Original Research Article

Status of fiber optic monitoring technology in the oil and gas field

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Abstract: Fiber optic monitoring technology demonstrates unique technical advantages and significant application value in oil and gas field . This paper systematically introduces the fiber optic monitoring technology from three dimensions: basic principle, deployment method and technical advantages, and focuses on its application in key areas, including real-time downhole parameter monitoring, reservoir dynamic monitoring, wellbore integrity monitoring, and safety production and risk warning.Practice shows that fiber-optic monitoring technology, as a modern monitoring means integrating science, advancement and safety, can realize dynamic monitoring of the whole life cycle of oil and gas wells.

Keywords: Fiber optic monitoring technology; Real-time downhole parameter monitoring; Reservoir dynamic monitoring; Wellbore integrity monitoring; Safety production and risk warning

1. Introduction

In the 1970s and 1990s, fiber optic monitoring technology emerged in the oil and gas field. In the 21st century, this technology has entered a period of rapid development abroad and has become a key technology for innovation in the oil and gas industry. The domestic application is relatively late, but the development is positive. Since 2015, fiber optic logging technology has been industrialized and rapidly iterated. Expanding to offshore oil fields in 2017. In June 2020, China National Offshore Oil Corporation (CNOOC) achieved distributed fiber optic temperature measurement through internal and external pipelines in Oilfield A. Realize distributed fiber optic temperature measurement of continuous oil pipes by 2022; In 2023, synchronous monitoring of bottomhole fiber optic temperature and pressure will be achieved in A and B oil fields. Nowadays, this technology has played an important role in various aspects of oil and gas exploration and development, promoting intelligent and precise development.

2. Principle of fiber optic monitoring technology

2.1. Principle of fiber optic temperature monitoring technology

2.1.1. Distributed fiber optic temperature sensor (DTS) measurement system

Distributed Temperature Sensing (DTS) system is built based on the combination of spontaneous Raman scattering signals in optical fibers and optical time domain reflection technology. The working principle is that Raman scattering occurring inside the fiber produces Stokes and anti Stokes light. Anti Stokes light is extremely sensitive to temperature changes, and the temperature information at any position on the fiber can be determined by the intensity ratio of Stokes light to anti Stokes light (**Figure 1**)[2]. Over the years, DTS technology has reached a high level of maturity and reliability, becoming one of the most reliable monitoring technologies in the oil and gas field.

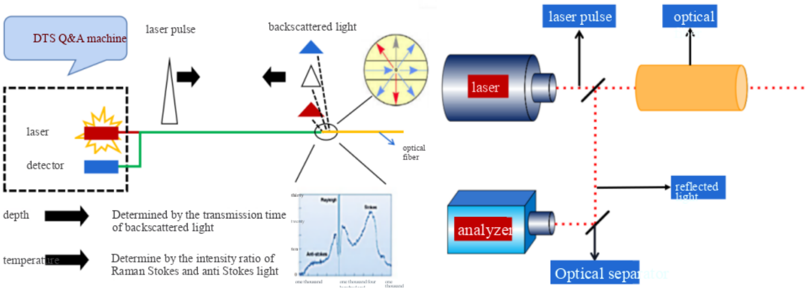

Figure 1. Schematic diagram of distributed fiber optic temperature sensor (DTS) measurement system.

2.1.2. Femtosecond laser fiber grating temperature measurement technology

Fiber Bragg Grating (FBG) has high sensitivity, excellent thermal stability, and strong multiplexing capability. Traditionally, FBG is engraved on a pre charged standard quartz single-mode fiber using ultraviolet laser combined with phase mask technology. However, it will gradually fail in environments with temperatures exceeding 300 °C, so it is not suitable for high temperature conditions. In contrast, femtosecond lasers have extremely short pulse duration and high peak power. When the laser energy reaches or exceeds the damage threshold of the fiber material, the fiber material in the femtosecond laser exposure area will undergo a micro explosion and melt, followed by rapid solidification and contraction, forming permanent Type II refractive index modulation. The FBG prepared by this method exhibits extremely high thermal stability and can withstand high temperature environments up to 1000 °C[3].

2.2. Principle of fiber optic pressure monitoring technology

When optical fibers are subjected to pressure, their physical parameters such as refractive index, length, and diameter will change, thereby affecting the propagation properties of optical signals. These changes include the propagation speed, phase, polarization state, etc. of light. Form a Fabry Perot cavity with a length of L in a sealed conduit, which is composed of two end coated optical fibers, forming a fiber Fabry Perot interferometer. A beam of light entering a pair of parallel plates at an angle will undergo multiple reflections and refractions, and these lights of the same frequency will interfere, forming multi beam interference. When external pressure acts on the Fabry Perot interferometer, the cavity length changes, affecting the reflection spectral characteristics, thereby achieving pressure monitoring[4].

2.3. Principle of fiber optic acoustic vibration monitoring technology

Fiber optic sensing is based on the interaction between light and the external environment, sensing physical quantities through changes in light signals. In acoustic vibration monitoring, optical fibers serve as sensing media, and acoustic waves or vibrations induce changes in their physical properties, modulating the phase, intensity, or wavelength of optical signals (Figure 2). There are two types of mechanisms: ① Acoustic sensing: Sound waves in the air apply periodic pressure to optical fibers, causing radial strain (sound pressure effect), while also causing changes in the refractive index of surrounding media (such as coatings/cladding), modulating the propagation characteristics of light; ② Vibration sensing: Mechanical vibration directly induces axial/radial strain in optical fibers, changing the phase or intensity of optical signals; By utilizing the distributed characteristics of optical fibers, it is possible to synchronously detect vibration signals from multiple locations.

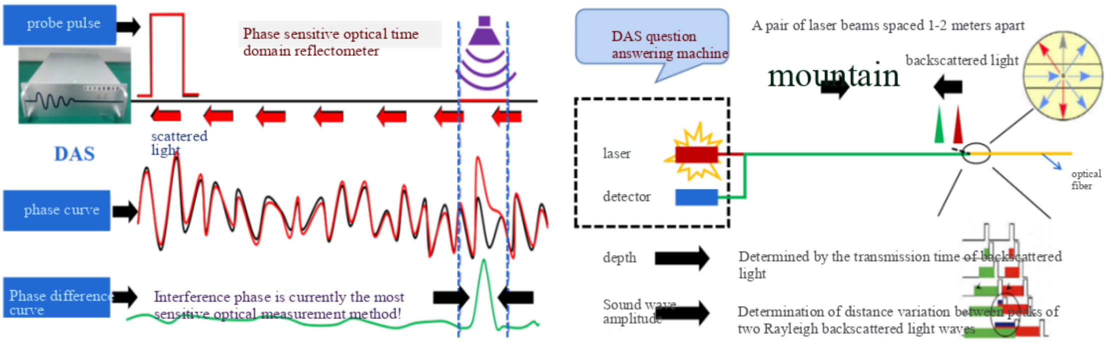

Figure 2. Principle of optical fiber acoustic wave vibration monitoring technology.

2.4. Principle of fiber optic strain monitoring technology

After the laser enters the sensing fiber, it will interact with phonons and undergo inelastic collision and scattering, which is called Brillouin scattering. At the same time, the propagation of sound waves in optical fiber materials will cause periodic changes in pressure difference and refractive index (Figure 3), resulting in a Doppler frequency shift of scattered light relative to incident light. This frequency shift is approximately linearly related to the temperature and strain of the optical fiber to a certain extent, and the relationship between the two is shown in the following formula[5]:

$$v_B = C_{v\varepsilon}\Delta\varepsilon + C_{vT}\Delta T + v_{B0}$$

Where:—Frequency shift after changes in fiber temperature and strain;—Frequency shift under initial temperature and no strain conditions;—Strain variation;—temperature variation;—Strain coefficient, can be determined experimentally;—Temperature coefficient, can be determined experimentally.

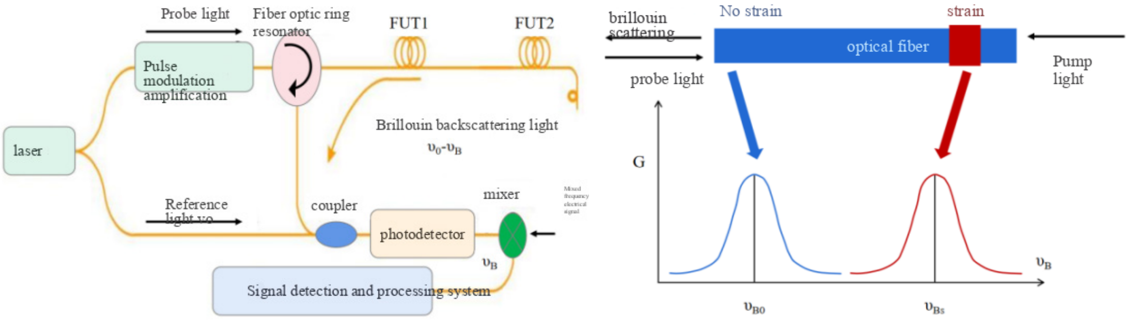

Figure 3. Schematic diagram of the principle of fiber optic strain monitoring technology.

2.5. Advantages of fiber optic monitoring technology

Fiber optic monitoring technology, as an advanced sensing method, has many significant advantages: ① It has extremely high sensitivity and measurement accuracy (temperature change of 0.1 ℃, strain change of 1 microstrain); ② Being able to achieve long-distance and continuous distributed measurement using a single optical fiber while controlling costs; ③ Made of quartz material, non-conductive and not affected by electromagnetic interference; ④ Has strong corrosion resistance and chemical stability, long service life, and low maintenance costs; ⑤ Capable of real-time data collection and transmission, as well as remote monitoring and data analysis; ⑥ It can simultaneously monitor multiple parameters and achieve multifunctional integrated monitoring; ⑦ Flexible installation and strong adaptability can be flexibly deployed according to actual needs.

3. Application of fiber optic monitoring in oil and gas wells

3.1. Real time monitoring of underground parameters

3.1.1. Temperature monitoring

Distributed fiber optic temperature monitoring technology can achieve continuous temperature distribution measurement along the entire fiber optic path. In 2024, the carbon dioxide injection well monitoring system built by Deng Chenghui's team achieved real-time dynamic monitoring of the entire wellbore temperature profile and bottomhole pressure (such as a pressurized carbon dioxide temperature of 70 ℃ during the trial injection period, 87 ℃ during the formal injection period, and a decrease to 56.049 ℃ at 3192m), effectively reducing operational risks and minimizing the impact on production.

3.1.2. Pressure monitoring

In oil and gas exploration and development, pressure monitoring is crucial for efficient reservoir development and equipment safety. With the expansion into deep and complex reservoirs, the accuracy and stability of traditional pressure sensors are facing challenges in high-temperature, high-pressure, and highly corrosive environments. Fiber optic pressure sensors, with their high temperature resistance, high pressure resistance, and corrosion resistance, can achieve real-time monitoring of downhole pressure and provide reliable technical support for pressure measurement in complex environments.

3.1.3. Flow monitoring

Fiber optic sensors have become a key technology for monitoring water content in oil and gas wells due to their high sensitivity, corrosion resistance, and chemical stability. The fluid scanning imaging logging tool (FSI) developed by Schlumberger uses circularly distributed optical and electrical probes to measure gas holdup and water holdup in real time by utilizing the conductivity and density differences of oil, gas, and water phases. The data is transmitted to the surface via optical fibers to achieve dynamic monitoring of water content.

3.2. Dynamic monitoring of oil and gas reservoirs

DAS technology is gradually becoming popular in the field of oil and gas geophysics due to its advantages of low cost and high spatial resolution. By conducting multi parameter, long-term, real-time, and interference free dynamic monitoring of existing oil and gas production wells, and optimizing development plans in a timely manner based on monitoring results, it is possible to maximize oil and gas recovery and reduce production costs. This approach has become the main direction for improving oil and gas field recovery. In 2012, Johannessen K et al. successfully obtained fiber optic signals of fluid flow in offshore oil and gas wells in Norway; In 2013, Van Der Horst J et al. successfully applied DAS technology for dynamic monitoring of tight sandstone gas wells; In 2016, Carpenter C et al. used DAS technology to monitor the fluid flow status in injection production wells in real time; In 2021, Ma Xiaoming et al. combined DAS and DTS technologies to reveal that adding sand to shale gas development wells in Changning, Sichuan can promote formation fracturing transformation.

3.3. Monitoring of wellbore integrity

3.3.1. Quality monitoring of well cementing

Cementing is a crucial step in the entire drilling project. As mentioned earlier, fiber optic monitoring technology can be used for temperature monitoring. Therefore, the quality of cementing at that location can be evaluated by measuring the heat released by the cement hydration reaction during the cementing process. In general, the greater and more uniform the heat released during the cementing process, the better the cementing quality. In 2014, Zhou Weiyong selected the initial setting state of cement, bond peeling, and bond cracks as the core monitoring indicators for evaluating cementing quality. Based on the principle of distributed fiber optic crack sensing and related technical means, a distributed cementing quality monitoring system with temperature compensation function was designed, which can effectively improve the reliability and measurement accuracy of cementing quality detection.

3.3.2. Sleeve damage monitoring

Long term use of tubing and casing can be damaged or deformed by various factors such as geological, chemical corrosion, and production factors, directly affecting oil and gas production. The monitoring technology based on distributed optical fibers provides a new solution for achieving permanent real-time monitoring of casing status. The theoretical basis for measuring sleeve strain using distributed fiber optic monitoring technology is the change in Brillouin frequency shift. By measuring the change in Brillouin frequency shift and combining it with the axial strain profile of the sleeve and the experimentally obtained sleeve damage limit, a sleeve damage warning limit monitoring diagram can be drawn[1]. The monitoring data is transmitted to the data processing system through optical fiber and compared with the preset warning limit. Once the strain of the casing exceeds the warning limit, the system will immediately issue a warning, prompting production to take corresponding maintenance and repair measures to ensure the safe production of oil and gas fields.

3.4. Safety production and risk warning

3.4.1. Oil and gas pipeline safety warning technology

As the core infrastructure for energy transmission, the safety of oil and gas pipelines is directly related to the stability of energy supply, environmental protection, public safety, and economic benefits. The Pipeline Safety Technology Report released by the US Department of Transportation (DOT) in 2021 further refined pipeline safety warning technology, with different technologies having different technical advantages and applicable scenarios **(Table 1**).

Table 1. Comparison of safety warning technologies for oil and gas pipelines.

Technical Type		Detection Principle	Advantage	Limitation
Real-time monitoring	fiber optic sensing	Monitoring vibration or temperature changes using Rayleigh/Brillouin scattering effects in optical fibers	It can achieve distributed monitoring, resist electromagnetic interference, and have a long lifespan	High installation cost, requiring professional interpretation of data
	acoustic method	Capture acoustic signals generated by leaks inside pipelines or external construction	Low cost, fast response (in seconds)	High false alarm rate, affected by environmental noise interference
External threat detection	Seismic wave detection	Deploy seismic detector arrays to analyze P/S waves generated by geological activities or mechanical vibrations	Can provide early warning for geological disasters such as landslides and fault displacements	High requirements for equipment deployment density, unable to identify static deformation
	satellite remote sensing	InSAR technology monitors surface deformation and hyperspectral imaging identifies vegetation anomalies (chlorophyll changes caused by methane leakage)	Large scale coverage, non-contact monitoring	Long revisit period and affected by cloud cover
Corrosion prevention and control	Intelligent anti-corrosion coating	Pre embedded conductive grid or RFID tag in the anti-corrosion layer, locate damage through impedance changes	Can detect corrosion hazards early and be compatible with drone inspections	Only able to detect the status of the external anti-corrosion layer, unable to determine the degree of corrosion of the pipe body

3.4.2. Fiber optic pipeline leak monitoring

Oil and gas pipeline leaks require long-term real-time monitoring. In recent years, monitoring technology based on distributed acoustic sensing (DAS) has developed rapidly. Innovative methods such as BOTDA distributed temperature measurement, DAS acoustic signal recognition, HiFi DAS high fidelity signal processing, DAS and neural network combined automatic classification, and high-performance DAS micro leak detection have improved the accuracy and intelligence level of pipeline leak monitoring.

4. Conclusion and understanding

This article introduces the basic principles and technical advantages of fiber optic monitoring technology, and discusses its application in the oil and gas industry, with a focus on its effectiveness in key areas such as real-time monitoring of downhole parameters (temperature, pressure, flow rate), dynamic monitoring of oil and gas reservoirs, monitoring of wellbore integrity, and safety production and risk warning. However, the current cost of fiber optic monitoring systems is still relatively high. In the future, fiber optic monitoring technology needs to balance installation costs, spatial resolution, and monitoring distance to ensure high-quality hardware, improve signal extraction accuracy and professional data interpretation capabilities, and combine with other technologies such as deep learning and neural networks. The integration of multiple technologies will enable fiber optic monitoring technology to play an important role in the oil and gas industry and new energy fields.

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