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Review of intelligent well technology

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ABSTRACT

Intelligent well technology is an oil and gas well optimization completion technology integrated with underground real-time monitoring, data analysis decision-making and remote control of downhole tools. It's of great significance to the transformation and innovation of China's oil and gas development projects. The author of this paper expounds the definition, principle, composition and characteristics of intelligent well technology, and introduces the development status quo of intelligent well technology abroad, including mature intelligent well system, key technology research of intelligent well and its application technology. After the introduction to the related technology research of intelligent well in China, the author puts forward some opinions on the development of our own complete intelligent well system.

1. Introduction

Oil and gas exploration engineering is one of the most complex projects as it often comes across problems such as large depth, small space, complicated environment and monitoring difficulty. With the gradual development of easy-to-exploit oil and gas resources, many oil and gas fields feature high recovery and water cut, aggravating oil and gas exploration. In order to cope with the challenges associated with oil and gas development, foreign countries have first proposed intelligent well technology (i-well) based on mechatronics and digital communication technology [1,2]. In recent years, it has been popularized and even gradually demanded as a conventional means of oil and gas exploitation. Domestic intelligent well technology research started late. And only part of foreign intelligent well technology can be introduced, but at a high price. In recent years, the problems such as difficult exploitation, regulation and monitoring of oil and gas exploitation in China have become more and more serious, and the exploitation technology needs to be innovated urgently. A large number of oil and gas development researchers have gradually realized the superiority of intelligent well technology. As a result, it's an urgent need for China to develop a complete set of intelligent well system. The mature intelligent well systems abroad and the research and development of key technologies of intelligent well at home and abroad will be introduced herein. Considering the characteristics of oil and gas resources in China, the author puts forward some thoughts on the development of intelligent well, hoping to contribute to China's early entry of the era of intelligent oil and gas resources development.

2. Introduction to intelligent well technology

2.1. Definition and principle of intelligent well technology

Intelligent Well Technology, or Intelligent Completion, is a complete system of the production well that enables continuous and real-time reservoir management. The core of the technology is to form a closed-loop control. Therefore, the data such as downhole temperature, pressure, flow, composition collected by the well sensor is fed back to the uphole system in real time. And then, the same data will be deeply processed, analyzed and judged on the software platform. After that, a reservoir management decision instruction is formed and transmitted to the downhole production tool for remote operation via the wireless communication control system.

Intelligent well technology helps to connect the surface with the downhole. Its specific application in reservoir development is mainly to optimize production and control the occurrence with the goal of maximizing recovery. Faced with more and more complex reservoir production projects, multi-layer combined production can give full play to the production capacity of oil well, which is better than sequential production.

The application of intelligent well technology can shut down the

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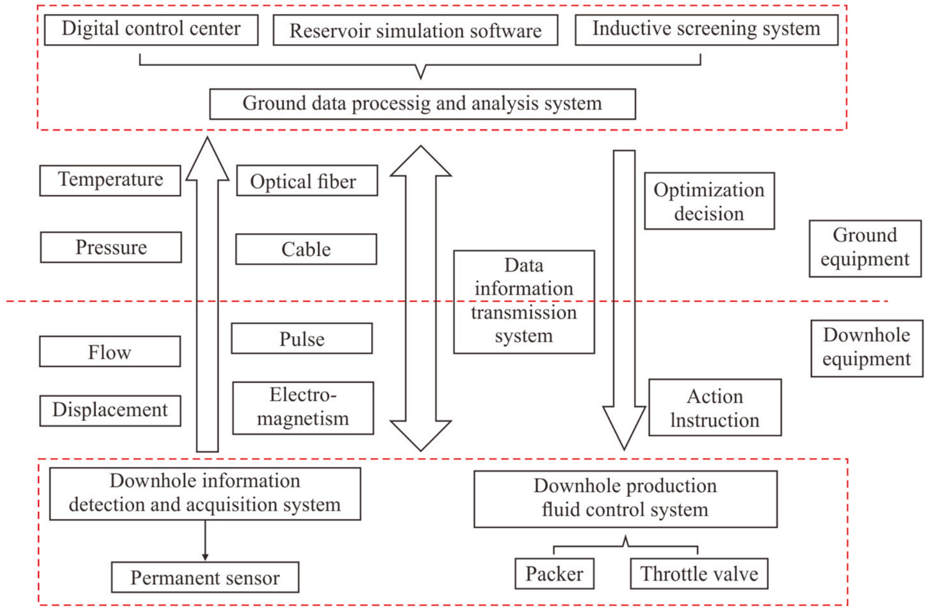

Fig. 1. Architectural diagram of intelligent well technology.

produced water that affects the production in time. When the pressure is not balanced, the intelligent downhole throttling technology and time balance can be adopted. The complete intelligent well system needs to have factors such as interlayer isolation, flow control, mechanical oil recovery, permanent monitoring and sand control taken into account. In this way, engineers can monitor and control the oil and gas production of single-well multi-segment oil and gas production or single-branch wellbore in multi-branched well in real-time. The resultant real-time reconfiguration of the well structure will help to improve well production and cut operating costs.

2.2. Composition of intelligent well technology

The intelligent well system is mainly composed of two parts: ground equipment and downhole equipment, including downhole information detection and acquisition system, production fluid control system, data information transmission system and uphole data analysis system [3–6], as shown in Fig. 1 and Fig. 2. The production fluid control system

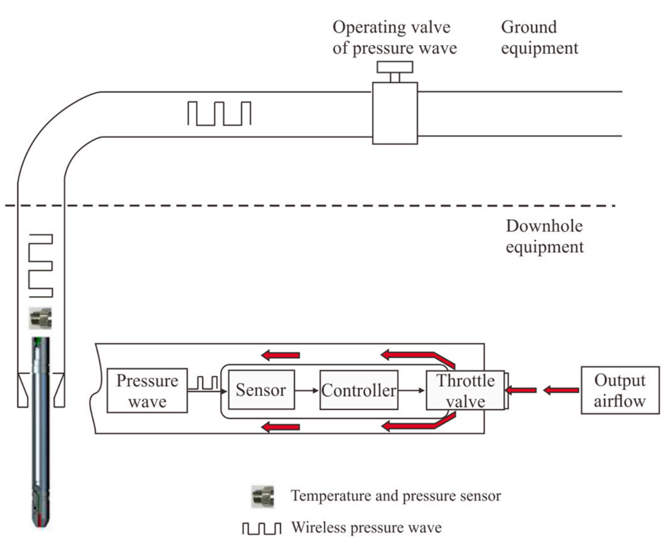

Fig. 2. Architectural diagram of intelligent well technology.

is an integral part of intelligent well technology. When the formation pressure is insufficient, the reservoir energy can be restored by adjusting the production rate. It may thus effectively control the interlayer interference, delay the water breakthrough, inhibit the water content, prolong the high-efficiency mining time of the reservoir, optimize production of the oil well, and enhance oil and gas production [7,8].

(1) Downhole information detection and acquisition system: It's mainly composed of downhole permanent or semi-permanent sensors. Several sensors, including electronic sensors, fiber optic sensors, and quartz sensors, are distributed throughout the wellbore to detect and collect real-time data such as downhole temperature, pressure, flow, displacement and time.
(2) Production fluid control system: It mainly consists of a series of downhole tools wireless controlled, including packers, throttle valves, flow control valves and branch wellbore sealing switch devices. Hydraulic and hydraulic-electric control methods are mainly used. But in recent years, all-electric control systems have emerged.
(3) Data information transmission system: It is an important bridge between production fluid control system and data analysis system. It plays the role of communication between real-time downhole data acquisition and transmission of control instructions to downhole. Generally, it is realized by cable or optical fiber. In recent years, it also transmits information by means of pressure pulse or electromagnetic wave decoding.
(4) Uphole data analysis system: It's used to process the raw data collected by the downhole sensor, and is summarized and screened by the software system to help the user to clearly understand the downhole occurrence. At the same time, the analysis software adopts reservoir engineering method, optimization method and reservoir numerical simulation and prediction technology to analyze and collect the production dynamic data and help users make corresponding adjustment decisions.

2.3. Characteristics of intelligent well technology

Compared with traditional completion technology, intelligent well technology has significant advantages in accuracy, continuity, convenience and efficiency [3,7–9]. Its main embodiments:

(1) Real-time downhole condition monitoring and data acquisition: Compared with the discontinuity and instability of the traditional logging technology, the data measurement of intelligent well technology is continuous and steady. It helps to ensure highers accuracy, avoid the impact of traditional logging on normal production and secure higher efficiency.
(2) Intelligent reservoir production simulation and convenient production engineering management: Through continuous, long-term, real-time and accurate downhole information data, the ground system simulates and analyses reservoir occurrence. It helps engineers to judge downhole conditions and make decisions, facilitate accurate management of production, improve production efficiency and mitigate safety hazards.
(3) Ground system analysis and decision making and closed loop control of downhole tools: Logging and control in traditional technology are two independent projects. They cannot be carried out at the same time. The well still changes continuously between the completion of logging and the start of regulation, leading to the inaccuracy of traditional technology in production optimization. The test and control of intelligent well technology can be carried out simultaneously. It not only has advantages in decision accuracy, but also reduces the workload and working time of logging and lifting tools, greatly improving production efficiency and cutting production costs.

In spite of manifest advantages of intelligent well technology, its development is also challenging. First, the establishment of intelligent well system has the same difficulties as traditional completion technology: small space, large depth and complex environment. Compared with digital coal mining, the underground space is sufficient for people to open to traffic, while the oil and gas well underground takes millimeter as the basic unit. The coal mines generally have a depth of 1000 m, with 1500 m as the standard for a deep well. Oil and gas well needs 3000 m–4000 m long-distance communication and control. The underground visibility of the coal mine well is better and the environment is well understood, while the oil and gas underground environment measurement is difficult and incomprehensible.

In addition to the difficulties inherent in oil and gas well, intelligent well technology has its own unique problems: The underground working environment features high temperature, high pressure, corrosion, electromagnetic interference, etc., posing higher requirements for the sensors and actuators placed underground. And again, the components of domestic intelligent well technology are solely imported at present. Their high costs also curb the development of intelligent well technology.

2.4. Limitations of intelligent well technology

(1) Input-output ratio. The cost of the whole intelligent completion system is high, even the application of one of the key technologies requires a high initial investment. For some wells with small production, there may be a smaller comparison between cost and benefit output, which in turn reduces the final economic benefits. Even some wells have an input-output ratio of less than 1, resulting in a loss. Therefore, when using the intelligent well technology, the expected production of the well is limited. In addition, the cost of intelligent well technology does not increase linearly, it has a higher investment in the initial stage. Even if the expected production of the well is high and the daily production is insufficient, the investment return period will be prolonged, and the final economic benefit will be reduced. Based on the two considerations above, it is generally believed that the daily production of the well using the intelligent well system should not be lower than 68 t.
(2) Requirements for well conditions. Since the downhole space of the oil and gas well is small, and the intelligent well system has more equipment and facilities, there are certain requirements for the well condition. In the implementation of intelligent well, interlayer packer, inflow control tool and multiple cables shall be installed in the well bore. In terms of the packer size of intelligent well system products, the well bore size is generally not less than 117.8 mm. Intelligent wells are generally suitable for self-drilling wells, gas lift wells and installation of large displacement pump wells (such as electric submersible pumps). Non-self-injection wells need to be equipped with more wellbore tools, which will lead to further reduction of downhole space, affecting the installation of intelligent well equipment and tools. As a result, the intelligent well system cannot perform its full function or even function properly.
(3) Technical research. The complexity of the intelligent well system is higher than any previous downhole tool, and the unpredictable downhole environment makes the development of the intelligent well system more difficult. Until today, we still can't guarantee that any intelligent well system can improve production stably and safely. Therefore, we need to attach great importance to the development of key technologies of intelligent well technology.

3. Development status quo of intelligent well technology at home and abroad

3.1. Overseas mature and complete intelligent well system products

In the 1990s, the concept of intelligent well technology has been put forward abroad, and at the end of the 20th century, a number of complete sets of intelligent well technology products have been developed and put into production [10–19]. After decades of development, foreign large-scale oil and gas production equipment enterprises led by Schlumberger and Beckhughes have further improved the technology of intelligent well from the aspects of electrification, electronics, remote communication and hierarchical control. At present, the representative mature intelligent well technology products are shown in Table 1.

3.2. Development status of key technologies for intelligent well

At present, the relatively mature and complete intelligent well

Table 1
Typical intelligent well technological products abroad.

Product	Company	Technical characteristics
In Charge	Schlumbergerbaker hughes	12 production layers can be controlled independently; single layer flow can be adjusted steplessly; First all-electric intelligent well system
Intelli Zone Compact	Schlumberger	Intelligent Segmentation of Long Horizontal Well; Comprehensive integrated intelligent well system
Intelligent Well System	British Shell	Production switching between Lower Ness/Etive-Broom/Rannoch
In Force	baker hughes	Permanent Adaptive Meter; Throttle Valve Over Packer
Smart Well	Halliburton	Realizing Intelligent Production of Three Reservoirs or Branch Well
Intelligent Well System	Roxar	Hydraulic Intelligent Well System for 4-reservoir Control
Intelligent Well System]	NHAA	The first multi-fiber sensor smart well in the field of intelligent well
Multi-Node	baker hughes	The first all-electronic intelligent well system in the world

Table 2
Intelligent well monitoring technology abroad [16,30,31].

Product	Company	Technical characteristics
Inter ACT	Schlumberger	On-demand query and remote control of key well site parameters; Web-based collaborative work mode
iAcquire™	Halliburton	Distributed Temperature Monitoring System (DTS); Data basic processing; Providing multi-well management scheme
DACQUS	Roxar	TCP/IP, ODBC, OPC and other interface protocols communicate with third parties
Optical sensing system	Weatherford	Supervisory Control And Data Acquisition (SCADA) is associated with the remote terminal MODBUS protocol
PROVson^{DSP}	Promore	SCADA implements data remote communication; Promore DATA Web network acquires data
Optimize^{IT}	ABB	Display data trends in real time and offline
ZA-Gauge ™	Halliburton	Capillary pressure measurement system; pressure sensor with high reliability and long life, but more ground facilities
PDMS	Pioneer	Low cost; wide application; especially in shallow well, normal temperature well, low cost well have obvious advantages
PR300	WTS	Storage underground electronic pressure gauge
Promorey	Promore	Electronic resonance film pressure measuring system; less underground electronic components and strong anti-interference ability

system is relatively few. In order to improve this complex system, many workers conduct targeted research on key technologies. In fact, most oil and gas well using intelligent well technology do not have a complete set of intelligent well technology. In spite of the application of only or several key technologies, the improvement of production and efficiency is obvious.

3.2.1. Monitoring technology

Downhole data monitoring technology is the "eye" of intelligent well technology. Unlike the traditional method of processing the downhole data through the calculation of the data on the well, the intelligent well monitoring technology is to obtain the downhole real-time data directly. In the 1960s, the first batch of permanent downhole instrumentation (PDG) was formally used. It heralded that oil and gas development has entered the era of digital intelligent monitoring. The development status quo of intelligent well monitoring technology is shown in Table 2.

3.2.2. Data processing technology

Data processing technology is the "brain" of intelligent technology. The intelligent well monitoring technology continuously acquires data in the well for a long time. Original data are characterized by massive data set, including abnormal points and noise, multiple stages of pressure rise and fall. Such data cannot be directly used for reservoir modeling or interpretation with existing well test interpretation theory. In order to effectively utilize the huge data set, appropriate data processing technology is indispensable. The development status quo of data processing technology for intelligent well abroad is shown in Table 3.

3.2.3. Flow control valve

Flow control technology is the "hands" of intelligent well technology. The ultimate goal of intelligent well technology is to regulate and reorganize production, relying on the wireless control throttling device. At present, hydraulic control valves are widely used, including full-open and fully-closed control valves, as well as step-wise and fine-adjustable control valves. With the advancement of mechatronics technology, electric-hydraulic integrated control valves have been gradually developed, exhibiting great advantages in deep well (see Table 4).

3.2.4. Optimization method

The optimization method is the "blood" of intelligent well technology. The excellent optimization method can make each component of the intelligent well system better connected, apart from a better communication with users. Production optimization methods are mainly divided into reactive strategies and proactive strategies. The difference between the two is that the former is to adjust and control after encountering production problems, while the latter is to formulate a set of cautionary plans (see Table 5).

3.3. Application of intelligent well system

In 1997, the first electronic hydraulic intelligent well system SCRAMS [20], developed by Halliburton and Beihai Petroleum Service Engineering Company, was installed on the Saga Tension Leg Platform in Beihai. Since then, intelligent well technology has developed rapidly in the field of foreign oil and gas development: in the first 10 years, the production well with intelligent well systems has grown at a rate of 27% per year, and more than a thousand production wells have been intelligently transformed. In the second decade, large foreign oil and gas development enterprises, including Shell Petroleum Company, have adopted the technical requirements of intelligent well as conventional means of production. The successful application of intelligent well technology exists in multi-layer production, automatic gas lift, water and gas injection, deep-water ocean, heavy oil exploitation, thin reservoir, multi-branch well and marginal reservoir development. More

Table 3
Data processing technology of intelligent well abroad [32–45].

Researcher	Technical characteristics
Schlumberger Decide!	Integrated Reservoir Simulator (ECLIPSE); Oil Well and Pipeline Modeling Tool (PIPESIM)
Landmark DSP	Combine Well SolverTM, Asset SolverTM, Asset LindTM
Athichanagorn	A multi-step method for processing and interpreting PDG long-term pressure data
Ouyang; Kikani	Polytope nonlinear regression method for long-term downhole testing (PDG) data
Soliman	Application of daubechies wavelet to pressure signal analysis
Olsen	The problem of "automatic" wavelet filtering and compression for real-time reservoir and production data is studied by using real-time wavelet transform.
Masahiko; Roland	Another processing method of PDG data
Li	A dynamic model method for diagnosing linear regions in nonlinear systems
Wang Fei	A new method using dynamic deconvolution and corresponding computer coding
Wang; Zheng	Using wavelet transform method to calculate unknown flow through downhole instantaneous pressure data
Liu; Horne	Use nuclear convolution method to interpret pressure and flow data measured by downhole permanent monitoring instruments
Tian; Horne	Deconvolution of pressure data using kernel ridge regression
Geir	Monitoring the reservoir status in the near-well zone by integrating Kalman filtering
Zafari; Reynolds	Prediction of reservoir state change using En KF assimilated production data
Alireza	Establish an automatic history matching workflow based on differential evolution algorithm

Table 4
Flow control technology of intelligent well abroad [32,46,47].

Product	Company	Control method	Throttling capacity
IV-ICV™	Well Dynamics	Electric-hydraulic	Level 100
CV-ICV	Well Dynamics	Hydraulic	Level 100
HVO-ICV	Well Dynamics	Hydraulic	Open/close
HVC-ICV	Well Dynamics	Hydraulic	Accurate and progressively adjustable
HVI-ICV	Well Dynamics	Hydraulic	Increase position sensing based on HCV
MCO-ICV	Well Dynamics	Hydraulic	Open/close
MCC-ICV	Well Dynamics	Hydraulic	Multi-position throttling; precise control
CC-ICV	Well Dynamics	Hydraulic	Open/close
HC-ICV	Well Dynamics	Hydraulic	Open/close
HCM-Plus™	baker hughes	Hydraulic	Open/close
HCM-A™	baker hughes	Hydraulic	Multi-position throttling; Level 8
ROSS	Weatherford	Hydraulic	Open/close
ROSS(Adjustable)	Weatherford	Hydraulic	Multi-position throttling
Indexing System	Schlumberger	Electric-hydraulic	Level 11
AICV	Halliburton	Electric-hydraulic	Fully automatic regulation

than 300 production wells have been equipped with complete intelligent well system, and tens of thousands of other production wells have adopted incomplete intelligent well technology such as downhole monitoring technology and downhole flow control technology. Although most intelligent well systems are used at sea, the intelligent digitization of land-based oil and gas exploration has become a trend [21,22]· The application situation of the intelligent well system abroad is shown in Table 6.

3.4. Development and application status of domestic intelligent well technology

With the development of oil and gas development projects, China's oil and gas exploitation has expanded from the initial land area to the sea and desert. The traditional completion technology can't reach the set target when dealing with such complex reservoirs, and the introduction of a foreign intelligent well system is priced between US$2 million and US$5 million, resulting in a sharp increase in development costs. Most production wells in China cannot afford such a high cost because their production capacity is not big enough.

Domestic research on intelligent well technology is still in its infancy. Faced by the blockade of import of intelligent well technology, the Chinese government has spent plenty of money and time on its research and development. Starting from basic hardware, China has carried out research on key technologies of intelligent well including intelligent downhole throttle valves, remote bidirectional communication and permanent downhole intelligent monitoring. We are committed to partial intelligent digitization of domestic oil and gas production well before embracing complete intelligent well system in the future [48,66–70]. At present, the domestic research on intelligent digital completion technology is shown in Table 7.

The downhole data transmission system and electronic sensors independently developed by Southwest Oil and Gas Company can monitor downhole temperature and pressure and transmit them to the ground in real time.

The distributed FBG temperature and pressure sensors of Beijing Ulanshi Company are divided into two kinds: single-point sensor and double-point sensor. Both of them can perform downhole temperature and pressure measurement. Single-point sensor can measure the temperature and pressure of tubing or annulus separately, and double-point sensor can monitor the temperature and pressure of tubing and annulus simultaneously. The supporting brackets of sensors are also divided into single-point type and double-point type, helping to better fix the supporting sensors and fully protect the sensors in the working process and effectively securing the safety and reliability of sensor signal transmission.

Daqing Petroleum Company's horizontal well intelligent well technology can be used to help judge the aquifer interval according to the downhole pressure and water injection curve. And again, increment of the annulus pressure is leveraged to switch the bottom hole valve for regulating the downhole flow. It may thus control the production state of oil well in low aquifer.

From 2011 to 2012, Xi'an Petroleum University designed two sets of intelligent well completion systems, namely "direct

Table 5
Development status of production optimization methods for intelligent wells abroad [49–65].

Types	Researchers	Optimization method
Reactive Strategies	Wang et al.	The steepest descent method
	Yeten et al.	Nonlinear conjugate gradient method
	Cullick et al.	Moisture threshold method
	Dilib et al.	General feedback model between monitoring data and ICV settings
	Amadi et al.	A closed-loop feedback control strategy
	Emerick et al.	Direct search algorithm
	F.A.Dilib et al.	Closed loop feedback control based on surface or downhole monitoring data
	Yang	Nonlinear predictive controller with model uncertainty
Proactive Strategies	Doublet	Augmented Lag Matrix Equation under KKT Constraint
	Brouwer et al.	A dynamic optimization method for a system
	Qing	Model Predictive Control, MPC
	Sarma et al.	Approximate solution method of nonlinear constraint algorithm based on objective function gradient and constraint gradient
	Alghareeb	Application of genetic algorithm
	Wang	The adjoint method calculates the objective function gradient value required for the optimization process
	Pinto et al.	Fast genetic algorithm,FGA
	Brouwer	Real-time update of reservoir model using set Kalman filter
	Sarma et al.	Gradient-dependent optimization method and Closed-loop optimization method for model updating of Bayesian inversion
	Carvajalet al	Smart Flow for SmartWells, SFSW

Table 6
Application situation of the intelligent well system abroad [13,15–18,23–29].

Location	Products
Tern Oilfield; North Sea	British Shell
Troll Oilfield; Oseberg Oilfield; Wytchfarm Oilfield; Wytchfarm Oilfield	Schlumberger
Roncador Oilfield, Brazil; Snohe Oilfield, Norway	In Charge
North Sea; Adriatic; Mexico; West Africa; Far East; Middle East; South America	Halliburton
Gulf of Mexico Maritime and Middle East Regions	Smart Well
DVSA Oil Well in Furrial Oilfield, Eastern Venezuela	Roxar
Osebergst (East) E − 11C well in Norwegian waters	NHAA
Total Fina EIF concagua gas field in New Orleans, Gulf of Mexico	Hydraulic electric intelligent well
Two branch wellbores of WYTCH-FARM [16]	Schlumberger
Shaybah Oilfield, Saudi Arabia	Intelligent completion system
Korchagina Oilfield in Caspian Sea, Russia	ICD; AICD; FCV
Norsk's P-30 production well in Bergen's Snore Oilfield	In Force
Fourier Well in Na Kika Oilfield, Mexico	Bottom-hole flow control valve
Kuwait Oilfield	Intelligent completion system
Well B-30, Well B-21, Well B-41 and Well B-29 in Qseberg Oilfield, Norway	Intelligent completion system
Well M-15 of W-Farm Oilfield in Southern England	Downhole flow control
Kwale Oilfield of Nigerian Agip Petroleum Company	Electro-hydraulic intelligent well

Table 7
Domestic research on intelligent digital completion technology.

Company	Product
Southwest Oil and Gas Field Company	Self-contained downhole data transmission system; high-precision electronic sensor
Beijing Ulanshi Company	A new distributed fiber bragg grating temperature and pressure sensor
Daqing Petroleum Company	A horizontal well intelligent well technology
Xi'an Petroleum University	Direct hydraulic + downhole electronic measuring instrument; direct hydraulic + downhole fiber measurement [13]
Shengli Oilfield	Permanently downhole intelligent detection device
Daqing Oilfield	Hydrodynamic oil recovery + Real-time monitoring of intelligent completion
Liaohe Oilfield	Optical Fiber Pressure Sensor Device with Metal Insulation and Wavelength Demodulation
Xi'an Petroleum University	Distributed fiber grating sensing technology at high temperature and high pressure
Southwest Oil and Gas Field Company	Permanent downhole temperature and pressure detecting device for natural gas well
Welde Petroleum Technology	Key technology of intelligent well in deep water oil fields
Shengli Oilfield	High-strength compression external packer; uniform liquid feeding sieve tube

hydraulic + downhole electronic measuring instrument" and "direct hydraulic + downhole optical fiber measurement". A downhole fluid control valve and a traversing packer are designed and they can traverse six 1/4 inch hydraulic pipelines or optical cables with inner diameter not less than Φ60mm and outer diameter less than Φ156mm. A fiber optic measurement system with a 3-point horizon and measurable in-column and annulus parameters was designed.

In Liaohe Oilfield, a fiber optic pressure sensor with metal insulation and wavelength demodulation is developed. Laser fusion technology is applied in the probe for stable operation of the pressure sensor in the downhole condition with high temperature and pressure.

Based on the "863" project "Key Technologies for Intelligent Well in Deepwater Oil and Gas Fields", Weide Petroleum Technology Development Co., Ltd. carried out mechanical design covering downhole inflow controller, interlayer packer, wellhead passer, and downhole fluid control valve. And the intelligent well production forecast software was developed to guide and optimize the intelligent well production strategy.

In terms of technical application, the segmented completion technology using the uniform liquid feeding sieve tube and data acquisition technology developed by Shengli Oilfield has been applied 50 times, exerting obvious water control effect. The permanent downhole temperature and pressure monitoring technology developed by Southwest Oil and Gas Field Company has been successfully tested in J17 and Z7 wells of Shunan Gas Mine in April and May 2004 respectively. In early 2016, the M03 and M08 injection wells of the Penglai 19–3 oilfield in Bohai were inserted into the hydraulic intelligent completion system of the Halliburton Company, Smart Well. It was the first time that the intelligent water injection completion technology was used for layered injection, marking the digital intelligent production of China's unmanned offshore platform.

4. Thoughts on the domestic development of intelligent well technology

Domestic research on the key technologies of intelligent well has achieved some success, but these achievements only have some functions of intelligent well system. And there is still a big gap compared with the mature and complete intelligent well system abroad. The British Shell Group has summarized the research direction of intelligent well technology in the future [70]:

(1) Production control of multiple reservoirs can be realized by a single well;
(2) Intelligent well technology should minimize the number of workovers in daily production;
(3) Rather than just the optimization of the basic production unit, the whole oil field production system should be optimized from a systematic point of view, so as to achieve excellent compatibility between downhole tools and ground equipment;
(4) Automatic production of oil well and optimization of production strategy of oil well;
(5) The continuous service life of the intelligent well system after putting into use should be 10 years, and the reliability should be more than 95%.

From this we realized that there has been great progress in Article 1 and 2 in China. However, we are still limited to the optimization of production units, which is to optimize production by improving one or several important hardware, that is to say, we are still not doing enough for Article 3. One of the important reasons is that Article 5 is not well done. The reliability of downhole and other components is the potential requirement of Article 5, the quality and performance of domestic downhole components are currently difficult to guarantee. At present, the quality and performance of domestic downhole components are difficult to guarantee, and expensive imported components increases the cost of research and development, largely restricting the development and application of intelligent well technology in China. In addition, due to the difference in geological conditions, unlike the high-yield well with long self-blowout period abroad, the reservoir energy in China is relatively low. Although there are some high-yield well, the self-blowout period is relatively short, posing higher requirements for the design of our intelligent well technology. After years of intensive injection and production, the contradiction between layers of oil and gas well is becoming more and more serious. The economic benefit of oil field is declining due to the decrease of production and the increase of liquid water content. China urgently needs to innovate the completion technology. China's intelligent well technology catches up with the trend of “China Creation”. The author puts forward the following considerations for the development of intelligent well technology in China:

(1) The key technology is the core, and the basic components are flesh and blood. Parallel with vigorous development of key technologies, we should also pay attention to the underground electronic components resistant to high temperature, high pressure, electromagnetic interference and corrosion. These components will be the foundation of the Baizhang Tower, the flesh and blood of the technology giant.
(2) Our own intelligent well technology should be of Chinese characteristics. We should understand more about the oil and gas well, design and improve non-self-blowout well with low reservoir energy but high expected production, so that intelligent well can adapt to China's geological conditions.
(3) Intelligence is the means and efficiency improvement is the goal. We should always remember that intelligent well technology is designed to optimize production and improve efficiency. If the current intelligent well technology is applied to a well of about 4000 m, an input of nearly RMB 8 million is required. It is generally believed that the daily production of oil and gas well should not be less than 68 tons. Otherwise, the higher initial investment in installing the intelligent well system will lead to lower production and longer return period. Therefore, in order to develop and promote intelligent well technology, we shall make sure that the cost is kept at a reasonable level. Otherwise, the intelligent well is just flashy.

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Appendix A. Supplementary data

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References

[1] Paulo Tubel, Mark Hopmann, Intelligent completion foe oil and gas production control in sub sea muhilateral well applications[C], Species 36582 (1996).
[2] Clark E. Robison, Overcoming the Challenges Associated with the Life-Cycle Management of Muhilateral Wells: Assessing Moves To-Wards the “Intelligent Completion”[C], (1997) SPE 38497.
[3] Jack Angel, Intelligent well systems-Where we've been and where we're going, World Oil 224 (3) (2003) 23–26.
[4] Junrong Liu, Jun Yao, Kai Zhang, Present situation and prospect of intelligent well, Pet. Geol. Recovery Effic. 14 (6) (2007) 107–110.
[5] Hongen Dou, Recent progress of Petroleum engineering technology abroad, China Pet. Mach. 31 (7) (2003) 69–72.
[6] Jie Li, Brief introduction of intelligent wells system, Oil Drill. Prod. Technol. 26 (1) (2004) 77–80.
[7] Demong Karl, Unique multilateral completion systems enhance production while reducing cost and risk in middle east off shore wells, SPECIES 63193 (2000).
[8] Nigel Snaith, Richard Chia, Experience with Operation of Smart Wells to Maximize Oil Recovery from Complex reservoirs, (2003) SPE 84855.
[9] Shuqin Xiao, Junbin Chen, Zhan Qu, Intelligent well completion system, Journal of Xi'an Shiyou University(Natural Science Edition) 19 (2) (2004) 37–40 44.
[10] Jinping Yuan, Status quo and research direction OF well completion technology IN China, Drill. Prod. Technol. 30 (3) (2007) 3–6.
[11] G.A. Carvajal, I. Boisvert, S. Knabe, A Smart Flow for Smart Wells: Reactive and Proactive Modes, (2014) SPE-167821-MS.
[12] Jinling She, Xinfang Wei, New development of intelligent well completion technology in Shengli oilfield, Pet. Drill. Tech. 39 (2) (2011) 67–72.
[13] F. Ebadi, SPE, D.R. Davies, Should “Proactive” or “Reactive” Control Be Chosen for Intelligent Well Management, (2006) SPE 99929.
[14] L.F. Almeida, Y.J. Tupac, et al., Evolutionary Optimization of Smart-Wells Control under Technical Uncertainties, (2007) SPE 107872.
[15] Research Institute of Oil Production Technology of Zhisheng Oilfield Company, Intelligent Completion Technology at Home and abroad vol. 6, (2013).
[16] Weatherford, Intelligent well system [EB/OL], Hcsp http://www.weatherford.com/weatherford/groups/public/documents/completion/cmp_intelligent.well.systems, (2010) 10.
[17] K.A. Pieter, Kapteijn. Intelligent oilfield, World Pet. Ind. (5) (2003) 12–16.
[18] Jianbo Song, Changliang Ding, Development and application of intelligent completion technology, China Pet. Chem. Stand. Qual. 7 (2014) 117.
[19] Wenxue Ling, Baker Hughes MultiNode^{TM} all-electric intelligent well system, Pet. Drill. Tech. 03 (2015) 81.
[20] Jingmei Wang, Development trend of intelligent well technology in the next decade, Oil Forum (02) (2008) 32–34.
[21] A. Abdullatif, A.L. Omair, Economic Evaluation of Smart Well technology[D], Texas A&M University, Texas, 2007.
[22] Changhong Gao, Rajeswaran, E. Nakagawa, A Literature Review on Smart-Well technology, (2007) SPE 106011.
[23] Obuekwe Chukwukadibia Mogbo, Intelligent Wells: Horizontal Well Simulation for Thin Oil Rims Abundant in the Niger-Delta - A Case Study, (2010) SPE133389.
[24] Chenliang Ruan, Heming Zhu, Lingying Feng, Introduction of intelligent completion technology abroad, China Pet. Mach. 39 (3) (2011) 82–84.
[25] Jinlin She, Xingfang Wei, Petroleum drilling techniques, Pet. Drill. Tech. 39 (2) (2011) 68–72.
[26] Congfeng Qu, Zhaohui Wang, Jinping Yuan, Development status and trend of intelligent completion, Energy Conserv. Pet. Petrochem. Ind. 26 (7) (2010) 28–31.
[27] Bukhamsin Ahmed, Home Roland, Using Distributed Acoustic Senseors to Optimize Production in Intelligent wells, (2014) SPE-170679-MS.
[28] Yongsheng An, Xiaodong Wu, Petroleum drilling techniques, Pet. Drill. Tech. (2007) 11.
[29] Chao Chen, Yu Lei, Deji Liu, Application of Smart Packer Technology in Underbalcanced Completion, (2012) IADC-15588.
[30] Shuqian Xiao, Research on Mathematical Model of Intelligent Well Comprehensive System[D], Xi'an Petroleum University, Xi'an, 2004.
[31] Daneshy Ali, Daneshy Consultants, Inflow-Control-Device Design:Revisiting Objectives and Techniques, (2012) SPE-133234.
[32] Jun Yao, Juneong Liu, Ji Zhang, Foreign Intelligent Well Technology[M], Petroleum Industry Press, 2011.
[33] Suwat Athichanagorn, Roland N. Horne, Jitendra Kikani, Processing and Interpretation of Long-Term Data Acquired from Permanent Pressure Gauges, (2002) SPE-80287.
[34] Liang-Biao Ouyang, Jitendra Kikani, Improving Permanent Downhole Gauge (PDG) Data Processing via Wavelet Analysis, (2002) SPE-78290.
[35] M.Y. Soliman, J. Ansah, J. Burris, Well test analysis in the new economy, J. Can. Pet. Technol. 42 (7) (2003).
[36] Stig Olsen, Jan-Erik Nordtvedt, A.S. Epsis, Improved Wavelet Filtering and Compression of Production 96800-MS SPE Conference Paper, (2005).
[37] Masahiko Nomura, Processing and Interpretation Pressure Transient Data from Permanent Downhole Gauges[D], Heriot-Watt University, 2006.
[38] Xiaogang Li, Processing and Analysis of Transient Data from Permanent Downhole Gauges (PDG)[D], Heriot-Watt University, 2009.
[39] Fei Wang, Processing and Analysis of Transient Pressure from Permanent Downhole Gauges, Heriot-Watt University, 2010.
[40] Fuyong Wang, Shiyi Zheng, Unknown rate history calculation from downhole transient pressure data using wavelet transform, Transp. Porous Media 96 (2013) 547–566.
[41] Yang Liu, Roland N. Horne.Interpreting Pressure and Flow Rate Data from Permanent Downhole Gauges with Convolution-Kernel-Based Data Mining Approaches, SPE-166440..
[42] C. Tian, R.N. Horne, Applying machine learning techniques to interpret flow Rate,Pressure and temperature data from permanent downhole gauges, Presented at the SPE Western Regional Meeting, Garden Grove, California, USA, 27-30 April, 2015 SPE-174034-MS.
[43] Geir Nævdal, Trond Mannseth, Erlend H. Vefring, Near-Well Reservoir Monitoring through Ensemble Kalman Filter, (2002) SPE 75235.
[44] Mohammad Zafari, Albert C. Reynolds, Assessing the Uncertainty in Reservoir

Description and Performance Predictions with the Ensemble Kalman Filter, (2007) SPE-95750.
[45] Alireza Shahkarami, Shahab D. Mohaghegh, Yasin Hajizadeh, Assisted History Matching Using Pattern Recognition Technology, (2015) SPE-173405-MS.
[46] Grebenkin, Ivan Mikhailovich, David R. Davies, A Novel Optimisation Algorithm for Inflow Control Valve Management, (2012) SPE154472-MS.
[47] Polina Minulina, Shahin AI-Sharif, Zeito George, The Design, Implementation and Use of Inflow Control Devices for Improving the Production Performance of Horizontal Wells, (2012) SPE-157453.
[48] A.S. AI-Dossary, S.P. Salamy, H.K. Mubarak, First Installation of Hydraulic Flow Control System in Saudi Aramco, (2005) SPE-93183.
[49] C. Wang, G. Li, et al., Production optimization in closed-loop reservoir management, SPE J. 14 (3) (2009) 506–523.
[50] B. Yeten, L.J. Durlofsky, et al., Optimization of Smart Well Control, (2002) SPE79031.
[51] A.S. Cullick, T. Sukkestad, Smart Operations with Intelligent Well Systems, (2010) SPE 126246.
[52] F.A. Dilib, M.D. Jackson, Closed-loop Feedback Control for Production Optimization of Intelligent Wells under Uncertainty, (2012) SPE 150096.
[53] L.F. Almeida, Y.J. Tupac, et al., Evolutionary Optimization of Smart-WellsControl under Technical Uncertainties, (2007) SPE 107872.
[54] A.A. Emerick, R.C.M. Portella, Production Optimization with Intelligent Wells, (2007) SPE 107261.
[55] F.A. Dilib, M.D. Jackson, Closed-loop feedback control for production optimization of intelligent wells under uncertainty, SPE J. 28 (4) (2013) 345–357.
[56] Qing Yang, David Davies, Design of nonlinear predictive controller for intelligent well, Contr. Eng. China 20 (3) (2013) 489–492.
[57] D.C. Doublet, S.I. Aanonsen, et al., An efficient method for smart well production optimisation, J. Pet. Sci. Eng. 69 (1–2) (2009) 25–39.
[58] D.R. Brouwer, J.D. Jansen, Dynamic Optimization of Water Flooding with Smart Wells Using Optimal Control Theory, (2002) SPE 78278.
[59] P. Sarma, W.H. Chen, L.J. Durlofsky, K. Aziz, Production Optimization with Adjoint Models under Nonlinear Control-State Path Inequality Constraints, (2006) SPE99959.
[60] L.F. Almeida, Y.J. Tupac, et al., Evolutionary Optimization of Smart-Wells Control under Technical Uncertainties, (2007) SPE 107872.
[61] Zijian Wang, Dynamic optimization techniques of smart wells using optimal control theory, Acta Pet. Sin. 33 (5) (2012) 887–891.
[62] M.A.S. Pinto, C.E. Barreto, et al., Optimization of Proactive Control Valves of Producer and Injector Smart Wells under Economic Uncertainty, (2012) SPE 154511.
[63] D.R. Brouwer, Dynamic Optimization of Water Flooding with Smart Wells Using Optimal Control Theory, (2004) SPE78278.
[64] P. Sarma, W.H. Chen, et al., Production optimization with adjoint models under nonlinear control-state path inequality constraints, SPE Reserv. Eval. Eng. 11 (2) (2008) 326–339.
[65] G.A. Carvajal, I. Boisvert, S. Knabe, A Smart Flow for Smart Wells: Reactive and Proactive Modes, (2014) SPE 167821.
[66] Jie Qian, Zejun Shen, Weiping Zhang, Opportunities and challenges for the development of intelligent completion technology in China, etc, Pet. Geo. Eng. 23 (2) (2009) 76–79.
[67] Sheng Xu, Yilei Chen, Yuankun Yang, Research status and application prospects of downhole instruments for intelligent well System, etc, Pet. Tubular Goods Instrum. 25 (1) (2011) 46–48.
[68] Jindong Wang, Feng Li, Yongjun Du, Predicting the behavior of sucker-rod pumping wells of double-layer separate recovery, Oil Field Equipment 30 (6) (2001) 7–9.
[69] Dongying District Science and Technology Bureau, National "863" key topic "Key technologies for intelligent completion of deep-water oil and gas fields" is progressing smoothly[EB/OL], 11,19, 2013. http://news.dongyingnews.cn/system/2013/11/29/010407659.shtml.
[70] Fei Liu, Yong Chen, Xiaojun Li, Shengpeng Zhang, New technology of intelligent well completion, Oil Field Equipment 02 (2010) 87–89.