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Research on online temperature and corrosion monitoring system for oil shale in situ heater

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Abstract. *The harsh environment during in situ heating of oil shale significantly impacts the structure and materials of downhole heaters. This paper presents the design of an online temperature and corrosion monitoring system for downhole in situ heaters in oil shale wells, utilizing thermocouple technology for temperature monitoring and fiber optic grating technology for corrosion monitoring. The system enables high-precision temperature measurements up to 500 °C using thermocouples and real-time, high-sensitivity corrosion monitoring via fiber optic grating technology. The measured corrosion rates are consistent with those obtained from the weight loss method and inductive probe method but exhibit faster response times. The monitoring system adopts oil pipes as the lowering carrier, with fiber optic grating installed along the horizontal section. Data are efficiently transmitted through wired transmission technology, combined with a short-section mounting structure and a nano-aerogel thermal insulation protection device to ensure the system's applicability and stability under high-temperature and high-pressure conditions. The online monitoring system developed in this paper provides a solution for designing and monitoring the performance of oil shale in situ heaters in the field.*

Keywords: *oil shale, in situ, temperature, corrosion, monitoring system.*

1. Introduction

China's oil shale resources are enormous, with about 4.76×10^{10} t of identified shallow resources at a depth of 1,000 m, ranking second in the world [1]. The existing in situ oil shale extraction process converts oil shale resources

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into shale oil and shale gas by drilling heating wells in oil shale-bearing formations and heating the oil shale layers with heaters [2–4]. However, the harsh downhole environment, characterized by high temperature, high pressure, and corrosiveness, greatly impacts the structure and materials of the downhole heater, which affects the efficiency of in situ mining and increases maintenance costs. Therefore, it is necessary to conduct online monitoring of the heater's temperature, corrosion, and other conditions under high-temperature and high-pressure downhole environments, so as to adjust the operating parameters in time to ensure stable heater performance and prolong its service life.

In the field of underground temperature monitoring, Baishan [5] focused on downhole temperature monitoring of submerged oil electric pumps, using 4–20 mA current signals for transmission and armored skinned earth wire as the signal transmission channel. This system has been tested in a 90 °C environment with high accuracy. Xu [6] proposed a downhole high-temperature power line communication system operating at 150 °C and an optimized evaluation coefficient method for high-temperature auto-regulation to support long-term downhole operation for up to 1,000 h. Lu [7] designed a monitoring system capable of measuring temperature and pressure at 175 °C and 138 MPa, mainly analyzing the actual operating conditions of downhole drilling columns. However, it does not meet the requirements for deep wells where the bottomhole temperature exceeds 175 °C. Wang [8] developed a carbon-coated, bellows-encapsulated fiber optic sensor for high-pressure, high-temperature downhole monitoring, and successfully applied it to oil wells with a resolution of 2.9 psi. Luo [9] established an integrated inversion procedure combining forward inversion and inversion modeling to simulate the temperature distribution of multistage fractured horizontal wells during each inversion iteration, and to interpret the flow profiles in liquefied petroleum gas stacks through the inversion of downhole distributed temperature measurements.

In the current field of corrosion monitoring for downhole conditions, Guo [10] designed and fabricated a cable corrosion monitoring sensor with a temperature-compensated probe to provide a highly sensitive method for cable corrosion monitoring, although it was only tested at 50 °C. Sathappan [11] developed a coil sensor based on the principle of magnetic leakage for detecting stress corrosion or pitting corrosion in oil transport pipelines, tested at room temperature and 200 °C. The study results showed that temperature did not affect the coil sensor, as no voltage changes occurred over the measured temperature range. Based on the principle of linear polarization, Zhang [12] designed an online corrosion monitoring system suitable for use at superheater pickling sites, with monitoring accuracy simulated indoors at 90 °C. Xi [13] preferred Rightrax DL2 as the main hardware and developed a multi-channel ultrasonic echo online corrosion monitoring system for ground-based gathering and transmission systems, with an operating temperature of about 120 °C.

Zhang [14] used resistance probes and corrosion lanyards for corrosion monitoring of underground oil pipelines, incorporating automatic temperature compensation components in the resistance probes to eliminate measurement errors caused by different operating temperatures, so as to enable online monitoring of oil pipeline corrosion. Lian [15] developed an electromagnetic ultrasonic corrosion monitoring system and corrosion rate calculation algorithms suitable for high-pressure conditions, transmitting data through wireless technology, with a temperature applicability range of 40–85 °C. Long [16] designed and developed a tubular corrosion probe monitoring system based on the principle of inductance, with a temperature resistance of 140 °C, pressure resistance of 70 MPa, and multi-channel simultaneous monitoring of oil casing corrosion. The deviation between the monitoring data and the high-temperature, high-pressure corrosion simulation results was less than 5%. Based on the principle of ultrasonic guided wave, Gu [17] set up corrosion monitoring points to obtain effective corrosion information from the beginning and end sections of a long-distance wet gas gathering pipeline in a high-sulfur gas field, with a pressure of 8.5 MPa and a temperature of 29.22 °C.

Although significant progress has been made in downhole temperature and corrosion monitoring both domestically and internationally, the accuracy of traditional monitoring methods decreases under high-temperature conditions, making it difficult to reflect the real corrosion status downhole. Furthermore, there is no reporting on monitoring systems or methods designed for the in situ heating of oil shale at 450–600 °C in a highly corrosive working environment. Existing monitoring systems mainly focus on oilfield wellbore pipelines, and while the pressure conditions usually meet the needs of oil shale wells, the temperature application range is often limited to below 200 °C. Therefore, there is an urgent need to design an online monitoring system for oil shale downhole heaters that can withstand high-temperature and high-pressure conditions. This paper utilizes thermocouple technology to monitor in situ heating temperatures and fiber optic grating technology to monitor corrosion under high-temperature and high-pressure conditions. It culminates in the design of an online monitoring device applicable to the downhole heating environment of oil shale wells, including the installation process, to enable real-time monitoring of temperature and corrosion under in situ heating conditions.

2. Methods and experiments

2.1. Thermocouple technology for temperature monitoring

The monitoring system uses a Kepson type K armored thermocouple probe to monitor temperature (Fig. 1). Thermocouples are a type of contact temperature measurement with a wide range of measurement capabilities. The armored probes can withstand temperatures up to 1000 °C and are designed to be in

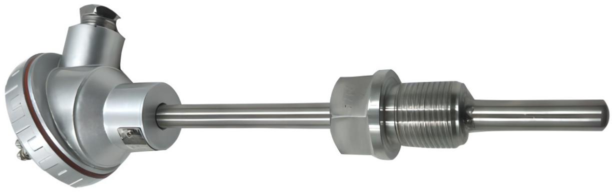


Fig. 1. Type K armored thermocouple probe.

direct contact with the object being measured. The thermocouple is mounted on the surface of the heater to measure temperature and is connected to the monitoring system [18, 19]. The temperature control instrument features an artificial intelligence display and control instrument with a PID adjustment function, offering a display accuracy of 0.1 °C, and allows for setting the desired control temperature. Thermocouple temperature sensors are based on the thermoelectric effect, including the Seebeck and Peltier effects. They consist of wires made from two different metals or alloys that are joined together at one end to form the temperature measurement point, while the other end is connected to a temperature measuring device [20, 21].

The schematic diagram of the temperature measurement system for the experimental equipment is shown in Figure 2. The type K thermocouple is calibrated before installation and correctly installed in the key position of the heater to ensure accurate temperature measurements. The distance between the thermocouple and the heater is suitable to be maintained within 10–30 mm. If the distance is too large, suitable mould temperatures cannot be ensured as well as malfunctions, such as overheating of the heater, may occur. The high-temperature core gripper features an annealed copper sleeve, which encloses the rock samples within a fully closed structure, and then compresses the sealing ring using a hydraulic cylinder to implement the sealing. The cables

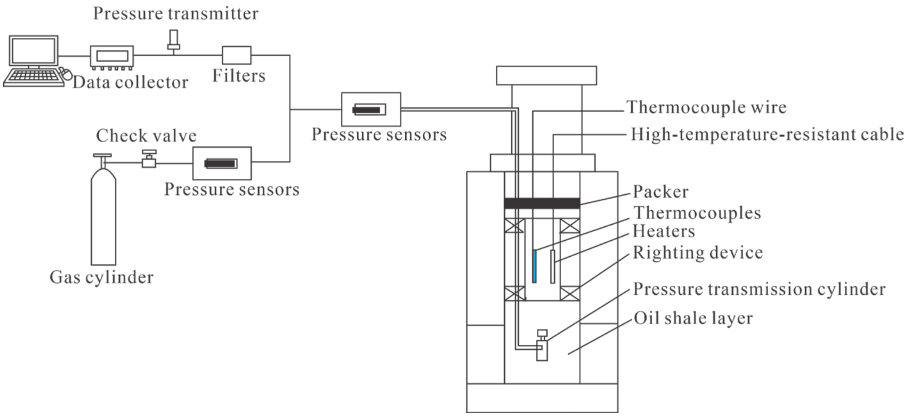


Fig. 2. Schematic diagram of temperature measurement system.

of this monitoring system are special heating cables, with lengths and outer diameters tailored to the conditions of the wells where they will be used. The experimental equipment utilizes the imported MOX C168H digital acquisition control card for digital acquisition and transmission. The acquisition frequency is 100 KHz/channel, and the temperature range is 270–1800 °C.

2.2. Fiber optic grating technology for corrosion monitoring

The Brillouin shift is related to the speed of sound in the fiber, which is affected by the thermo-optic and elasto-optic properties of the fiber material. As a result, both temperature and strain within the fiber cause changes in the Brillouin shift. When corrosion occurs, corrosion-induced strain or temperature changes affect the spectrum of the fiber grating, leading to shifts in the Brillouin frequency, providing information about the extent, location, and rate of corrosion, thus enabling online corrosion measurement. By installing fiber optic gratings inside downhole tubular columns and measuring changes in their spectral properties, corrosion development can be monitored in real time.

The schematic diagram of the corrosion monitoring device selected for the experiment is shown in Figure 3. The downhole corrosion monitoring device mainly consists of an injection system, mixer, preheater, reactor, stirring system, cooling protection system, fast cooling coil system, process piping system, pressure and temperature measurement and control system, gas-liquid separation system, outlet back pressure system, and safety protection system. The main body of the simulated in situ heating system is a high-temperature reactor (Fig. 4), with a working pressure of 50 MPa, a volume of 500 mL, and a maximum working temperature of 500 °C. The reactor uses hearth-type electric heating, with the temperature controlled automatically by a temperature controller. The dynamic reactor is equipped with a magnetic stirring mechanism and is made of Hastelloy C material, which is extremely resistant to high temperatures. Given that the temperature of the reactor can be as high as 500 °C, a water jacket cooling device is designed at the upper end of the dynamic reactor to prevent the stirring part of the magnetic block from failing due to excessive heat.

The corrosion monitoring device is set up based on three monitoring principles: the hanging chip weightlessness method, the inductive probe method, and the fiber optic grating method, all positioned in the high-temperature reactor. In situ heating conditions are established, and CO_2, H_2S gas, and formation water are injected into the reactor, with the injection port at the top and the outlet at the bottom. The corrosive liquid remains in a constant flow state. The monitoring object is the material used in the well-field oil shale downhole heater, specifically Q235 steel. The corrosion rate monitoring results from the three methods are compared over a monitoring period of 72 h. Additionally, four monitoring points are selected in the field downhole for further monitoring.

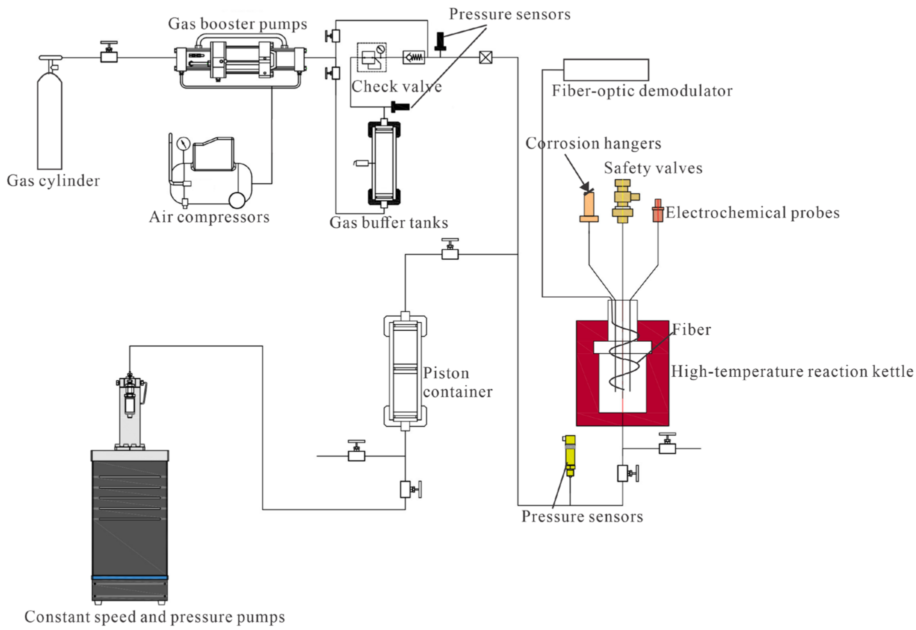


Fig. 3. Schematic diagram of corrosion system.

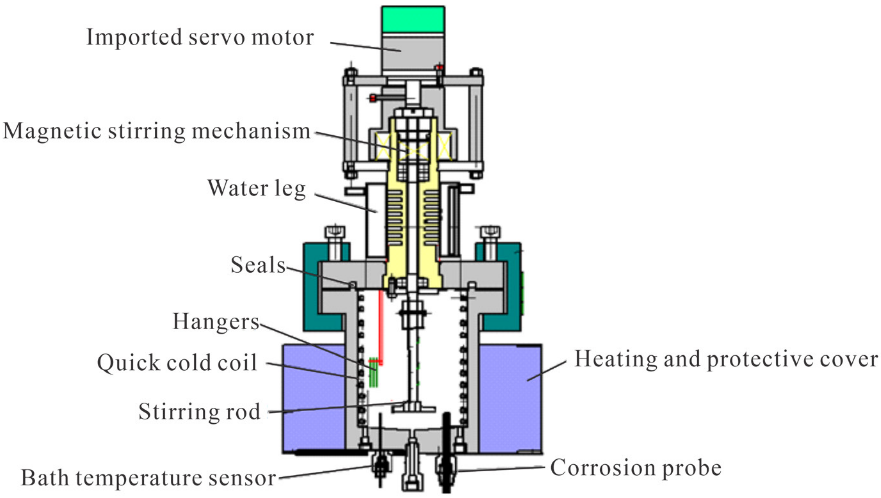
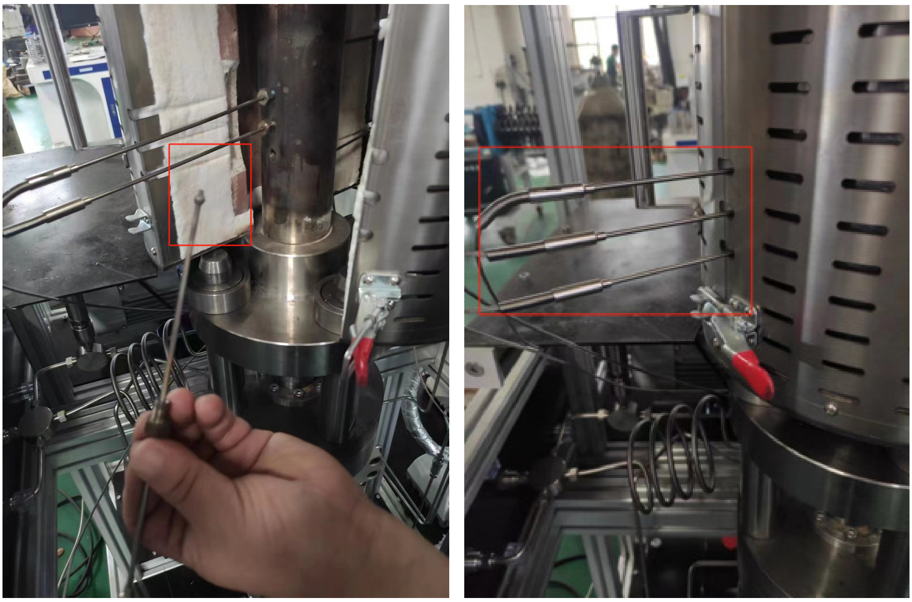


Fig. 4. Structure of high-temperature reaction kettle.

3. Results and discussion

3.1. Temperature monitoring

The cylinder corresponding to the rock sample is designed with four blind holes for temperature measurement points, with intervals of 25, 50, 50, 50, and 25 mm, respectively, to monitor temperature changes at different locations. Temperature measurement experiments are conducted with three type K thermocouples arranged at the 50 mm intervals. By collecting and comparing the temperature data from these three locations, the effect of the type K thermocouple's hot spot coupling temperature measurement is determined (Fig. 5).



Thermocouple probes | Temperature measurement points on cylinder

Fig. 5. Indoor in situ heating temperature test.

By heating the kettle, the high-temperature and high-pressure environment of an oil shale well is simulated, with thermocouples used for temperature monitoring. The temperature test was conducted in a room at atmospheric pressure, and the kettle temperature was controlled to increase stepwise from 100 to 500 °C, with each step monitored for 1000 s. The experimental results are shown in Figure 6.

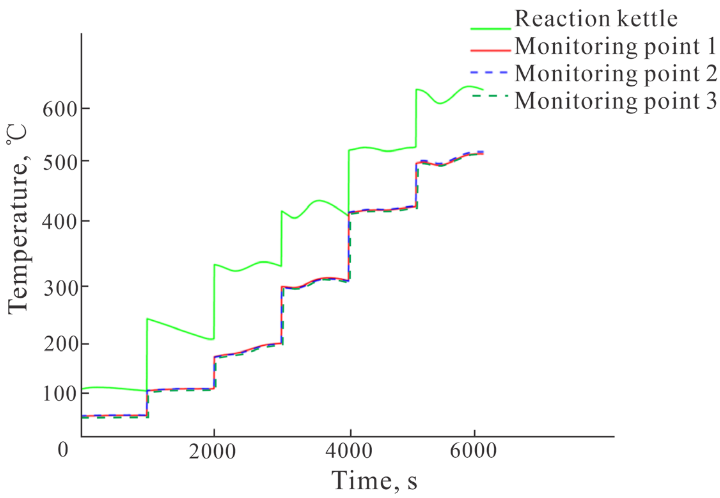


Fig. 6. Real-time temperature profile at atmospheric pressure.

The slight differences in the data among the three curves in the figure are attributed to thermocouple production errors. Under atmospheric pressure conditions in the room, as the temperature increases to 500 °C, the results obtained from the three temperature measurement points have the same trend. The difference between the kettle's controlled temperature and the measured temperature is mainly due to the thermocouple measuring the temperature at the surface of the kettle, while the kettle's controlled temperature is the internal temperature. The temperature curve for real-time continuous to meet the requirements of online monitoring. The experiments verified that the monitoring technology performs well within the 500 °C range, validating the suitability of the type K thermocouple for downhole temperature monitoring.

3.2. Corrosion monitoring

Using the fiber optic grating method at 500 °C in the reactor, corrosion was monitored online at four selected points, with the results shown in Figure 7. Monitoring points 1 and 2, located 2 cm apart at the far end from the heating source, exhibited average corrosion rates (C_v) of 0.2312 and 0.2167 mm/a, respectively. These values are consistent with the corrosion rate of 0.2259 mm/a obtained using the corrosion pendant monitoring method during the same period, which indicates that the data are real and effective. Monitoring point 3, located 10 cm proximal to the heating source, had an average corrosion rate of 1.3607 mm/a, while monitoring point 4, located 7 cm proximal to the heating source, had an average corrosion rate of 1.5386 mm/a. Due to the time required for the transfer of heat in the pre-heating stage, the temperature is high near the heating source in the pre-

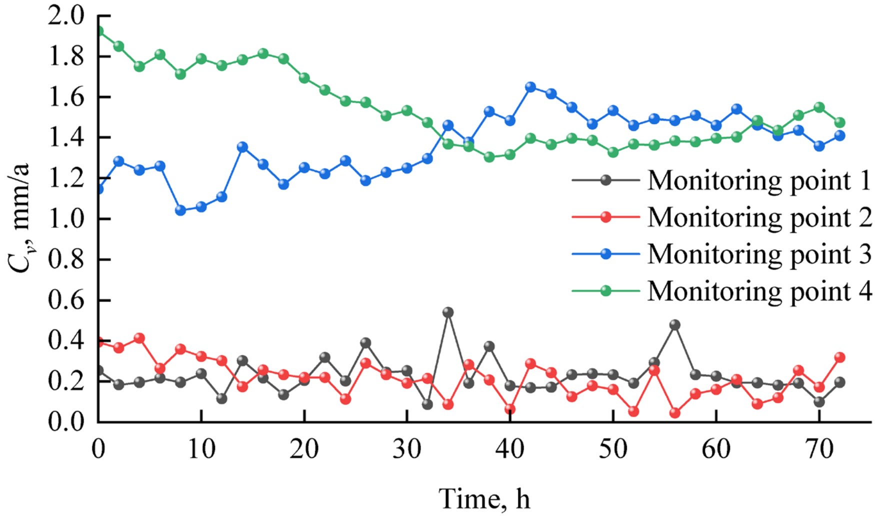


Fig. 7. Corrosion monitoring results.

heating stage, and the chemical activity is intense, resulting in an accelerated corrosion rate. As the heating process proceeds and heat is evenly distributed, the disparity in corrosion rates between the monitoring points decreases.

To verify the accuracy of the monitoring results, the outcomes of different monitoring techniques were compared. It was found that all three methods exhibited the same trend under the same conditions at 500 °C in the high-temperature reactor, with the corrosion rate accelerating over time (Fig. 8).

The hanging piece weight loss method is simple to operate and data reliability is high, but it only provides the average corrosion rate over a specified period. It does not allow for continuous monitoring or provide real-time corrosion data, resulting in low sensitivity and lengthy detection cycles [22, 23]. For instance, over 72 hours, the corrosion rate was calculated at six specific intervals by removing and weighing the hanging piece. This method cannot reflect instantaneous corrosion changes, making it unsuitable for real-time monitoring.

Inductive probes have the advantage of resistance to pitting, scouring, and pressure, but they also calculate the average corrosion rate over a given period based on the accumulated thinning of the material [24, 25]. After 60 h, some differences were observed between the corrosion rate curve from inductive probes and the fiber optic grating method. Although the general trend of increasing corrosion rates was consistent, the inductive probes could not capture the instantaneous increases and decreases in the corrosion rate. This limitation prevents timely adjustments to the operating environment of oil shale in situ heating, making the method insufficient for real-time online monitoring.

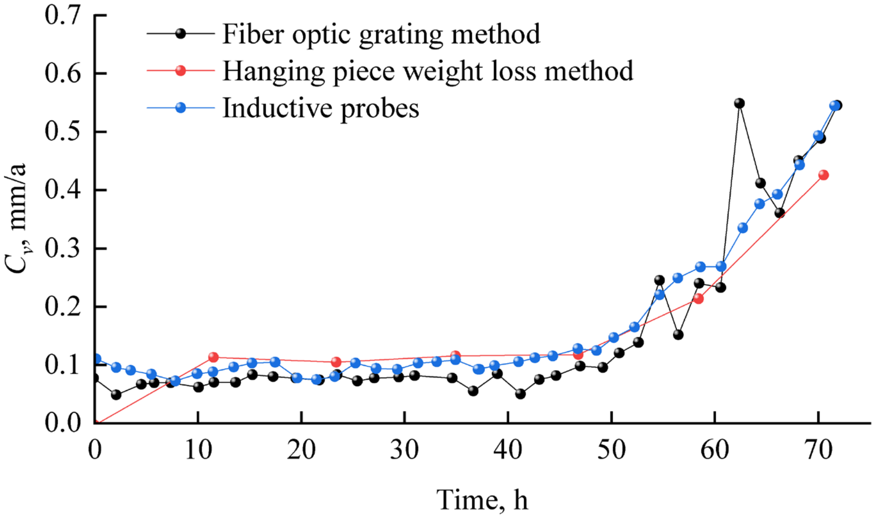


Fig. 8. Comparison of corrosion rates of different monitoring methods.

In contrast, the fiber optic grating method is resistant to electromagnetic interference and corrosion, and has a wide transmission band, suitable for high-temperature and high-pressure environments [26, 27]. In particular, it measures the instantaneous corrosion rate, and it can be seen from the curve that the corrosion rate fluctuates up and down, unlike the data values monitored using the inductive method. Therefore, the fiber optic grating method meets the monitoring requirements of downhole heaters in oil shale wells.

4. Installation process of the online monitoring system into the well

It is crucial for the oil shale downhole monitoring device to be safely lowered into the well, as this guarantees the safety of downhole operations, prevents safety accidents caused by equipment failure or improper operation, and provides accurate and reliable downhole data. Through real-time data monitoring, problems in the production process can be discovered in a timely manner, optimizing the production process and improving the productivity and conversion rate of oil shale. The downhole data transmission of the oil shale downhole heater online monitoring system is the communication basis and key link for collecting temperature data from thermocouples and corrosion data from fiber optic gratings. Downhole data transmission technology is currently divided into two categories: wired and wireless. Wired transmission includes cable transmission, special drilling rod transmission, and optical fiber transmission technology, while wireless transmission includes mud pulse transmission, electromagnetic transmission, and acoustic wave transmission technology.

In conjunction with the monitoring of in situ heating parameters in oil shale wells, cable transmission technology is considered suitable for use with the technology described in this paper due to its advantages of fast data transmission and independence from working conditions and drilling mediums. Wireline transmission cable technology was chosen as the preferred option for underground data transmission. The cable is laid directly in the oil pipe for signal transmission. The cable is made of pure nickel core 1000 °C flame-retardant high-temperature wire, rated for 600 V, with a size of 2.5 mm^2. It consists of four layers of mica-coated and glass-fiber wrapped pure nickel wire filaments, capable of withstanding a pressure of 50 MPa at room temperature and 35 MPa at 700 °C. Long-term temperature resistance is more than 700 °C, while short-time temperature resistance exceeds 900 °C. The heating end of the cable is sealed with metal of the same material as the cable body, ensuring pressure resistance of at least 35 MPa at 700 °C.

This online temperature and corrosion monitoring system for oil shale in situ heaters selected oil tubing as the preferred carrier for the lower entry. A conical guide was added to the bottom of the instrument to facilitate passage through the well wall during lowering. Additionally, a high-strength spring-loaded retainer was installed on the casing of the monitoring instrument to reduce the friction area between the instrument and the well wall.

The transmission cable is threaded into the tubing, after which the tubing and cable system are coiled together on a specialized winch. The downhole instrument is connected to the system, and the winch is turned to lower the system. The downhole instrument is positioned at the predetermined depth at the bottom of the well, and the test is performed. For wells with a large dip, the monitoring device is installed in a metal casing with a wall thickness of several inches, and lowered with the drill pipe into the downhole section of the layer to be measured. Then, the high-temperature-resistant cable enters the center of the drill pipe from a bypass short section at the wellhead. The mud pump is turned on to press it down to the bottom of the well, where the downhole instrument is protected by built-in shock absorbers and force gauges.

Since the horizontal section of oil shale extraction typically uses barehole completion, with liquid and gas phases in the horizontal section running relatively smoothly inside the tubing, the monitoring equipment is installed in the horizontal tubing line near the bottom. This positioning allows for better monitoring of downhole conditions. The test device is welded into a short section, which is lowered together with the tubing, as shown in Figure 9.

The material of the short section is usually Q235 carbon steel or stainless steel. The fiber optic grating is directly deployed into the oil pipe, allowing for installation in completed oil wells and retrieval of the fiber optic. To protect electronic components at the root of the thermocouple sensor and the connection interface between the high-temperature-resistant cable and the thermocouple, a nano-aerogel insulation device is welded into the short section, as shown in Figure 10.

The insulation device mainly consists of a nano-aerogel insulation board, buffer material, and reflective layer. A reflective layer is laid between the nano-aerogel insulation panels to reduce downhole radiation. The buffer material prevents excess heat generated by the panels from escaping. Tightening and temperature resistance between the structural panels is achieved by polyimide screws within the housing. Heat injection and production wells are installed with high-temperature-resistant packers. The packer barrels are made of polyimide rubber, while the shells are made of a high-temperature nickel-based alloy N07750 with a ceramic coating. Flexible graphite gaskets are used for sealing, ensuring that the packers are unaffected by the temperature at 500 °C, and that the oil and gas cracked by the heater heating is transported from the production section of U-shaped wells [28, 29].

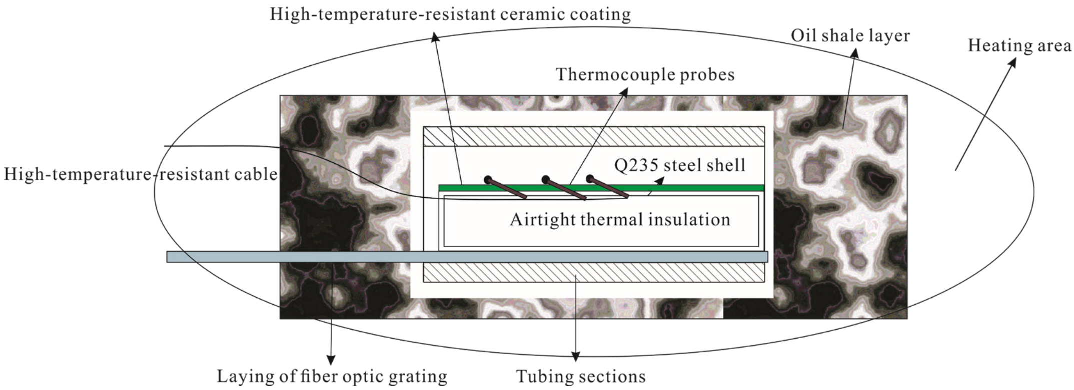


Fig. 9. Schematic diagram of the structure of the lower entry short section.

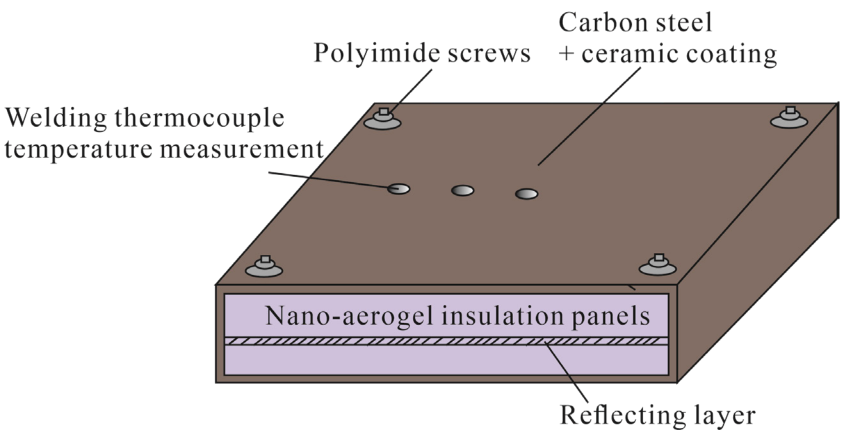


Fig. 10. Test system insulation.

5. Conclusions

1. After the in situ heating test under atmospheric pressure conditions, as the temperature rises, the thermocouple can measure the data from the three measurement points with a 50 mm interval online. In the range of 500 °C, the thermocouple's temperature change trend is the same, and the monitoring effect is satisfactory.
2. Fiber grating monitoring measures the instantaneous corrosion rate. In the 500 °C reactor, the average corrosion rate at monitoring point 1 is 0.2312 mm/a, at monitoring point 2 it is 0.2167 mm/a, and the corrosion rate measured by the corrosion pendant during the same period is 0.2259 mm/a. This meets the requirements for monitoring the downhole heater in oil shale wells and is suitable for high-temperature and high-pressure environments.
3. The online temperature and corrosion monitoring system uses the oil pipe as the preferred carrier for the lower entry. The transmission cable is threaded into the tubing, and the test device is placed in a short section and lowered into the tubing. A nano-aerogel insulation device is welded into the section to protect the sensor, and the fiber optic grating is laid directly into the tubing, allowing it to be installed in wells that have already been completed.

Data availability statement

Some or all of the data used in this study are available from the corresponding author upon request.

Acknowledgments

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