



# Production logging via coiled tubing fiber optic infrastructures (FSI) and its application in shale gas wells

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## Abstract

Multistage stimulation operation using plug and perf technique is the main development mode in domestic shale gas play. Because of the particularity of well trajectory, well geometry caused by rapid drilling operation in shale gas wells, the residual plug debris after plug milling, the complexity of multiphase flow in horizontal section, etc., it is difficult for conventional production logging to meet the needs of shale gas wells. However, a number of shale gas wells need to be evaluated in the effects of well drilling and completion and fracturing, providing the guidance for the next fracturing design, so the production logging via coiled tubing fiber optic infrastructures (FSI) can satisfy the needs of shale gas wells, really reflect water holdup and gas holdup in different fracturing stage, and effectively evaluate fracturing effect of each stage.

**Keywords** Coiled tubing · Fiber optic · FSI (flow scanned image) · Shale gas wells · Production logging

## Preface

At present, the shale gas wells in China are mainly composed of cluster well, long horizontal section, multistage perforation, and large zipper type sand fracturing. The production of gas test and pressure are unstable. It is difficult to implement the production of single well, and it is difficult to correctly understand the actual production situation of the formation and influence the formulation of the production plan of Lv et al. (2012). In view of the special completion mode of shale gas, the dynamic monitoring technology has no effective means to select the domestic and foreign post pressure evaluation technology, and gas production profile testing technology is the most economical and effective means to solve the above problems.

At present, most of the downhole tools used in domestic conventional testing are multi-array distance and single rotor.

The testing work is complicated, the rotor needs larger start speed, and the monitoring error is large; the underground fluid type cannot be distinguished clearly. According to the optical fiber production profile testing technology with continuous tubing as the carrier, the main production layer and the bottom hole liquid condition can be found clearly under the ultra-long horizontal section and multilevel fracturing development mode of shale gas well. At the same time, the technology uses optical fiber as the data transmission means, the anti-interference ability is strong, and the electrical signal of the downhole monitoring tool is used. It is converted into light signal to transfer data faster and more accurately. The flow scanned image (FSI) production logging tool in the tool string has a multistage rotor. It can identify the downhole fluid dynamics more clearly. It has many characteristics, such as convenient field operation, high detection precision, and reliable interpretation results.

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## The system of coiled tubing fiber production profile test

### Coiled tubing equipment

The test of the continuous tubing fiber production section is to connect the downhole instrument to the top of the continuous tubing with fiber in the inner tube. The instrument is carried

out by the continuous tubing and the instrument is driven to complete the test. This method has the advantages of large power, high success rate, and convenient depth control. According to the actual situation of domestic shale gas wells, the continuous tubing with 50.8 mm outer diameter and longer than 5000 m is generally chosen, and the lifting capacity of the continuous tubing unit is more than 360 kN.

### The system of transmission for optical fiber

The ACTIVE fiber transmission system can obtain the downhole data in real time through the continuous tubing transmission, including the bottom hole pressure (inside and outside of the tubing), the actual depth (CCL, GR), the stress situation of the downhole tools, the temperature of bottom hole, the full wellbore temperature distribution curve, and so on. In the construction process, the operation scheme can be optimized at any time and the downhole is quickly and accurately judged. The situation reduces the job risk. The system mainly consists of three parts: optical fiber, downhole instrument, and ground electronic equipment.

#### Optical fiber

As can be seen in Fig. 1, the optical fiber used in the system is to place four fibers in the Cr Ni Fe alloy fiber carrier, and then the fiber carrier is placed in the continuous tubing. Of these four optical fibers, two are used for signal transmission of downhole tools. Another one or two can be used to obtain wellbore temperature curve. Ni Cr ferroalloy fiber carrier diameter is only 1.8 mm and weight is 10 kg/1000 m, compared with cable which is smaller and lighter. The continuous tubing used in this system can carry out normal pitching, pumping liquid, acid, or other corrosive solvents.

The characteristics of optical fiber used in ACTIVE optical fiber transmission system are as follows:

1. Includes four optical fibers
2. Does not affect pitching in a continuous tubing
3. Can be used for normal pumping
4. Fiber has a lighter weight

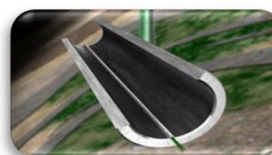
**Fig. 1** The optical fiber used in ACTIVE optical fiber transmission system



Conventional cable

(134-521 kg/1000 m)

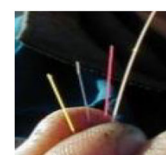
Outer diameter 5.8-12.7 mm



optical fiber

10 kg/1000 m

Outer diameter 1.8 mm



4 optical fibers

5. Relatively simple fiber relaxation processing
6. Is not corroded by acid and solvent
7. Can obtain the wellbore temperature curve

#### The downhole instrument

The downhole instrument of ACTIVE optical fiber transmission system mainly consists of three parts, which can be assembled individually or in combination.

**Fiber optic head** After termination of the terminator of optical fiber head, optical fiber can connect any kind of conventional coiled downhole tool.

**PTC-G-TC** The pressure of downhole temperature, bottom hole pressure (inside and outside of tubing), and downhole tools can be monitored in real time, and the depth of the continuous tubing can be determined by the hoop positioner and gamma ray.

**Photoelectric signal converter** It can connect the cable production logging platform without replacing the coiled tubing with cable and other cable logging equipment.

#### The electronic equipment on the ground

The last part of the ACTIVE fiber transmission system is the electronic equipment on the ground. The data will be transmitted from the continuous tubing to the computer through wireless transmission, and the software on the computer will interpret and display the real-time data in the downhole. If we need to measure the wellbore temperature distribution curve, we need to install a downhole Ultra box and connect it to the optical fiber inside the coiled tubing for measurement.

#### The fluid scanning imaging logging tool

The downhole flow pattern is complex, including laminar flow, mist flow, and circulation flow. The variation and the flow pattern affect the flow profile. When conventional

instruments measure the existence of bubbling flow at the top of the shaft, heavy phase circulation, or inclined flow in a stratified flow at different velocities, there will be problems. The flow loop experiment also reveals that conventional logging tools are ineffective in multiphase flow. The medium measurement of these instruments cannot describe complex flows, because the most important information exists on the vertical plane along the diameter of the wellbore.

Flow scanned horizontal well and deviated well production logging system are specially developed for large deviated wells, horizontal wells, and near horizontal wells. As shown in Fig. 2, the instrument has four micro-rotor flowmeters on one arm of the instrument, measurement of flow velocity profile, and five electrical probes and five optical probes on the other, to measure the local water holding rate and gas holding rate respectively. In addition, there are fifth rotator flowmeters and sixth pairs of electrical probes and optical probes to measure the flow at the bottom of the wellbore. The instrument is an eccentric instrument, and the main body of the instrument is located at the bottom of the wellbore. The measuring arm can be expanded to the inner diameter of the wellbore. As well as the caliper, the full range measurement of (Bao et al. 2013) is provided for the calculation of the flow rate.

As shown in Fig. 3, the velocity profile along the wellbore diameter direction is measured by Flow Scanner, which can measure the velocity changes that cannot be detected by a single central rotor. It can measure mixed and stratified flow patterns, including the independent measurement of gas flow velocity in horizontal wells with multiphase flow. It can even detect the circulating flow of water in the well. Each of the five



Fig. 2 The fluid scanning imaging logging tool (FSI)

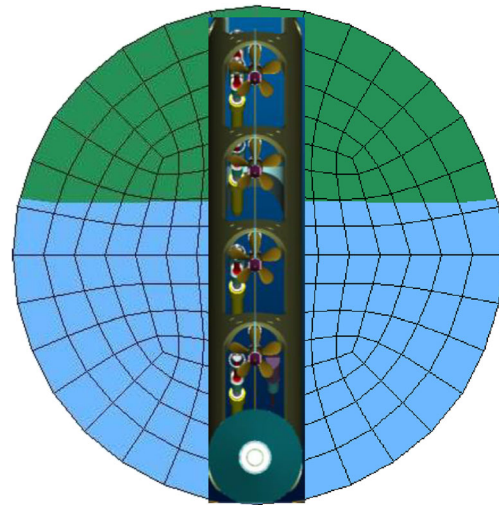


Fig. 3 The distribution of the rotor in the fluid scanning imaging logging tool

micro-rotors can directly measure the velocity of fluid flowing through it, so as to calculate the multiphase flow velocity profile (Zeng et al. 2014).

Flow Scanner detects water by measuring fluid impedance through six low-frequency probes. Because water is electrically conductive, oil and gas cannot be set. A threshold is set to enable the instrument to identify oil and gas and water. When a droplet or bubble in a continuous water phase or a continuous oil vapor droplet touches the probe tip, the probe generates a binary signal. The water holding rate can be calculated according to the time when the circuit is connected, and the water holding rate profile accurately shows the flow pattern in the wellbore.

Conventional low-frequency probes can only identify water from oil and gas, but Flow Scanner is equipped with optical probes for gas detection. The six gas holdup optical probes are sensitive to the optical refractive index of the fluid. Typically, the refractive index of gas is close to 1, the water is about 1.35, and the crude oil is 1.5. Because oil and water have similar optical refractive index, optical probes are used to distinguish gases from liquids. The bubble count can also be obtained from the original data, which is used to determine the location of the first gas production point.

The combination of optical probe and electrical probe can provide the answer to the same depth of three-phase hold rate.

Characteristics of the fluid scanning imaging logging tool:

1. Can be combined with production logging platform and other cased hole logging tools
2. Because of the short length of the instrument, it can operate in a dog's well
3. Measurement of complete three-phase holdup at the same depth
4. Scan the sensor to detect the interface between the phases more accurately

5. Measurements of mixed and separated flows
6. Independently measures gas flow velocity in multiphase horizontal wells
7. Clear flow profiles in non-vertical wells are independent of mixed or cyclic flow

### The comparison of several production profile logging

This paper compares the commonly used production profile testing methods in concentrated shale gas wells, such as Table 1, which shows high precision, high reliability, and high equipment utilization ratio (Wang et al. 2006).

### The technology of well logging

As the continuous tubing fiber optic logging technology needs to pass through the optical fiber to transfer the data collected by the logging tool in the wellbore, the optical fiber needs continuous tubing as the conveying equipment, so the fiber must be passed through the continuous tubing to connect with the logging tool in the lower part. The continuous tubing is shown in Fig. 4. As shown in Fig. 4, only through a hydraulic pump: fiber from the optical fiber roller, through a very small inner diameter speed tube, by friction force into the tubing

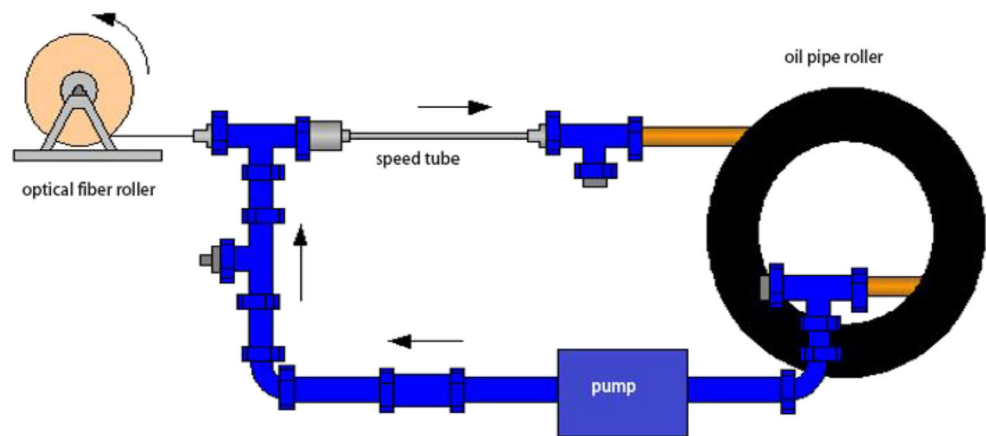
cylinder, after entering the tubing, and because the outer diameter of the fiber diameter is very small, only the hydraulic can be sent to the other end of the tubing. Although the weight of the fiber is very small and the outer layer of Cr Ni Fe alloy is strong, the possibility of fiber winding may be smaller, but as the fiber is frequently used in the process of using the oil pipe and its own gravity and the water power of the cycle, the fiber may be at the bottom of the tubing very much, so every 2–3 wells work, light. The fiber demand is managed by a single margin, which is the circulating water from the end of the tubing, so that the fibers gathered at the end of the tubing are evenly distributed in the tubing.

Because of insufficient understanding of drilling plug technology in the early stage of domestic shale gas well, there are some difficulties in the application process of the wellbore after drilling and plugging, and there are some difficulties in the application process: (1) the debris of the wellbore is gathered, resulting in the obstruction of the continuous tubing in some wells, failure to reach the target depth, and at last the production data of all the wells are not taken; (2) well FSI logging tools damage or affecting the normal work of the rotor and probe; (3) the debris carried by the logging tool is brought to the wellhead, and the gas flow to the ground production process leads to the blockage of the adjustable needle type throttle valve.

**Table 1** The comparison of production well logging in horizontal well

Logging mode	Key feature	Chief application	Weight	Installation	Fluid circulation pitching
Crawler wireline logging	<ol style="list-style-type: none"> <li>1. High accuracy</li> <li>2. Inferior reliability</li> <li>3. High fee</li> <li>4. Slow speed</li> <li>5. Fragile instrument</li> <li>6. Unable to add weight on bit</li> </ol>	Logging	/	/	The ball cannot be thrown
Storage type coiled tubing logging	<ol style="list-style-type: none"> <li>1. Low accuracy</li> <li>2. Inferior reliability</li> <li>3. Jobs that are prone to causing numerous data or data gaps</li> </ol>	Logging, well washing, gas lift, etc.	/	/	The ball can be thrown
Wireline type coiled tubing logging	<ol style="list-style-type: none"> <li>1. High accuracy</li> <li>2. High reliability</li> <li>3. Single job type</li> <li>4. Need common coiled tubing for auxiliary operation (well washing, etc.)</li> </ol>	Logging	Large cable volume, increase the overall weight of the coiled tubing	It is difficult to install and cannot be taken out after being pumped into the cable	Blocked the fluid circulation channel, unable to throw the ball
Optical fiber coiled tubing logging	<ol style="list-style-type: none"> <li>1. High accuracy</li> <li>2. High reliability</li> <li>3. Suitable for all kinds of coiled tubing operations</li> <li>4. Improve equipment utilization</li> </ol>	Logging, perforation, gas lift, acidification, well washing, DTS, etc.	Optical fiber is small in size and light in weigh	Easy to install and can be removed from the coiled tubing at any time	The liquid circulation channel is unimpeded and the ball can be thrown

**Fig. 4** The schematic of put optical fiber into coiled tubing



In accordance with the shale gas production well, more than 20 wells have been applied in China, and a set of complete construction technology is formed without affecting the normal mining.

1. Early wellbore processing. In order to reduce the requirements of pump injection in production wells and the actual situation of the debris in the wellbore which are mostly compound bridge plug metal kava, a special magnetic fishing device is designed and produced for the production section test, and the operation of the continuous tubing and the fishing debris is increased before the formal test. Due to the maximum outer diameter of the fishing vessel being restricted by the gas production wellhead, the groove is designed for 73 mm. At present, the strong magnetic fishing device has achieved good application effect in the early testing of the wellbore, and the effect of iron scraps fishing is better. It effectively reduces the obstruction of the continuous tubing caused by the debris gathering of the wellbore and the damage of the underground instruments. At the same time, the strong magnetic salvage device has been applied to the scraping salvage after the end of the drilling plug and effectively increased the return rate of the bridge plug debris during the test process. The next step is to use the screw motor with the pump nitrogen to carry on the well operation with the grinding shoe; the nitrogen pump injection has little influence on the production well, and the drilling tool combination can handle the wellbore more effectively.
2. Logging technology. In formal logging, the output is observed near the A point first, and the output is observed. If the output meets the logging requirements, the continuous tubing is placed down to the bottom of the artificial well and then to the A point. The appropriate logging data, if the data is qualified, will be completed and the pipe string

is completed. Logging is real-time monitoring, and if there are any problems during the period, it can be solved in time.

3. The protection measures of the continuous tubing. In order to ensure the safety of construction, it is suggested that the external force of the coiled tubing body should not exceed 7 MPa; otherwise, the tubing will be collapsed under the condition of downhole stress. The shale gas wells in China have high wellhead pressure in the early stage of production, and some wells may be as high as 30 MPa. Therefore, it is suggested that liquid nitrogen should be used in the inner oil pipe to make the internal and external pressure difference of internal and external pressure of the tubing not more than 5 MPa.
4. The selection of the test system. In order to obtain a good contribution rate of gas production, two systems are recommended for testing. The yield spacing between the two systems is  $5 \times 10^4 \text{ m}^3/\text{day}$ . As the continuous tubing has a certain volume after entering the well, the volume of the casing is reduced. It has certain drainage effect for the casing production well. It is suggested that a larger test system be used before the well pass through the well; the system test can be carried out first in the test, and the effect is better.
5. Test speed selection. In order to ensure the interpretation of the results, the test is carried out and two tests are carried out in the test. At the same time, the speed of the tubing is faster and the speed of the tubing is quicker; the interpretation result is more accurate, under the premise of ensuring the safety.
6. It is of great significance to ensure the safety of well control because of the whole course belt pressure operation of the gas well, and the well head equipment must be checked regularly. At the same time, it is suggested that the logging continuous tubing is equipped with an on-line detection device to prevent the leakage or fracture of the tubing caused by the physical damage of the tubing.

## Application examples

The optical fiber production profile of coiled tubing has been tested in a well in the Sichuan basin. The bottom hole of the well is 4214.14 m and the horizontal section is 1375 m long, which is divided into 16 stages. At the time of testing, the well head pressure is 30.1 MPa, and liquid nitrogen is used in the oil pipe to carry out the filling operation. The first strong magnetic fishing operation is 3.47 kg and the largest kava tooth diameter 16 mm is removed from the wellbore; the debris in the wellbore is cleared effectively. The work system of  $20 \times 10^4$  m<sup>3</sup>/day and  $29 \times 10^4$  m<sup>3</sup>/day on the ground measurement output is tested respectively. It is being done.

The results of the test interpretation show the following:

1. The results of the production profile show that all the fractured sections have gas production contribution, of which 16 perforated cluster (35.6%) yield is lower than the average production of 1/3, and 17 perforated cluster (37.8%) yield is higher than the average production; this result and the US shale gas homogeneous fracturing results are in line with those in Zhao et al. (2010).
2. There are 4 segments of gas production in the 16 segments; the 8 segment contribution is low, and the 4 segment contribution value is on the average, of which in 3 segments in the 8 sections with lower contribution value, it is difficult to add sand during the fracturing process.
3. Under the two working systems, it is found that there are 8 sections of the fracturing section with relatively large output changes. Under the  $29 \times 10^4$  m<sup>3</sup> system, the water holding rate in the wellbore is obviously lower than that in the  $2 \times 10^4$  m<sup>3</sup>/day system.
4. The downhole flow pattern is dominated by horizontal laminar flow, and the variation of well deviation is very small. In the horizontal wellbore, water is at the bottom of the wellbore, and the gas is in the middle and upper parts of the wellbore. The water is stuck in the wellbore, and the gas flow velocity is fast. In the horizontal wellbore, the water holding rate in the wellbore increases with the depth. With the change of the well deviation, the “reflux” phenomenon can often be observed, as shown in Fig. 5, which is also one of the difficulties in the horizontal well production test. The reflux will affect the response of the single rotor instrument.

## The conclusions

1. The fiber output profile test of continuous tubing can truly get the gas production profile and the

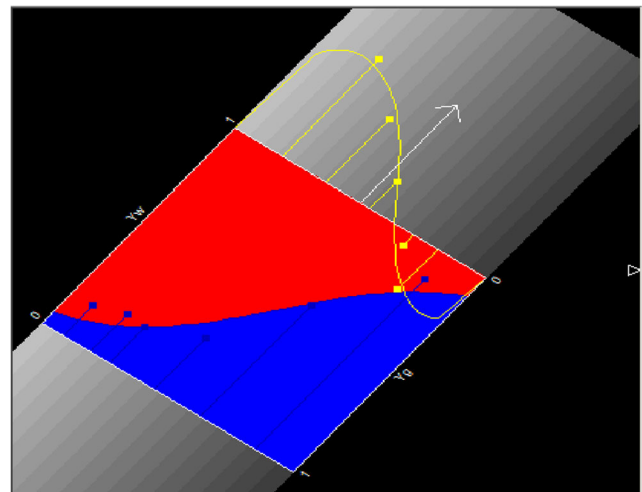


Fig. 5 The distribution section map of oil-water interface in the well

- contribution of various perforated gas producing liquid. The field operation is convenient, the testing precision is high, the interpretation results are reliable, and the fracturing effect at all levels can be evaluated effectively.
2. The downhole data can be obtained in real time, including the bottom hole pressure (inside and outside of the tubing), the actual depth (CCL, GR), the stress situation of the downhole tool, the bottom hole temperature, and the whole wellbore temperature distribution curve, etc.; in the process of construction, the operation scheme can be optimized at any time in the construction process; and the well can be quickly and accurately judged. The lower the situation, the lower the job risk.
  3. According to the characteristics of multiphase flow in horizontal well, FSI logging tool sets 5 micro-rotors, and 6 pairs of probes can directly measure the velocity of fluid flow through its position, calculate the velocity profile of multiphase flow, and combine the flow phase obtained by the 6 probe, and the output profile of the downhole fluid can be obtained.
  4. Aiming at the gathering of shaft debris and increasing the opening of the continuous tubing strong magnetic fishing device and fishing debris, it can appropriately alleviate the problems of the obstruction of the continuous tubing in some wells, the damage of the underground instruments, and the clogging of the well-head process. In the later stage, it is possible to further study the feasibility of driving the grinding shoes to drive wells through the pump nitrogen driving screw drill.

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