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Present Situation and Development Trend of Oil and Gas Well Perforation Technology

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Abstract:
Perforation technology is a key process in oil and gas development. With the continuous improvement of the complexity of oil and gas development objects and operation requirements, perforation technology has experienced an evolution process from simply opening oil and gas channels to protecting oil and gas reservoirs, improving completion effects, and then combining with production stimulation measures to further liberate oil and gas reservoirs. During this period, a series of advanced technologies and supporting processes such as negative pressure perforation, composite perforation, combined perforation, ultra-high temperature and ultra-high pressure perforation, fixed surface/orientation/fixed azimuth/fixed angle perforation, and cluster perforation have been developed, which have significantly improved the completion effect, increased production and transformation effect, and protected oil and gas reservoirs and improved operation efficiency. However, there is still a certain gap between perforation technology in our country and foreign countries. By combing the current situation of perforation technology, analyzing the technical gap between China and foreign countries, and combining the actual situation and characteristics of China's oil and gas development, this paper puts forward targeted perforation technology development suggestions, aiming to promote the progress of perforation technology, make it better serve oil and gas development, and provide technical support for the high-quality development of our country's oil and gas industry.

Key words: perforation technology; oil and gas development; technology gap; development suggestions

1. Introduction

With the continuous growth of global energy demand, the development and utilization of oil and gas resources as an important energy pillar has received extensive attention. Perforation technology has always played a crucial role in the complex process of oil and gas development. Perforation is a key process in the completion stage of oil and gas wells. Its main purpose is to establish a channel for oil and gas to flow from the reservoir to the wellbore by penetrating the wellbore wall and part of the reservoir, so as to realize the effective exploitation of oil and gas. However, with the complexity of oil and gas development objects, especially the development of special oil and gas reservoirs such as deep, high temperature and high pressure, and low permeability, traditional perforation technology has been difficult to meet the needs of modern oil and gas development. Therefore, perforation technology must continue to innovate and develop to adapt to new challenges. In recent years, perforation technology has undergone a transformation from single function to multi-function integration, from conventional perforation to close integration with production stimulation measures. From the initial simple opening of oil and gas channels, to today's protection of oil and gas reservoirs and improvement of well completion effects, to the coordinated operation with fracturing, acidification and other production stimulation measures, perforation technology

has become increasingly important in oil and gas development. In this process, a series of advanced perforation technologies have emerged, such as negative pressure perforation, composite perforation, combined perforation, ultra-high temperature and ultra-high pressure perforation, fixed surface/orientation/fixed azimuth/fixed angle perforation, clustered perforation, etc. These technologies not only improve the productivity and completion quality of oil and gas wells, but also play an important role in protecting oil and gas reservoirs and improving operation efficiency.

The changing role of perforation is accompanied by the development of perforator technology, perforation detection and evaluation technology, perforation process technology, perforation optimization and software technology, etc. From these aspects, the perforation technology is sorted out and summarized, the current situation of Chinese and foreign technologies is compared, and the gap is identified. The development direction is explored to promote the development of perforation technology, so that it can better serve the oil and gas development.

2 Perforation technology development

In the early days, foreign companies such as Halliburton, Schlumberger, and Baker Hughes introduced equal-aperture perforators with an aperture deviation of 2.1% to 9.2%, such as the Maxfrac series, Stimstream series, and True-jet series. Domestic perforator manufacturers also introduced equal-aperture perforators with an aperture deviation of generally less than 10%. Foreign Hanting company's cluster perforators Each perforator is composed of three rounds of the same plane, with a gun length of 7.5 inches. Baker Hughes' fracturing optimization perforator adopts an internal orientation method and a gun length of 18 inches. Domestic companies have gradually begun to apply short perforators in shale oil and gas development. In terms of initiation technology, addressable electric detonator technologies such as explosive bridge wire detonators (EBW) or impact plate detonators (EFI) with anti-stray voltage, current and radio protection are widely used at home and abroad. Foreign countries have also introduced technologies such as modular connection technology, such as Schlumberger's Fractalflex system and Halliburton's Maxfire ® electric ignition system to simplify on-site operation. In China, shale oil and gas clustering perforation technology has developed rapidly. The clustering perforation technology of aerospace energy has been developed since 2012. In 2015, the first generation of voltage-controlled clustering perforation system was developed. In 2018, the second generation of electronically controlled clustering perforation system was developed and applied in batches. The domestic market share of core products reached more than 80%. CNPC Logging's "Pioneer" perforating shells are also gradually going international, February 4, 2025, The API RP 19B Section II registration data table of the "Pioneer" 114 perforating projectile was released on the official website of the American Petroleum Institute (API). The Wireline Group launched a fully automatic-self-directed-modular-addressable selective pumping perforation service, with a directional angle deviation of less than 5 ° and high perforation accuracy. The application scale of the company's new perforation technology has increased from 20% in 2023 to 80% in the first half of 2024. By the end of December 2024, the third-generation intelligent perforation system developed by the Seventh Institute of Aerospace Energy of China Aerospace Science and Technology Corporation has completed the down-hole test[1]. Nowadays, although perforation technology has made significant progress, it also faces challenges such as low standardization, cost pressure, and the need to accelerate technological upgrades to adapt to complex oil and gas extraction conditions.

3. Research Status of Perforation Technology

3.1 Negative pressure perforation technology

Negative pressure perforation technology is an advanced perforation technology that forms a negative pressure difference in the moment of perforation by reducing the pressure of the liquid column in the wellbore and making it lower than the formation pressure. It can effectively remove the debris and compacted layer in the perforation hole, reduce the damage to the oil and gas layer, and significantly

improve the productivity and completion quality of oil and gas wells. In recent years, with the emergence of new technologies such as dynamic negative pressure perforation and self-cleaning perforation, the application effect of negative pressure perforation technology in the development of complex formations and special oil and gas reservoirs has been further improved. At present, negative pressure perforation technology has been widely used and developed at home and abroad. In foreign countries, for example, in a large oil field in the Middle East, due to the characteristics of low porosity and low permeability of carbonate rock reservoirs, the conventional perforation completion method was not effective in the past. Later, advanced negative pressure perforation technology was adopted. By optimizing perforation parameters and string structure, and using YouTube to transmit negative pressure perforation technology, the compaction pollution of shaped perforation projectiles to the formation was successfully eliminated, and the formation penetration rate in the near-well area was greatly improved, which increased the average oil well production of the oil field by more than 30%, effectively improving the overall development efficiency of the oil field[2]. In China, the Bohai drilling in the North China Oilfield No. 4 oil production plant Xing 9-10X well, in view of the high technical difficulty of the well, construction risks, etc., using negative pressure perforation and perforation combined with injection technology for gas testing, using full-diameter testing tools and double ignition head with accurate calculation and determination of the scientific and reasonable string structure, breaking through the long perforation section, multi-interlayer, inclined wells, deep wells, high-temperature well construction technical difficulties, and finally put into production with 8mm oil nozzle, the daily production of natural gas 48,576 cubic meters, 10.83 cubic meters of crude oil flow, providing a strong technical guarantee for the capacity construction and development of North China Oilfield.

3.2 Composite perforation technology

Composite perforation is an oil and gas well completion and production stimulation technology that combines perforation with high-energy gas fracturing. In the same string operation, the dual functions of perforation and small-scale fracturing are completed in sequence. The basic principle of composite perforation is that after the perforation projectile explodes and shoots the casing and formation, the gas-producing materials such as gunpowder or propellant in the composite perforation device are used to generate high-temperature and high-pressure gas within a certain period of time to further fracture and dredge the newly formed perforation channel. The gas produced by the gas-producing material expands rapidly in the perforation channel, causing multiple micro-cracks in the rock around the channel, expanding the seepage channel of oil and gas, thereby improving the productivity of oil and gas wells. This technique makes use of the instantaneous penetrating ability of perforation and the fracturing action of high-energy gas to realize the double transformation of the formation. The composite perforation device is mainly composed of perforation gun, perforation projectile, detonation system and gas production device (such as gunpowder or propellant). The perforating gun is a shell that carries the perforating projectile and the gas production device, usually made of high-strength steel[3] to withstand the high-pressure environment downhole; the perforating projectile is a key component used to penetrate the casing and formation, and its performance directly affects the perforation effect; the initiation system is responsible for triggering the sequential action of the perforating projectile and the gas production device to ensure the smooth progress of the perforation and fracturing process; the gas production device releases the gas at a predetermined time and pressure after the perforation, and fracturing the formation.

In the eastern Venezuelan oilfield, PDVSA operates two wells, RG-231 and AM-102, located in a layered reservoir with low porosity and complex geological characteristics, in which the gas penetration rate of the RG-231 well is extremely low, less than 0.02 mD. In order to increase gas recovery and well capacity and reduce operating costs, the ultra-positive pressure composite perforation fracturing technology is adopted. The technology uses a standard perforation combination and procedure to generate extremely high pressure carbon dioxide gas in millisecond time by using propellant, overcoming in situ stress, dredging the

gunhole, and generating micro-cracks near the wellbore, effectively increasing the capacity of the well. In 2007, Tongyuan Petroleum successfully implemented the combination of composite perforation and testing in a well on the CNOOC Bohai drilling platform for the first time. The perforation device adopts Tongyuan F178-40DP28 composite perforation device, and the perforation section length is 16m. From 2007 to 2008, more than 10 wells were successfully combined with composite perforation and testing in Qinghai, Bohai and Xinjiang oilfields, all of which were successful, solving the problem that the combination of composite perforation and formation testing had not been realized for a long time2. In addition, the composite perforation technology was introduced into the perforation completion of horizontal wells in Well 2-Ping 25 of Daqing Oilfield, and the perforation section, perforation phase, perforation gun type and compound charge were determined according to the reservoir distribution. The operation was successfully completed, laying the foundation for the mature application of the composite perforation technology in horizontal wells.

3.3 Directional perforation technology

Directional perforation uses special directional devices or facilities to control the perforation direction, thereby optimizing the perforation design and improving the operation efficiency. Mainly, it is divided into two types: vertical well directional perforation and horizontal well directional perforation. In oil reservoirs, during the development process, conventional perforation usually opens cracks in the horizontal direction. But in actual reservoirs, there are usually inclination angles α 1 and α 2 between the maximum principal stress direction of the reservoir and the horizontal direction. Sometimes it is necessary to use a gyroscope or rotate the perforation string to make the perforation direction point in the main direction, thereby reducing the fracturing pressure of the later reformed reservoir, reducing the difficulty of fracturing and improving the perforation efficiency; at the same time, it can increase the effective oil discharge area of the reservoir and improve the oil well productivity[4].

Some large oil service companies in the world such as Halliburton, Schlumberger, and Baker Hughes are leading the way in directional perforation technology. For example, Baker Hughes proposed a fracturing optimization perforator for horizontal wells drilling perpendicular to the minimum principal stress plane. The internal orientation method is adopted, and there are only three orthogonal energy-gathering perforating projectiles. Through field tests, the treatment pressure is effectively concentrated and the fracture length is extended. CNOOC Shenzhen Branch has innovatively applied the hollow oblique directional perforation technology in the eastern oilfield of the South China Sea, and has implemented 7 wells on a large scale, accumulating 47,000 tons of oil and increasing production by more than 55%, effectively solving the problem of scarcity of wells and declining production capacity in old oil fields.

3.4 Fixed perforation technology

It can accurately control the direction of perforation, and make the perforation channel highly match the perforation channel of the oil and gas layer according to the direction of the oil and gas layer and the development of cracks, etc., thereby improving the efficiency of oil and gas flow and increasing production; during reservoir transformation, planar perforation allows perforation holes to focus on a specific plane, helping to evenly distribute fracturing fluid, forming a more effective fracture network, improving reservoir permeability and discharge area, and enhancing production capacity and recovery rate; it can also avoid unnecessary perforation of non-target layers, reduce damage and pollution to non-productive layers, protect geological structure, reduce costs, and improve oil and gas quality; for repeated transformation of old wells, planar perforation can accurately target the target area and re-perforate, tap the remaining oil potential, avoid inefficient areas, and rebuild oil and gas flow channels Overall, the fixed perforation technology not only improves the economic benefits of oil and gas field development, but also promotes the effective utilization and sustainable development of resources[5]. The cluster perforator introduced by Hunting is a short perforator for fixed perforation. Each perforator is composed of three bullets in the same plane, which can eliminate the interference between the bullets, and can also achieve addressable initiation. It does not need a

detonating cord and is directly detonated by the detonator without wiring. It uses equal-aperture perforating bullets with a gun length of 7.5 inches and can connect up to 50 clusters at a time. The perforator was tested at two stages in a well, and the results showed that it can reduce the pressure of fracturing treatment by 10% while increasing the number of clusters. In the repeated transformation of old oil fields, the fixed perforation technology has achieved good application results. Changqing Oilfield introduced the fixed-surface perforation technology into the repeated transformation of old wells, and carried out the field test of fixed-surface perforation and fixed-point repeated fracturing in 18 wells. After the test well measures, the average daily oil increase of a single well is 1.8 times that of conventional fill-up fracturing in the block. It shows a good application prospect in the longitudinal remaining oil potential tapping, and provides a reference for the optimization of repeated transformation measures in old oilfields.

3.5 Positioning perforation technology

Directional perforation is a new type of YouTube transmission perforation technology developed in recent years. It can control the orientation of the perforation according to needs, so that the perforation projectile can only be fired along and determine the orientation. It is a improvement and supplement to the conventional perforation process. The technology can solve the problems of low efficiency of conventional perforations in fractured oil and gas layers and large bending friction of fracturing, and has a good effect on improving the hydraulic fracturing effect[6]. Halliburton has launched the Maxfrac series of equal-aperture perforators, which can make the fracture pressure of each hole change less, improve the pressure distribution, and increase the effectiveness of fracturing. Baker Hughes proposed a fracturing optimization perforator for horizontal wells drilling perpendicular to the minimum principal stress plane. It adopts the internal orientation method, and there are only three orthogonally oriented shaped perforating bullets, two of which are placed on both sides of the large-bore projectiles, and one deep penetration is set on the high side. It can concentrate on processing pressure, maximize fracture length and extension, and reduce competitive fractures and curvature near the wellbore.

3.6 Clustering perforation technology

In a fracturing section, by precisely controlling the perforation position, multiple perforation clusters are shot at one time with a certain perforation cluster spacing, and multiple perforation holes are formed in each cluster. By using the principle of fracture preferentially perpendicular to the minimum horizontal stress expansion, initial holes are formed in favorable perforation orientations, in order to form multiple cracks or complex fracture networks in the section during fracturing, thereby maximizing the contact area between cracks and reservoirs and improving oil and gas well production[7]. In North American shale oil and gas development, such as the Bakken and Trident Wells formations, the limited viewership of perforation technique (XLE) is used for clustering perforation. In the XLE 1.0 fracturing section, 30-32 segments are designed, each section is 6-15 clusters, 2-3 holes per foot, cluster spacing is 33 feet, and perforation cluster efficiency reaches 73% -95%; XLE 2.0 designs fracturing 25-27 segments, each section is 8-20 clusters, 1 hole per foot, cluster spacing is less than 30 feet, and cluster efficiency is 85% -100%. This technology has the advantages of improving the fracturing effect, accurately controlling the fracture direction, optimizing resource development, and reducing construction costs, but it also faces challenges such as difficulty in parameter optimization, high tool reliability requirements, and the risk of casing damage. At present, it has been widely used in shale oil and gas development and other fields at home and abroad and has achieved certain results. In the future, it will develop in the direction of intelligence and automation, integration with other technologies, and research and development of new tools and materials.

4. Perforation technology development

The future development trend of perforation technology presents multi-dimensional characteristics. On the one hand, the degree of intelligence and automation will continue to improve. With the help of big data, artificial intelligence, Internet of Things and other technologies, intelligent decision-making and automated

operation can be realized based on real-time downhole data, just like the fully automatic perforation service launched by The Wireline Group and the development of the intelligent cluster perforation system of the aerospace energy of the Seventh Academy of China Aerospace Science and Technology Corporation; on the other hand, it is deeply integrated with other technologies, covering geological engineering integration, fracturing technology, drilling technology, etc., and integrates multiple factors for overall optimization design and coordinated development. In terms of new tools and materials, in order to adapt to extreme environments such as ultra-deep, ultra-high temperature and high pressure, the temperature and pressure resistance and corrosion resistance will be further improved, and the perforation performance will also be optimized, such as improving the penetration depth and pore diameter, and developing perforators with self-cleaning and sand control functions. In terms of operation concept, we are moving towards high efficiency, environmental protection and low cost. We should not only improve operation efficiency, but also use green and environmentally friendly materials to reduce pollution and optimize the process. In addition, due to the different conditions and needs of different oil and gas fields, customized and personalized services will also be continuously enhanced. We will tailor-make perforation programs, tools and services for customers to meet their development needs.

5. Conclusion

With the development of oil and gas resources becoming more diverse, the connotation of perforation technology continues to enrich, and its role and status in oil and gas development are also constantly changing. Perforation is a special technology that integrates multi-disciplinary knowledge, and its progress marks the improvement of the entire system. At present, oil and gas development is facing complex conditions such as deep high pressure and unconventional reservoirs. The development of perforation technology needs to adhere to the all-round integration of basic theoretical research, R & D innovation, production and manufacturing, engineering application, effect evaluation and technical optimization. In this way, we can calmly cope with the various challenges brought by oil and gas development to perforation and help the development of the oil and gas industry.

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