Review of Key Technical Principles of Multi-stage Segmented Fracturing Sleeve

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Abstract. Oil and gas development at home and abroad face the problem of low natural productivity of low permeability reservoirs. As it can effectively improve the recovery rate and reserve utilization rate of low permeability reservoirs, the multi-stage segmented fracturing technology today is one of the important means for the development of unconventional reservoirs. The fracturing sleeve is the core tool of multi-stage segmented technology. Major foreign companies have launched target-specific research and achieved many advanced results. In spite of a latecomer in this field, some domestic experts and scholars have proposed some characteristic techniques and tools. The author of this paper is poised to analyze the key technical principle of domestic and foreign fracturing sleeve and discuss the advantages and applicability of various relevant tools and processes with the purpose of laying a foundation for the development of fracturing sleeves in China.

1. Introduction

Multi-stage segmented fracturing technology is widely used to improve development of shale gas and coalbed methane, and has broad application prospects while the unconventional reservoirs featuring low permeability and low porosity are increasing\textsuperscript{[1-3]}. Multi-stage segmented fracturing technology refers to a kind of layer-by-layer reservoir transformation technology where the fracturing sleeve is placed before cementing and the sleeve of each layer is opened after cementing by means of the lowering open/close tool according to the reservoir layer conditions\textsuperscript{[4, 5]}. This technology can increase the contact area of the reservoir and reduce the pressure difference, thereby greatly improving the fluid extraction efficiency. Compared with the traditional fracturing technology, the multi-stage fragmented fracturing technology has a number of advantages, including high number of construction fracturing stage, high liquid return rate, small influence of subsequent lowering tool and high construction reliability, apart from no need for drilling\textsuperscript{[6,7]}

The fracturing sleeve is the core tool for multi-stage segmented fracturing technology. The key is open/close stability, seal reliability and plugging effectiveness. Specifically, the fracturing sleeve should meet the following requirements\textsuperscript{[8-10]}:

- The sleeve is required to open and close accurately under the set pressure;
- It is required that the sleeve is effectively sealed in the closed state, that is, other fluids such as fracturing fluid are not leaked;
It is required that inter-layer plugging is effective during fracturing operation on a certain layer.

At present, foreign countries have made great progress in the research of fracturing sleeve, and a series of characteristic tools and techniques have been formed. Based on the opening and control method of the fracturing sleeve, the author of this paper will analyze the key technical principles of the related research on fracturing sleeves at home and abroad.

2. Status Quo of Key Technical Principles of Fracturing Sleeves at Home and Abroad

2.1 Pitching and sealing

(1) Traditional stage-by-stage pitching

The traditional stage-by-stage pitching sleeve is applicable to the segmented fracturing process column of a variety of horizontal well. It’s mainly composed of ball seat, fracturing passage, sleeve, locking mechanism, outer tube and various seals, as shown in Fig. 2-1. The traditional stage-by-stage pitching sleeve has a simple structure. In addition to layer fracturing in sequence, selective fracturing may be performed on the reservoir without moving the column. Apart from little operation risk, the traditional stage-by-stage pitching sleeve may greatly shorten fracturing time and effectively boost production of the horizontal wells.

In the field application, the column is connected to the segmented fracturing column of the horizontal well. In the preset downhole position, the low-density ball is put in to pressurize and close the ball seat passage. When all the packers are set, the operators continue to pressurize and cut the shear pin in the differential pressure opening sleeve, as shown in Fig. 2-2a. The pressure continues to push the inner sleeve down into position and the locking mechanism is activated. Segmented fracturing is carried out through the injection hole on the outer tube, as shown in Fig. 2-2b.

Fig. 2-1 Structure of the traditional stage-by-stage pitching fracturing sleeve

Fig. 2-2 Traditional stage-by-stage pitching

At present, most of the traditional stage-by-stage pitching fracturing sleeves in oilfield are used in vertical or inclined wells. The limitations include:

- The pitching sleeve cannot be self-locked after opening;
- Due to the grit in the sleeve, the low-density ball cannot enter the ball seat smoothly so that the sleeve cannot open normally;
- If the ball seat is not made of a drillable material and the circumferential fixation between the inner sleeve and the outer tube is not enabled, the ball seat cannot be drilled. Or else, it will affect the oil well drainage and subsequent production;
- For the traditional pitching sleeve fracturing process, the number of stages is limited (about 10 stages domestically, 24 stages overseas), and the diameter reduces over stages. It’s difficult to meet new process requirements such as full-bore fracture, no restriction on fracturing stages, selective fracturing and continuously adjustable opening.

(2) One ball multi-cluster

Only one conventional multi-stage fracturing sleeve may open per pitching. Due to the limitation of the stage difference, the seaming capability is restricted, and the construction displacement is limited when only the single sleeve opens. The one-ball multi-cluster segmented fracturing sleeve
and process technology have thus been developed. This technology ensures one-ball multi-cluster segmented fracturing through a metering process. By greatly enhancing the existing process technology, this technology provides new ideas for efficient exploration of unconventional reservoirs. At present, the foreign well-established one-ball multi-cluster segmented fracturing sleeves are: Halliburton RapidFrac™ system, Weatherford ZoneSelect MASS Frac Sliding Sleeve system and Packers Plus QuickFrac system [11,12,13].

- Fig. 2-3 Weatherford MASS one-ball multi-cluster fracturing sleeve and column

The one-ball multi-cluster fracturing sleeve is similar to the traditional pitch sleeve. The size of the fracturing ball also increases stage by stage, but the fracturing density increases. Stage 1 fracturing layer has one or multiple sleeves and the last sleeve is used as a pitching sealing sleeve. In addition, since the fracturing fluid is continuously pumped, the operation cycle and water consumption are reduced, saving operating time and cost. Matching and selection of parameters such as hole diameter, number, opening pressure, construction displacement, number of clusters, and number of stages is the key to the tool design and field application. Customized sleeves according to special fracturing requirements can more efficiently reduce operation risks and enhance post-fracturing output.

(3) The same size pitching

The size of the fracturing ball of the conventional pitching and the one-ball multi-cluster fracturing sleeve increases stage by stage. Therefore, the number of stages is limited and the diameter of the flow path reduces stage by stage. In order to address this problem, the same size pitching fracturing sleeve and process technology have been developed. Represented by the Weatherford 1-ball system, the diameter of its sleeve is close to the inner diameter of the main oil pipe, and can be installed in an area with infinite number of stages (to ramp up production). Each area uses the same size fracturing ball to break through the stage difference of the fracturing layer [14, 15].

The main structure of the same size pitching fracturing sleeve includes top module, five sets of base units, rotating cage, inner sleeve, coil spring, ball catcher and bottom module, as shown in Fig. 2-4.

- Fig. 2-4 Structure of Weatherford same size fracturing sleeve

The process of the same size pitching fracturing sleeve is shown in Fig. 2-5. Its main features:

- Theoretically unlimited number of stages reduces the cost of grinding and milling the ball
The diameter of the fracturing ball is constant, there is no need to determine the ball sequence, and the entire system is highly automated;

- It requires lower fracturing pressure and ground hydraulic horsepower than the traditional stage-by-stage sealing sleeve;

- The structure is more complicated, the layer fracturing coupling is strong, the reliability reduces, and the hazard is higher;

- In spite of no grinding and milling, reverse drainage is required and the efficiency may not be improved.

2.2 Coiled tubing open

The coiled tubing open fracturing sleeve mainly refers to the annulus fracturing bottom hole assembly (BHA) hydraulic starting sleeve installed on the coiled tubing. At present, the foreign well-established coiled tubing open fracturing sleeves are: Weatherford ZoneSelect Mono-bore system of, Baker Hughes OptiPort fracturing sleeve technology and TMK QUANTUM CT coiled tubing multi-stage fracturing system, etc.[16]

![Fig. 2-6 Coiled tubing open sleeve and tool](image)

The main structure of the coiled tubing open fracturing sleeve includes coiled tubing open sleeve, positioner and open/close tool etc., as shown in Fig. 2-6. Its main features:

- Infinite stage of fracturing of cementing or non-fixing wellbore and subsequent re-fracturing;

- Reduce water consumption and horsepower requirements and minimize downtime between fracturing layers;

- Circulate the fracturing fluid through the coiled tubing so that the cycle efficiency is higher;

- A large (ramping up production) area will result in additional stroke of coiled tubing, increasing manpower as well as operating time and associated costs.

2.3 Hydraulic open

During the development of domestic reservoirs, it is found that the water content of different layers in the same well or different segments of the same layer is often different. Conventional completion technology cannot adjust the production layer, or control the water and gas cone advancement during multi-layer mining. And the mining results are poor. In order to cope with these problems, the hydraulic open fracturing sleeve controlled by a hydraulic pipeline has been developed. Its structure includes upper spindle and outer tube. The first hydraulic passage and second hydraulic passage parallel to the center line are disposed on the tube wall of the upper spindle. And upper seal combination, middle seal combination and lower seal combination between the upper spindle and the outer tube will divide the space between the upper outer tube and upper spindle into the upper and lower hydraulic chamber. The first hydraulic passage is connected to the upper hydraulic chamber, and the second hydraulic passage is connected to the lower hydraulic chamber. The outer tube may move up and down by pressurizing the upper and lower hydraulic chamber, as shown in Fig. 2-7 [17].
Fig. 2-7 Hydraulic open fracturing sleeve

1-Upper joint 2 - Upper spindle 3 - Sheath 4 - Scraper ring 5 - Upper outer tube 6 - Upper seal assembly 7 - Retraction ring 8 - Middle seal assembly 9 - Lower seal assembly 10 - Seal base 11 - Lower outer tube 12 - Bottom seal 13 - Lower spindle 14 - Spring outer tube 15 - Compression spring 16 - Lower joint 17 - Oil production hole 18 - First hydraulic passage 19 - Second hydraulic passage 20 - Positioning ring 21 - Upper hydraulic chamber 22 - Lower hydraulic chamber 23 - Spring 24 - Spring stop

The hydraulic open fracturing sleeve has the advantages of simple structure, easy operation and safety and reliability. It is only necessary to pressurize the hydraulic pipeline for opening/closing the fracturing sleeve. However, during field application, we should ensure opening/closing reliability of the hydraulic pipeline. Restricted by the size of the wellbore, the number of hydraulic pipelines that can be installed from the ground is limited. And it’s unable to achieve infinite stage of fracturing operations.

2.4 Dart open

The dart open fracturing sleeve represented by Schlumberger TAP sleeve uses hydraulic technology and special dart open/close tool, as shown in Fig. 2-8. Its process principle: the darts of fixed size are put into the wellhead, sit in the C-ring of the sleeve, pressurize to open the sleeve and perform the fracturing. At the same time, the fracturing pressure is transmitted to the next layer of sleeve piston through the pressure guiding pipeline, and the piston squeezes the C-ring to form a ball seat and receive the next stage of dart, thereby achieving continuous segmented fracturing between different production layers [18,19].

Fig. 2-8 TAP cementing sleeve (sleeve valve dart) and main components

Apart from hydraulic and pitching advantages, the dart fracturing sleeve has additional advantages:
- Use of a C-ring variable ball seat allows the same size dart to open all fracturing formations;
- No need for extra perforation; the transformation is highly targeted, and the ball seat has a large diameter;
- No need for tools such as hanging packer, open-hole packer, small construction risk and low cost;
- The number of fracturing stages is not limited, and the sleeve can be closed later by using the coiled tubing open/close tool.

But there are also some shortcomings: the passability of darts is worse than that of fracturing balls, and special tools are needed to open/close each TAP valve. In addition, as with the coiled tubing, the coupling between the fracturing layers is strong. If the layer is not properly fractured, the C-ring in the next layer cannot form a ball seat, resulting in the inability to continue to sealing fracturing so that the overall risk is higher.
2.5 Electronic control sleeve
The electronic control fracturing sleeve is to apply radio frequency identification technology (RFID) to the sleeve control system. Its main structure includes RFID sleeve, fall-through-fender (FTF) gate valve, hydraulic power unit (HPU) and radio frequency identification control module, as shown in Fig. 2-9.

After opening the toe sleeve by the pressure control program, the programmed RFID tag moves through the column in a closed loop as well as each un-opened RFID fracturing sleeve. The antenna inside the sleeve capture the control signal and the layer address signal carried by the tag to trigger the corresponding sleeve action. The sleeve control uses the programmed time delay sequence to open the fender after a delay for fluid flow in the lower region [20, 21].

Fig. 2-9 RFID fracturing sleeve

The advantages of RFID electronic control fracturing sleeves:
⚫ Infinite stages of sleeves can be used in the completion, and each sleeve has a unique code address (layer address);
⚫ Provide a substantially faster and more efficient continuous operation;
⚫ The sleeve can open and close at the same time as required;
⚫ The sleeves are physically identical, and the completion column can have a uniform inner diameter to mitigate the loss of pressure;
⚫ When the battery power is no longer available, it can be mechanically opened or closed (using coiled tubing);
⚫ Equipment and manpower demands are greatly reduced.

Although the electronic control fracturing sleeve has great advantages, the RFID tag and the electronic control device such as the reader and the reader antenna have certain requirements for the installation space and the pressure rating, as well as the characteristics of electronic device insulation and the battery discharge, etc. Therefore, it is very difficult to design, manufacture and install, and the corresponding cost will increase.

2.6 Electro-hydraulic controllable horizontal well intelligent sleeve
The electro-hydraulic controllable horizontal well intelligent sleeve has been improved on the basis of the electronic control sleeve. For the first time, electromagnetic wave conduction, measurement and control technology and fracturing technology are combined. The main structure is shown in Fig. 2-10. The first joint with the fracturing port, the sleeve with the convex ring, the central core tube with the groove and the second joint; the first end of the first joint is connected to the first end of the central core tube, the second end of the central core tube is connected to the first end of the second joint, and the first joint, the central core tube and the second joint connect with each other to form an inner chamber [22].

Multiple stages of intelligent sleeve of the horizontal well can be mounted on the column, and the electromagnetic wave signal is transmitted through the ground control system to control the opening of underground intelligent sleeve for forming the O-ring ball seat. The same size fracture ball can complete fracturing of various layers, thus meeting process technology requirements for unlimited number of stages and continuous fracturing.

Fig. 2-10 Intelligent sleeve of the horizontal well

The advantage of the horizontal well intelligent fracturing sleeve is that the horizontal well intelligent sleeve is directly connected to the sleeve, and the sleeve fracturing is conducted after the cementing is completed. Removal of column is not required in case of the large displacement of the volumetric
fracturing. It greatly simplifies the fracturing process, improves the construction efficiency, and ensures controlled mining in the later stage. However, the presence of gas-liquid mixture during use leads to low control reliability.

3. Key Technology Development Direction of Fracturing Sleeve - Downhole Wireless Communication Technology

In order to cope with the increasingly complex reservoir mining needs, digitization and intelligence are the development direction of all wellsite equipment in the future. As an important part of intelligent well technology, downhole wireless communication technology can provide an "eye" for identifying downhole working conditions for downhole tools including fracturing sleeves. Based on underground wireless communication technology, real-time access to downhole data and wireless control is an important development direction of fracturing sleeves. A brief analysis of several current methods of downhole wireless communication technology will be given below.

Downhole wireless communication technology relies on a tester placed at the formation to measure dynamic parameters such as downhole temperature and pressure. The dynamic data of the downhole formation is obtained by using media such as earth, drill pipe, sleeve, annulus or mud as a transmission route. Because of its advantages of timeliness, no cable, simple operation, etc., it has become the main technical direction of downhole data acquisition and transmission technology. At present, it is a cutting-edge technology at home and abroad. The main methods include mud pulse, sound wave and electromagnetic wave.

(1) Mud pulse communication

Mud pulse communication is a method of transmitting encoded signals using mud pressure waves. In the mud pulse system, the downhole instrument changes the mud pressure in the drill string through a pulse generator to form a pressure wave and transmits the measurement data to the ground in the form of a pulse. At present, the signal transmission modes using mud as a transmission medium include positive pulse signals, negative pulse signals, and continuous wave signals. The positive pulse and negative pulse transmission modes have lower transmission rate and poor anti-interference ability, but the pulse generator has a simple structure and proven technology; the continuous wave mode has a high transmission rate, a large amount of information, and strong anti-interference ability, but the instrument principle and structure are complex. When the negative pulse signal generator is working, the leaked mud will wash the mud cake of the well wall, and the signal transmission rate is low, the power consumption is large, and the application range is constantly shrinking. Although the advanced wave pulse generator is advanced in technology, it can use complex signal coding, making the data transmission efficiency high. And the highest data transmission rate is 100 bit/s. However, the instrument structure is complex and the manufacturing process requirement is high.

Generally speaking, the advantage of the mud pulse transmission method is that no insulated cable or special drill pipe is required, and the equipment requirements are low. The mud is used as the carrier, which reduces the development and application cost of the instrument, but the transmission speed is slow.

(2) Sound wave communication

Sound wave communication is the use of a downhole sound generator to emit sound waves, and the vibration wave signal or sound wave signal is transmitted to the well through the drill pipe or the earth. Sound wave communication telemetry can meet the open-hole wells, sleeve well and offshore test requirements. However, sound wave transmission has major technical problems such as echo ringing, nonlinearity, narrow-band frequency shift, and weak signal and attenuation. The difficulty of providing underground energy and the interference of background noise waves also limit the application of sound wave communication.

Affected by the attenuation of the downhole channel, the current sound wave telemetry transmission rate is less than 10bit/s, and the one-time sound wave transmission distance is less than 2000m. Since the gas well greatly interferes with the transmission of sound waves, the sound wave communication is currently only used in the testing of oil wells.

(3) Electromagnetic wave communication

Electromagnetic wave communication is the transmission of signals by the mutual conversion of the downhole electric field and magnetic field. Since the earth has a small attenuation of the low frequency
signal, in order to prevent the signal from being seriously attenuated, an ultra-low frequency signal is usually selected as the transmission electromagnetic wave signal. However, such background noise will affect the acquisition of the signal, making the detection of the signal difficult. Representative products of electromagnetic wave communication include French De-meter tool (low frequency electromagnetic wave remote wireless transmission tool), Schlumberger ENACT wireless telemetry transmission system, and EXPRO wireless telemetry (CATS) system.

4. Conclusions
Fracturing sleeve is the key to apply the multi-stage segmented fracture technology. In the current development of domestic fracturing sleeves, three basic requirements need to be addressed: open/close stability, sealing reliability and plugging effectiveness. On the basis of ensuring the number of fracturing stages, the equipment structure is simplified as much as possible, and the coupling between the fracture layers is reduced to cut the cost and mitigate hazards of the fracturing operation. As the difficulty of reservoir exploration continues to increase, multi-stage segmented fracturing technology will face more problems. It is an important requirement in the future development of reservoirs to obtain real-time downhole data and control fracturing sleeves in time. To this end, wireless communication technology should be combined with multi-stage segmented fracturing technology to develop intelligent digital fracturing sleeves and supporting tool systems. Such practice will help to better cope with the challenges of fracturing operations in future oil and gas development.

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