separated low water-cut crude oil is lifted to the ground via the equipment. Thus, water injection and oil production can be simultaneously realized in a well, and a new displacement relationship is established. Swept volume and recovery ratio for water injection are improved, and ineffective water circulation is reduced. The energy complementation between the layers of small fault block oil reservoir and remote blocks can be realized, and mutual injection and production can be conducted, which aid in reducing infrastructure investment (Wang, 2010; Veil and Quinn, 2005). Injection-production in the same well subverts the traditional development mode of high water-cut wells. It reduces energy consumption for lifting, gathering, and transportation and lessens ground sewage treatment. It can also stabilize oil production, control water condition, save energy, and enhance efficiency.

The core equipment for injection-production in the same well is the downhole oil-water separator (Liu et al., 2018). Hydrocyclone is a typical centrifugal separation device, which separates crude oil from water in the wellbore on the basis of the different density and centrifugal force in the rotating flow field between oil and water. It is a tapered tubular device, on which inlet, overflow orifice, and underflow orifice are set. The inlet is the passage for the oil-water mixture in the wellbore to enter into the hydrocyclone, the overflow orifice is a passage for the separated oil and a small amount of water to be lifted to the ground, and the underflow orifice is a passage for the separated water back to the reinjection layer. During operation, the oil-water mixture enters the hydrocyclone from the tangential inlet and rotates at a high speed. Under the centrifugal force, the relatively denser water is "splashed" to the outside, and the relatively lighter oil is concentrated in the center of the hydrocyclone. Thus, the oil can be separated from the water.

On the basis of the existing hydrocyclone, CNPC has successfully developed the cubic curve and the inner cone hydrocyclone, respectively. Cubic curve hydrocyclone optimizes the internal molded lines using the cubic curve, and overcomes the local flow field disorder between the straight pipe section and the cone section of the hydrocyclone and between the two cone sections due to structural mutation. It also improves the stability of rotating flow field. Upon optimization, the separation efficiency of the single-stage hydrocyclone is improved by 6%–7%. When the split ratio is between 25%–35%, the separation efficiency will exceed 98% (Fig. 3). The inner cone hydrocyclone promotes the coalescence of small oil droplets and their migration to the overflow orifice through an inverted cone structure.

CNPC's hydrocyclone is tested in 20 wells on site. The water generated from the ground is decreased by 74.2% on

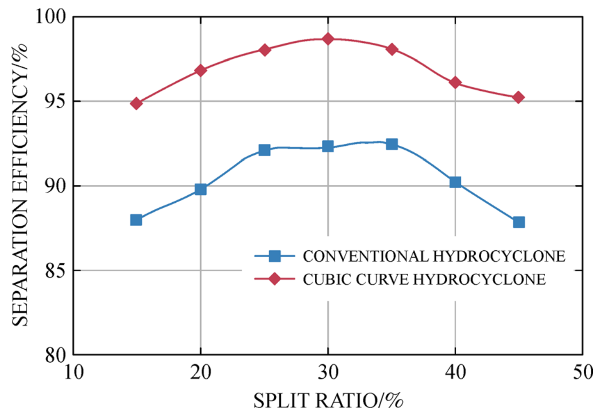

Fig. 3 Comparison of separation efficiency between conventional and cubic curve hydrocyclones.

average, and the water-oil ratio is decreased by 74.0% on average, while the daily oil production is not decreased. Taking La 3-3616 well in Daqing Oilfield as an example (Table 2), the annual cost of comprehensive energy consumption for lifting, gathering, transportation, and rejection is reduced by 410000 yuan after adopting the injection-production technology in the same well, which is equivalent to reducing the carbon emission by 512 t. Developing high water-cut wells with injection-production technology in the same well can substantially reduce the water amount generated from the ground and effectively lower the energy consumption for lifting, gathering, transportation, and ground sewage treatment as well as comprehensive development cost.

4 Problems and prospects

To develop low-carbon economy, Chinese oil companies must make innovations for their low-carbon technologies. The key development contents for Chinese oil companies under the low-carbon economy is to accelerate the research and development of low-carbon technologies, improve the

Table 2 Water and oil production changes with injection-production technology in the same well for 5 of the 20 test wells

Test well	Production technology	Liquid production (m^3/d)	Oil production (m^3/d)	Water production (m^3/d)	Water-oil ratio (%)
La 3-3616	Conventional production	145	2.77	142.23	51.35
	Injection-production technology in the same well	37	2.75	34.25	12.45
Fang 6-1	Conventional production	128	3.21	124.79	38.88
	Injection-production technology in the same well	32	3.20	28.80	9.00
Fang 4-12	Conventional production	131	2.49	128.51	51.61
	Injection-production technology in the same well	36	2.48	33.52	13.52
Gao 124-44	Conventional production	161	1.38	159.62	115.67
	Injection-production technology in the same well	41	1.38	39.62	28.71
Bei 2-6-40	Conventional production	39	1.17	37.83	32.33
	Injection-production technology in the same well	8.7	1.2	7.5	6.25

level of low-carbon technologies, absorb foreign advanced low-carbon technologies, and improve low-carbon technology system. At the present stage, Chinese oil companies are generally weak in the research on the low-carbon technology of petroleum engineering and the development and utilization of supporting technologies. They must establish a low-carbon technology system with continuous integration of engineering technologies.

(1) The low-carbon economy is characterized by the reduction of greenhouse gas emission and construction of economic development system based on low pollution and energy consumption. CO_2 waterless fracturing is an effective CO_2 storage method. However, this technology has not entered the industrial application stage due to the limitation of some factors, such as high cost, long transport distance of CO_2 source, and unavailable pipe network support. To capture considerable scattered CO_2 requires multiparty coordination. Moreover, government support and local protectionism are uncertain, and long-distance cross-administrative region transportation may result in many changes. These realistic problems cannot be ignored by enterprises. Therefore, low-cost flue gas and CO_2 capturing technology, methane utilization technology, and carbon capturing and emission reduction technologies of refining equipment must be overcome urgently. A unified and high-level cross-industry strategic layout or operation mechanism should be established to form a complete and guiding CO_2 industry chain, so as to realize scale application.

(2) In terms of energy conservation and consumption reduction, considering that the domestic oilfields are currently at the high-cut stage, excessively increasing energy consumption must be restricted. Improving the operation efficiency of the machine production system and reducing the inefficient lifting of the formation water are important to reduce energy consumption and carbon emission. Energy conservation technology of conventional pumping unit should be further implemented, promoted, and applied. New rodless lifting technology and measures for injection-production technology in the same well should be promoted. The problems related to artificial lift should be solved through the integration of design, manufacturing, application, management, and evaluation.

(3) CNPC is a typical SOE with huge oil production and energy consumption. Low-carbon management must be realized comprehensively to meet the requirements of low-carbon economic development. To achieve low-carbon management in the future, top-level design and investment strategy research on China's petroleum industry under low-carbon economy must be conducted well. The low-carbon policy should be upheld in terms of management function, concept, and system. Moreover, the management content and scope for low-carbon development should be clarified. Overall planning should also be made for management activities.

5 Conclusions

Low carbon is the general trend of worldwide economic and social development. To study the growth strategy of China's petroleum industry under low-carbon economy, make low-carbon technology breakthroughs, and establish engineering demonstrations is of great importance to ensure the sound and stable growth of China's petroleum industry under the background of low-carbon economy. CNPC takes low carbon as an important aspect to fulfill its social responsibilities and realize strategic development. It has innovatively developed a series of green low-carbon petroleum engineering technologies as follows. (1) CNPC has established a new model of anhydrous fracturing with unconventional resource by using 100% CO_2 to replace water for fracturing operation. It has achieved multiple objectives of CO_2 burying, water resource conservation, and improvement of single well production and ultimate recovery. (2) CNPC has vigorously developed energy-saving technologies for pumping unit optimization, ground-driven screw pump, rodless and artificial lifting with improved efficiency, and lifting energy consumption and carbon emission reduction. (3) CNPC has also created the same well injection and production mode for high water-cut wells, achieving water injection and production in the same wellbore through downhole oil-water separation and subverting the traditional development mode. The energy consumption of lifting, gathering, and transportation to achieve oil stabilization, water control, energy saving, and efficiency improvement has been reduced.

In the future, CNPC will further establish a fine integrated energy-saving management mode characterized by modularized work, clarified responsibilities, streamlined operation, standardized technique, and quantified objective. Taking energy saving as the standard, technology is coordinated with management to provide a standardized, orderly, and controllable management and operation system, achieve energy saving, consumption reduction, and CO_2 emission reduction, and contribute to the construction of beautiful China with ecological civilization.

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