

Article

Optimization of the Monitoring of Coal Spontaneous Combustion Degree Using a Distributed Fiber Optic Temperature Measurement System: Field Application and Evaluation

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Abstract: Coal spontaneous combustion (CSC) in gob not only leads to wasted resources and casualties, but also produces a lot of waste gas that pollutes the underground environment. Mastering the degree of CSC helps ensure that timely and effective control measures are taken. The real-time and accurate monitoring of temperature, as the primary indicator of the extent of CSC, is difficult due to the harsh and hidden environment of gob, resulting in a reduced ability to anticipate and prevent CSC. In this work, a complete distributed optical fiber temperature sensing system (DTSS) set with strong anti-damage ability was developed. The optical cable is protected by internal parallel steel cables and external protective pipes, which greatly improve the system's reliability and integrity when used in gob. During its application in the Wangyun Coal Mine, an abnormal temperature rise in gob was discovered in time, and the effect of inhibitor spraying was monitored and evaluated. The degree of CSC in the gob was accurately identified, which shows that the work of coal mining can be targeted. This work is expected to improve early warning capability to prevent the risk of CSC in gob, and has promising applications.

Keywords: coal spontaneous combustion (CSC); distributed temperature sensing system; protective pipe; online monitoring; gob



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1. Introduction

As a major fossil energy source, a small portion of coal is inevitably left in gob due to the limitations of mining technology [1,2]. The residual coal undergoes oxidation and gradually releases heat under the coupling effect of multiple physical fields [3,4]. The continuous accumulation of heat can easily lead to the occurrence of coal spontaneous combustion (CSC), which is difficult to extinguish in a short period of time [5,6]. CSC gravely threatens the safety of coal production and the safety of workers [7,8]. It not only leads to a large amount of wasted coal resources [9], but also destroys the underground geological and ecological environment [10]. When certain conditions are met, it may even cause secondary disasters such as gas explosions, thus causing large-scale casualties [11–13]. Therefore, corresponding measures must be taken to prevent the occurrence of CSC disasters in gob [14].

In order to implement targeted governance measures, it is particularly vital to grasp the degree of CSC in gob [15,16]. The main characteristics of CSC include rising temperature

and the generation of gases such as alkane [17]. And CO is usually used as the main iconic gas for the early warning and prediction of CSC in gob [18,19]. The mapping relationship between iconic gases and the degree of CSC is generally determined through mathematical models established in the laboratory [20,21]. However, applying this mapping relationship in large-sized gob may raise doubts about the accuracy of the model due to numerous uncertain factors [22], and iconic gases are the products of a coal oxidation reaction, so it exhibits hysteresis when predicting CSC in gob [23]. Given that the direct effect of the oxidized exotherm of the coal body is to cause an increase in temperature, it is feasible and reasonable to use temperature indicators to anticipate CSC.

Due to the concealment and complexity of gob [24], the selection of temperature monitoring technology should be comprehensively considered from various aspects, such as the accuracy, continuity, stability, and intuitiveness of data results. The current commonly used probe-based temperature measurement method is point-of-contact, which has the disadvantages of long measurement time, a large workload, and the inability to continuously monitor. Most notably, the probe and cable are easily damaged, and it is not suitable to use it on a large scale [25]. A characteristic of methods such as isotope radon measurement [26] and magnetic and infrared induction [27,28] is that they cannot achieve directly contact in high-temperature locations, which leads the positioning and value of temperature anomaly points to be inaccurate. The radio wave detection method has high accuracy and low cost, but the transmission technology used in gob still needs further improvement [29]. In recent years, fiber optic sensing technology has been widely applied in temperature monitoring and warning in various industrial fields [30,31]. However, the complex underground environment of coal mines places higher demands on the safety performance of equipment. And in the application of coal mine gob with coal/rock caving and mining stress, determining how to prevent the negative effect of perception and the transmission of temperature caused by damage to optical cables is a challenge that hinders the application of optical fiber temperature measurement technology [32].

To address the above issues, herein, a new set of products and technologies are developed that can improve the safety of the temperature measurement method through the design of safety barriers. And a method is designed to improve its damage resistance from the internal and external structures of optical cables, which can ensure the accuracy and continuity of online temperature monitoring in complex environments with gob. This product and technology were successfully applied in the Wangyun Coal Mine in China and greatly improved the monitoring and warning capabilities for CSC hazards in gob.

2. Detection System

2.1. Technical Principle

The technology of distributed optical fiber temperature detection is achieved through Raman scattering [33,34]. Figure 1 shows the technical principle of the distributed optical fiber temperature sensing system (DTSS), which mainly includes a device host, a terminal computer, optical cables for temperature measurement, and a meta-plane of temperature perception.

The device host sends a laser pulse into the optical cable, and the interaction between the laser pulse and the fiber molecules generates Raman-scattered light [35,36]. A small fraction of it is called back-scattered light, which is oriented in the opposite direction to the incident light. The intensity of this back-scattered light has a certain correlation with the temperature of the scattering point in the optical cable. The higher the temperature, the higher the intensity of the back-scattered light. When the back-scattered light signal returns to the device host, it can be converted into a digital signal through demodulation technology and output on the terminal computer to display its temperature and position information. This technique can detect temperature anomalies in a timely manner, which facilitates the implementation of risk prevention measures.

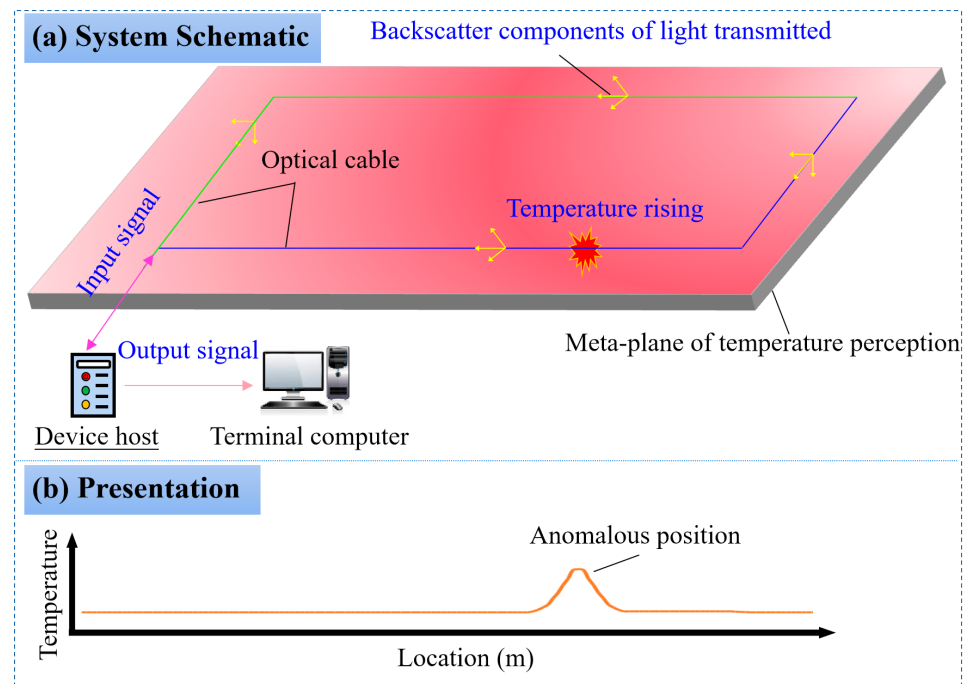


Figure 1. Technical principle of DTSS. (a) System schematic (b). Presentation.

2.2. Demodulation Process

Figure 2 shows the demodulation process of DTSS. The laser pulse is emitted by a laser with a high-power semiconductor. The laser pulse entering the external optical cable generates back-scattered optical signals and transmits them back to the signal receiver. Next, a wavelength division multiplexer (WDM) separates the temperature-insensitive Stokes light and temperature-sensitive anti-Stokes light from the back-scattered light, and amplifies their gain through a signal amplifier. A photoelectric converter demodulates the temperature information carried by the light into electrical signals, and finally, outputs them to an external computer [37,38].

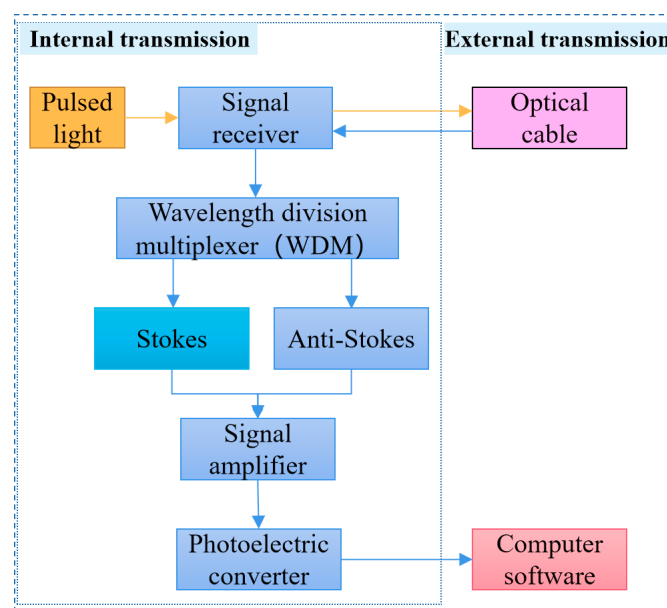


Figure 2. Demodulation process.

The specific principle of signal demodulation involves the following mathematical formula. The scattering photon frequencies of Stokes and anti-Stokes light are [39–41]:

$$\nu_s = \nu_0 - \Delta\nu \quad (1)$$

$$\nu_{as} = \nu_0 + \Delta\nu \quad (2)$$

where ν_0 is the vibrational frequency of the optical fiber molecule, and $\Delta\nu$ is the frequency shift value of Raman scattering, 1.32×10^{13} Hz.

The intensity of Stokes and anti-Stokes at L (measuring point) shall be expressed as Equations (3) and (4), respectively [42,43]:

$$I_s = E_0 k_s B \nu_s^4 \cdot \exp[-(a_0 - a_s) \cdot L] \times R_s \quad (3)$$

$$I_{as} = E_0 k_{as} B \nu_{as}^4 \cdot \exp[-(a_0 - a_{as}) \cdot L] \times R_{as} \quad (4)$$

$$R_s = (1 - \exp(-h\Delta\nu/kT))^{-1} \quad (5)$$

$$R_{as} = (\exp(h\Delta\nu/kT) - 1)^{-1} \quad (6)$$

where R_s and R_{as} are the coefficients related to the population of optical fiber molecules at low and high energy levels; E_0 is the intensity of the initial incident light in the optical fiber; k_s and k_{as} are the scattering coefficients related to the aperture (scattering cross-section) of the optical fiber; B is the back-scatter coefficient; ν_s and ν_{as} are the frequency of Stokes and anti-Stokes scattering light; α_0 , α_s , and α_{as} are the average transmission loss of incident light, Stokes light, and anti-Stokes light in the optical fiber; L is the location of the measuring point; H is the Planck constant, $6.62607015 \times 10^{-34}$ J·s; k is the Boltzmann constant, 1.380649×10^{-23} J/K; and T is the temperature of the measuring point.

Comparing Equation (3) with Equation (4), the temperature information of L can be obtained:

$$F(T) = \frac{I_{as}}{I_s} = \frac{k_{as}}{k_s} \left(\frac{\nu_{as}}{\nu_s} \right)^4 \cdot \exp(-h\Delta\nu/kT) \cdot \exp[-(\alpha_{as} - \alpha_s)L] \quad (7)$$

The temperature information when the reference temperature is T_0 is:

$$F(T_0) = \frac{I_{as}}{I_s} = \frac{k_{as}}{k_s} \left(\frac{\nu_{as}}{\nu_s} \right)^4 \cdot \exp(-h\Delta\nu/kT_0) \cdot \exp[-(\alpha_{as} - \alpha_s)L] \quad (8)$$

Combining Equations (7) and (8), the temperature T of the measuring point can be obtained based on the reference temperature T_0 :

$$\frac{1}{T} = \frac{1}{T_0} - \frac{k}{h\Delta\nu} \ln \frac{F(T)}{F(T_0)} \quad (9)$$

In the optical time domain, the position of the measuring point is [42]:

$$L = \frac{1}{2}vt = \frac{1}{2} \frac{c}{n}t \quad (10)$$

where v is the propagation speed of light in the optical fiber; c is the speed of light in a vacuum; n is the refractive index of the optical fiber; and t is the measuring time.

The temperature value and the position of a certain point in the optical cable can be obtained using the above demodulation method.

2.3. Description of DTSS

In this work, a new DTSS technology that can be used in coal mine gob is proposed [44,45]. Figure 3 shows the complete DTSS set. Figure 3a illustrates the fiber optic device host. The left side of the device host is the power supply, the right side is the signal transmission

interface, and the screen in the middle of DTSS is a visualization window that can directly display the detected temperature data. Figure 3b illustrates the optical cable used for temperature measurement. The design of a flat appearance increases the temperature detection area; the design of parallel steel cable reinforcement enables the optical cable to have very strong compressive and impact resistance. Figure 3c illustrates the software interface displayed in the visualization window, which can display the position and temperature values of a certain point on the optical cable. The horizontal axis of the coordinate map represents the length of the optical cable, and the vertical axis represents the temperature value detected by the optical cable. Figure 3d illustrates the internal structure of the detection host, where the device has added safety barriers and backup batteries to improve safety performance and prevent the impact of power outages. In addition, the bias plate component used can conduct small signals and improve the signal-to-noise ratio.

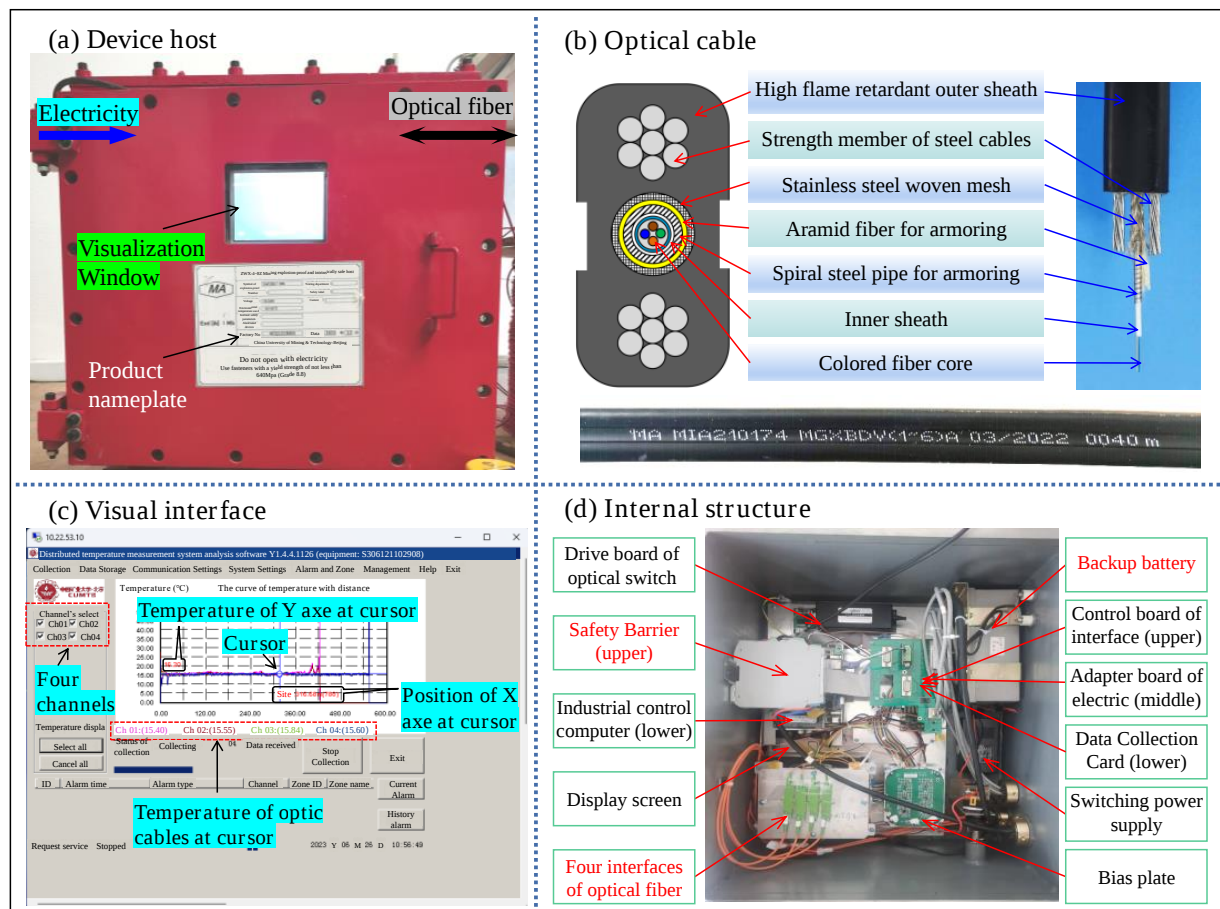


Figure 3. Complete DTSS set (a) Device host. (b) Optical cable. (c) Visual interface. (d) Internal structure.

2.4. Performance Characteristics

This product has obtained a safety label certificate (No. MFE230006) for mining products and is classified as explosion-proof and intrinsically safe equipment.

Table 1 shows the performance parameters of the device host, with a high positioning accuracy of 0.4 m, a temperature measurement accuracy of 1.54 °C, and a reaction time of 2 s, which can be applied to multi-mode optical fiber with a diameter of 62.5/125 µm. It has four channels and can be connected to four optical cables. The working current is 800 mA.

Table 1. Performance parameters.

Performance Index	Parameters
Supply voltage	AC127V
Working current	800 mA
Number of channels	Four
Distance for temperature measurement	4 km for one channel
Scope of temperature	(0~100) °C
Spatial resolution	2 m
Accuracy of positioning	$\leq \pm 0.4$ m
Accuracy of temperature	1.54 °C
Response time	2 s
Wavelength of the detection light	1550 nm
Emission power of the detection light	≤ 0 dbm
Communication interface	RJ45, RS485
Type of fiber that can be connected	Multi-mode optical fiber: 62.5/125 μ m
Inside connectors of optical fiber	E2000

3. Comparative Experiment of Casing on Optical Cable

3.1. Testing Method

The environment of underground gob is relatively harsh, and optical cables may break and be damaged under the high stress of falling rocks. We propose a protection method that uses high-pressure rubber hoses as casing pipes on the optical cables. To determine the effect of the protective pipe on the detection results, a comparison experiment was designed and performed without and with the protective pipe, and the changes in the temperature value and temperature sensing speed were analyzed.

The test design is shown in Figure 4. A silicone flexible electric heating film connected to a PID temperature controller is used as the heating strap for better contact and transfer of heat to the optical cable. The heating strap that wraps around the optical cable is fixed with several sealing strips. A DN19 high-pressure rubber hose with four layers of steel wire winding reinforcement was selected as the protective pipe. The protective pipe can fully meet the requirements for use on gob, with a maximum working pressure of 42.0 MPa and a minimum blasting pressure of 168.0 MPa.

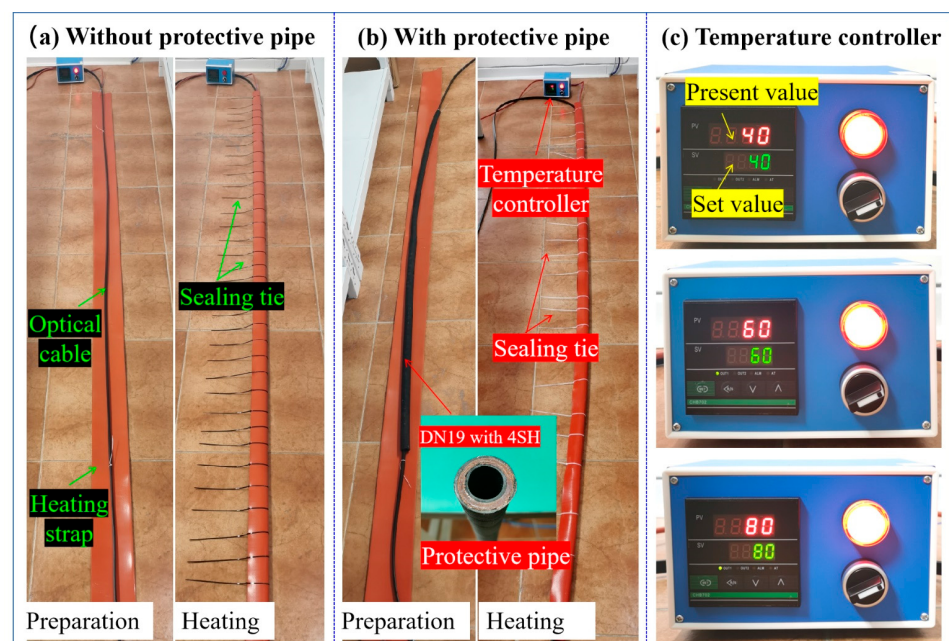


Figure 4. Test without and with protective pipe. (a) Without protective pipe. (b) With protective pipe, (c) Temperature controller.

The length of the optical cable for heating is 2 m, the length of the high-pressure rubber hose is 2 m, and the length of the heating strip wrapped externally is 3 m. The detection temperatures are set at 40 °C, 60 °C, and 80 °C, respectively.

During the experiment, PID was used to control the temperature to the present value, and then, the temperature detected by the optical cable within 70 min was observed. A set of data was exported every 1 min by the device host. And the heating strap temperature could increase to 60 °C and 80 °C sequentially after the first temperature detection was finished.

3.2. Analysis of Temperature Value Accuracy

Figure 5 indicates the changes in temperature values detected without and with the protective pipe. The horizontal axis is the length of the optical cable, and the vertical axis is the average temperature value of five tests. From Figure 5, the maximum detection temperature values for the three preset temperatures (40 °C, 60 °C, and 80 °C) without the protective pipe are 38.48 °C, 59.42 °C, and 79.27 °C, respectively. After using the protective pipe, the maximum detection temperature values for the three preset temperatures are 37.21 °C, 58.75 °C, and 79.41 °C, respectively. The differences between the two experiments are 0.87 °C, 0.67 °C, and 0.24 °C, and neither of them exceed 1 °C, as shown in Figure 5d. And the trend of their temperature changes is consistent, which indicates that the influence of the protective pipe on the temperature value is very small and can be ignored.

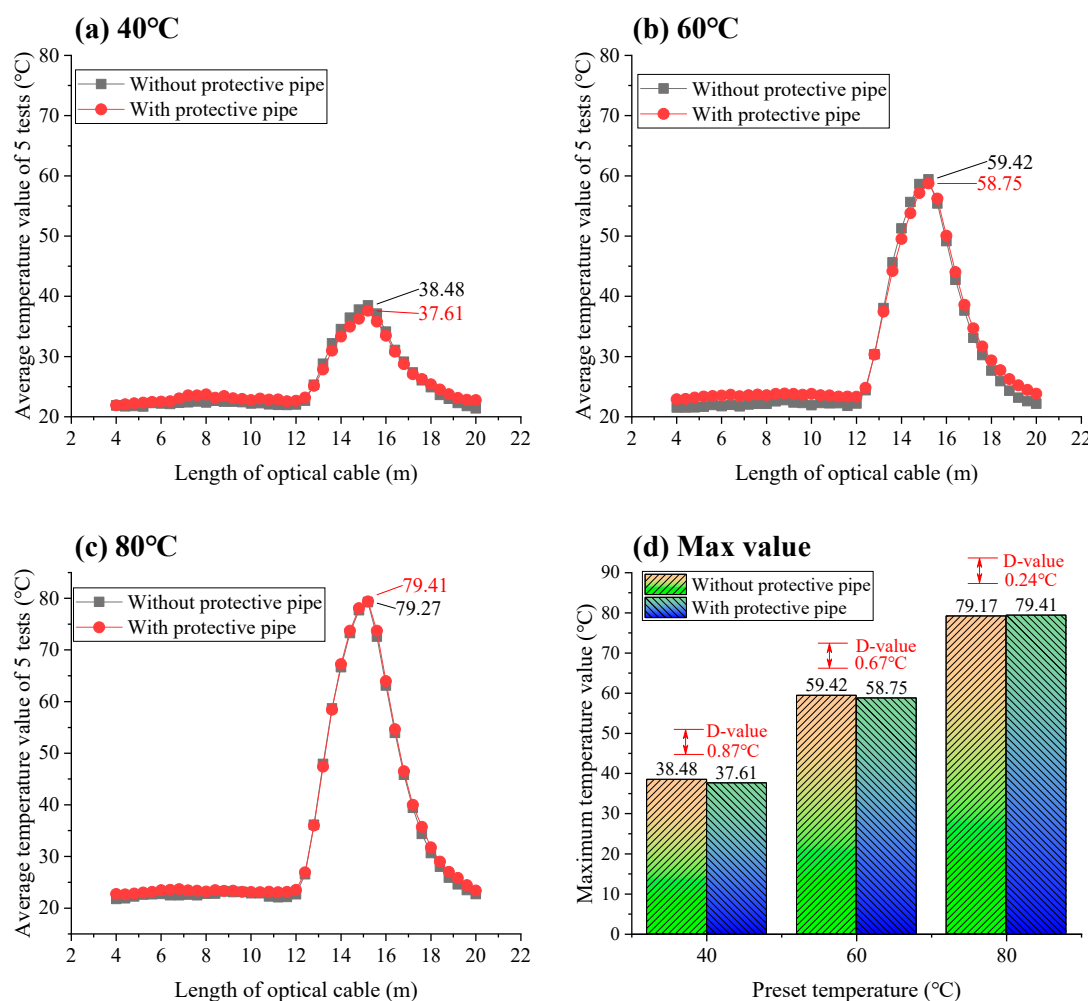


Figure 5. Comparison of temperature values without and with protective pipe. (a) 40 °C. (b) 60 °C. (c) 80 °C. (d) Max value.

In addition, it is worth noting that the lengths with temperature variations at the three different set temperatures were all 12–20 m, which is more than the heating length of 3 m. This length with increased temperature distribution is the response distance, which conforms to the temperature measurement principle of the temperature measurement system [46]. The test temperature only affects the value of the response temperature and does not change the response distance (length with increased temperature distribution).

3.3. Analysis of the Speed of Temperature Sensing

In order to understand the influence of the protective pipe on the temperature sensing speed, the temperature detected at the highest temperature measuring point within 70 min was analyzed over time without and with the protective pipe, as shown as Figure 6. The maximum temperature values without the protective pipe appear at 24 min, 38 min, and 56 min, respectively. After using the protective pipe, they are delayed to 47 min, 54 min, and 65 min, respectively, and delayed for 23 min, 16 min, and 9 min, respectively. In addition, the temperature rises rapidly in the first 10 min without the protective pipe. And after using the protective pipe, the overall temperature rise rate is very slow and there is no sharp increase.

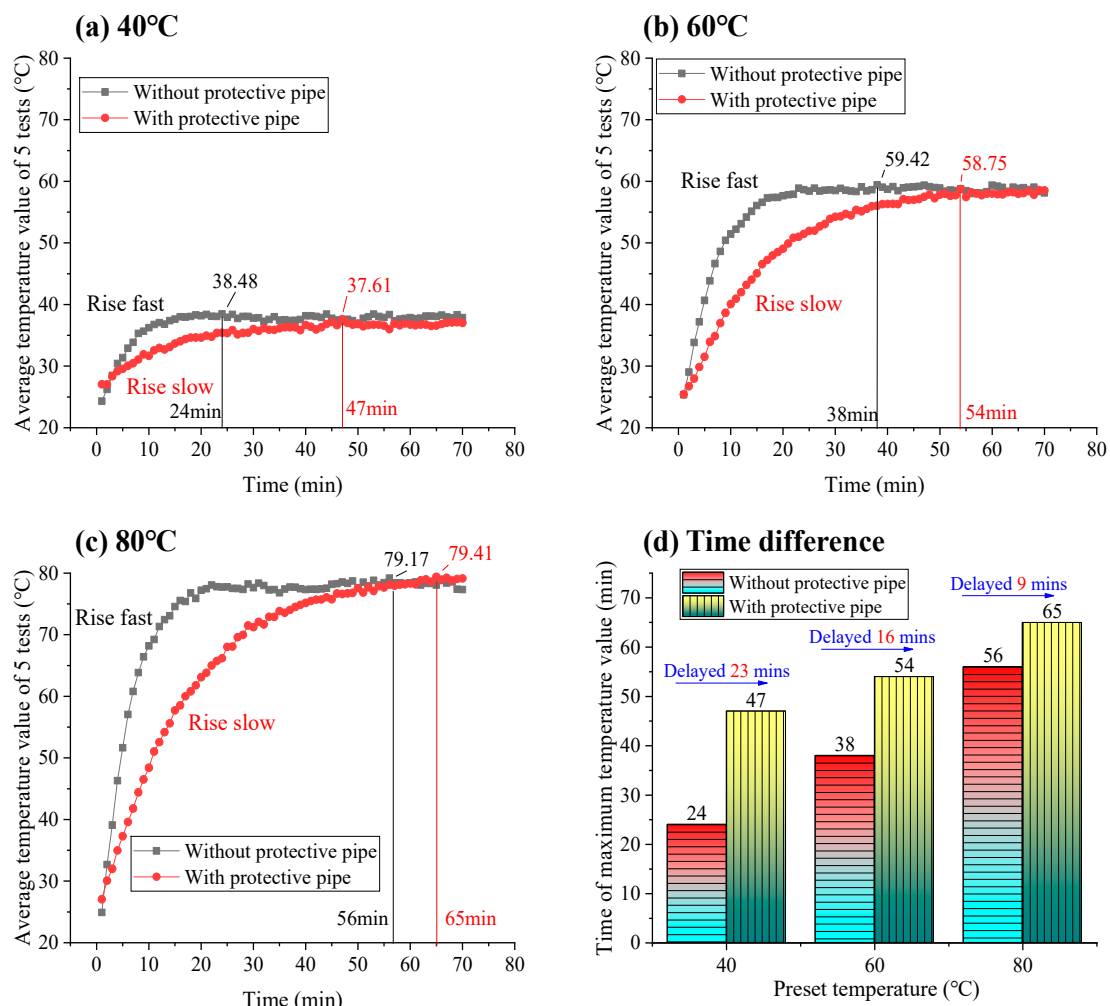


Figure 6. Comparison of temperature sensing speed without and with protective pipe. (a) 40 °C. (b) 60 °C. (c) 80 °C. (d) Time difference.

Overall, although the time required for the temperature detection value to stabilize after using the protective pipe increases, the final temperature value is basically unchanged,

and this lag time can be ignored for large-scale gob. Therefore, using protective pipe to protect optical cables in gob will not affect the accuracy of the temperature values.

4. Application

4.1. Field Temperature Measuring Design

The Wangyun Coal Mine, located in Shanxi Province, China, has an annual output of 1.8 million tons. Currently, the 15th coal seam is being mined, with a thickness of 4.7 m and an oxygen absorption capacity of $0.84 \text{ cm}^3/\text{g}$, classified as type II spontaneous combustion coal seam. The cut length of the 15106 working face currently being mined is 180 m. In order to grasp the real-time spontaneous combustion status of residual coal in gob, the DTSS proposed in this work was used to monitor the temperature changes in the gob. Figure 7 illustrates the application design of the DTSS, with the 1# and 2# optical cables distributed on both sides of the roadway with the protective pipes. The DN19 high-pressure rubber hose with four layers of steel wire winding reinforcement was selected as the protective pipe, and its safety sign number is MEE150868. The protective pipes are each 10 m long, with a screw joint machined at each end. An optical cable is laid in the roadway, and then, the first protective pipe is placed on the optical cable at the working face and pulled to the entrance of the roadway. Then, this is repeated with the remaining protective pipes inserted. After all the protective pipes have been installed, the joint between the two protective pipes is tightened to complete the installation.

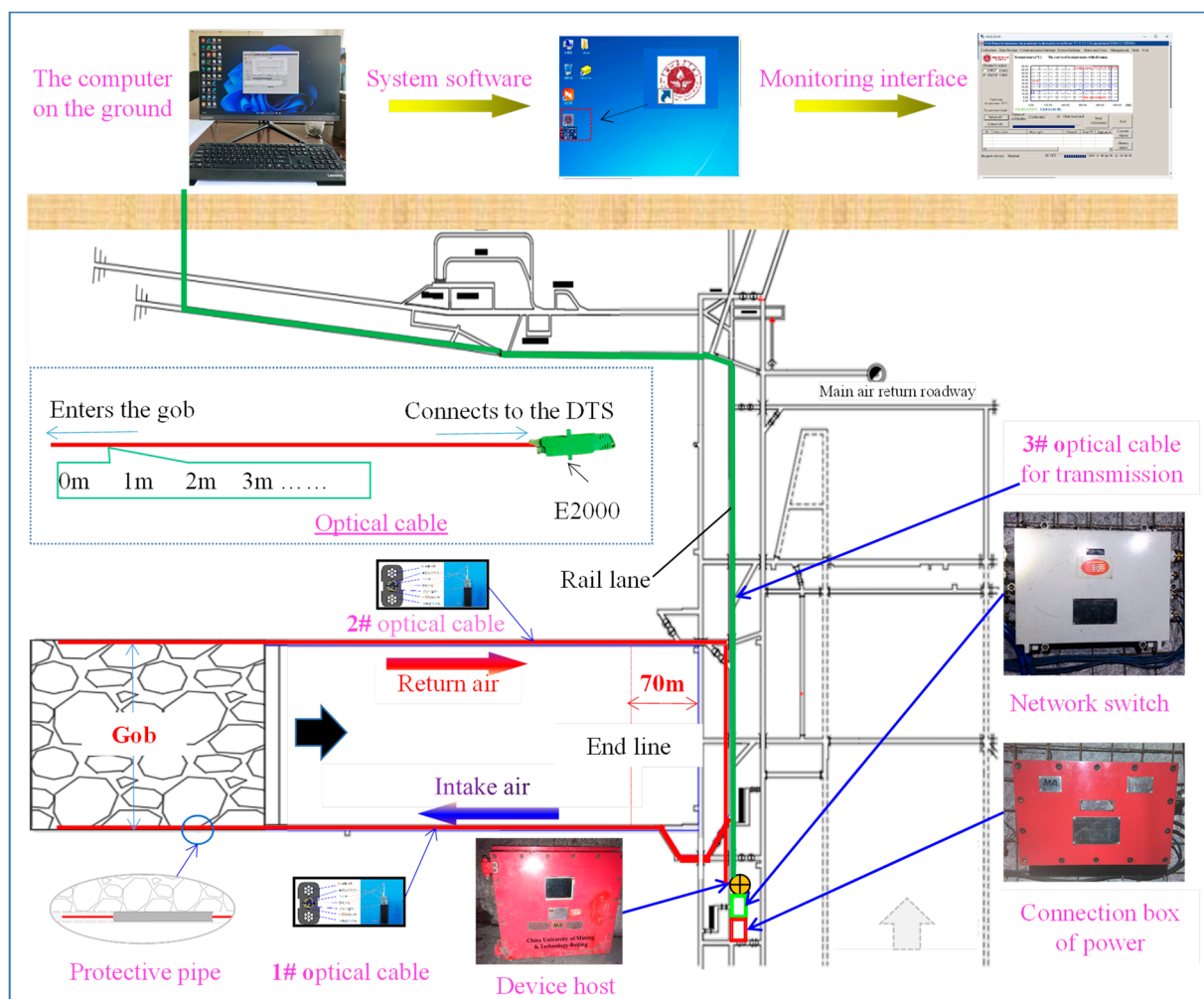


Figure 7. Application design of DTSS in gob.

One end of the optical cable with an E2000 fiber optic connector enters the device host. And as the working face advances, the other end, beginning a 0 m, is buried in the gob. The connection box of power supplies power to the device host. The temperature signal demodulated by the device host is transmitted to the ground computer through a network switch and the 3# transmission optical cable, which achieves the ground monitoring of temperature data in the underground gob.

4.2. Application Effect

Figure 8 shows the construction of each part of the DTSS on-site, and Figure 8a,b show the laying of optical cables with identification labels on them. Subsequently, the wiring work is completed using a fusion splicer. The connection of optical cables, electric cables, and network cables to the device host is completed in the wiring chamber shown in Figure 8d. The on-site layout of the DTSS is shown in Figure 8g.

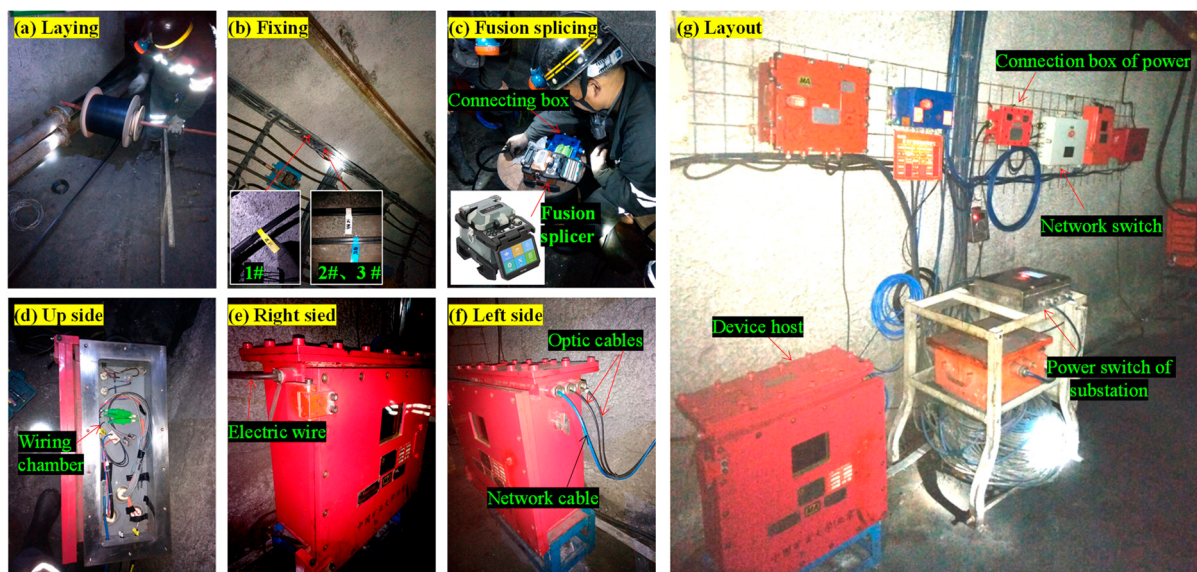


Figure 8. Construction effect of DTSS. (a) Laying. (b) Fixing. (c) Fusion splicing. (d) Top side. (e) Right side. (f) Left side. (g) Layout.

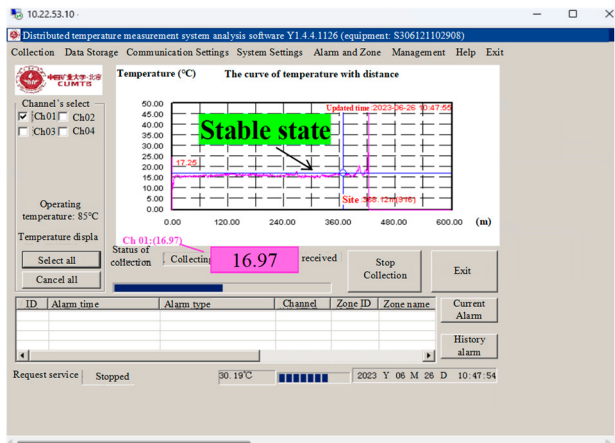
After the completion of the DTSS, the system software of the ground computer obtains temperature data from four channels, as shown in Figure 9. The optical cables used in this work are dual-mode with two cores (double insurance), so channel 1 and channel 2 display the temperature data of the 1# optical cable, while channel 3 and channel 4 display the temperature data of the 2# optical cable. The temperature data detected by the four channels has a certain degree of fluctuation, but the difference is not significant, and the temperature on the entire optical cable remains stable. Real-time data show that the temperature of the gob is between 15.45~16.97 °C, with an average value of 16.09 °C. It should be noted that there is an irregular fluctuation in temperature at the end of each channel, which is a normal disturbance phenomenon at the end of the optical cable and can be ignored.

4.3. Evaluation of the Effectiveness of Inhibitors

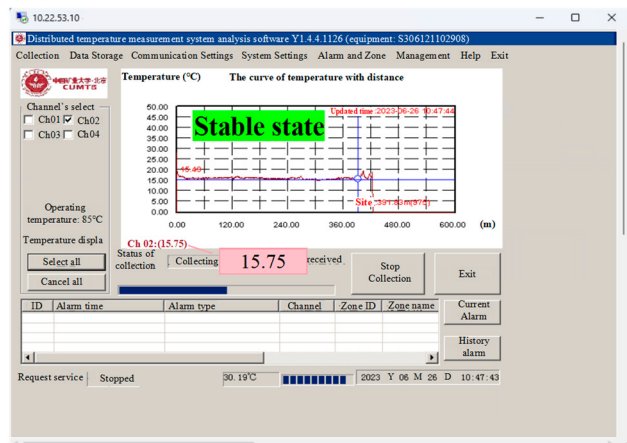
The above research indicate that the DTSS established in this work can accurately monitor temperature changes in gob areas. In addition, the DTSS can effectively support the prevention and control of natural fires. During the use of the DTSS, a geological formation appeared while the 15,106 working face advanced to the position of 347 m. This resulted in a decrease in forward speed and a decrease in daily forward length from 2.4 m to 0.5 m. A certain range of gob behind the working face has been in the oxidation zone for a long time. The temperature monitored by the optical cable of the DTSS on 26 June 2023 showed

that the temperature in the gob at 18 m behind the working face (with an optical cable length of 399.6 m) was about 20 °C, which was 4 °C higher than normal.

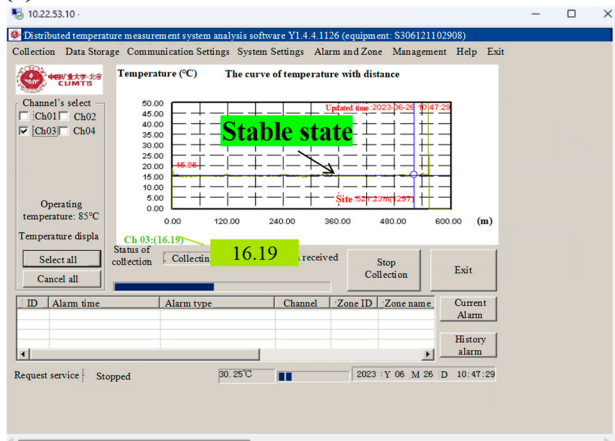
(a) Channel 1



(b) Channel 2



(c) Channel 3



(d) Channel 4

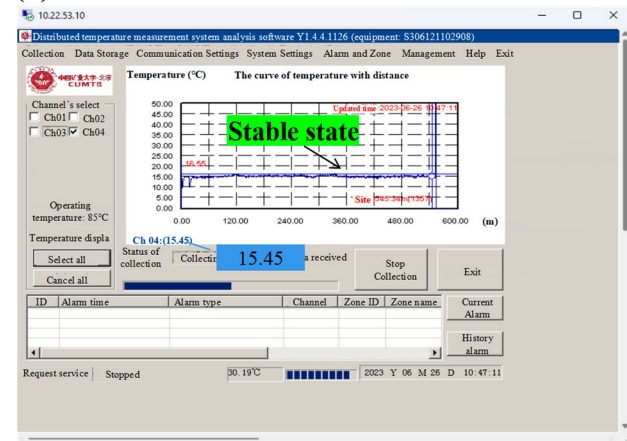


Figure 9. Results of temperature detection. (a) Channel 1. (b) Channel 2. (c) Channel 3. (d) Channel 4.

To control the increase in temperature after receiving the warning information issued by the DTSS, the method of using spray inhibitors in the gap between the hydraulic supports was employed to suppress the oxidation reaction of residual coal. Figure 10 shows the spraying process of the inhibitor solution. The inhibitor is industrial calcium chloride ($\text{CaCl}_2 \cdot 5\text{H}_2\text{O}$), with a concentration of 15%. The mixed inhibitor solution was delivered to the working surface through a pressure pump of model BZ-40/2.5 (manufactured by Shandong Changye Machinery Equipment Co., Ltd., China), and then, sprayed through a spraying gun from the gap between two hydraulic supports towards the gob, for at least 6 min each time, with a flow rate of no less than 35 L/min. Due to the temperature anomaly point detected by the 1# optical cable being close to the air intake side, inhibitor spraying was designed to be carried out at 60 m (34th hydraulic support) on the air intake side.

The working face advanced by 30 m within 65 days from 26 June 2023 to 31 August 2023. The effectiveness of the inhibitor solution was evaluated through temperature changes monitored by the 1# optical cable of the DTSS. Figure 11 shows the temperature values of the gob on the air intake side. In order to improve the reliability of data comparison, temperature data from 10:00 am, 14:00 pm, and 20:00 pm one day before and after spraying were selected. The data before spraying were selected from 26 June 2023, and the data after spraying were selected from 31 August 2023.

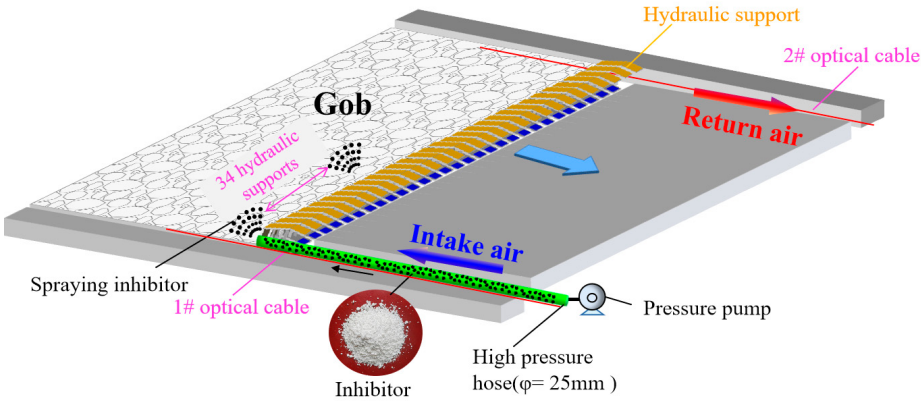


Figure 10. Spraying process of inhibitor.

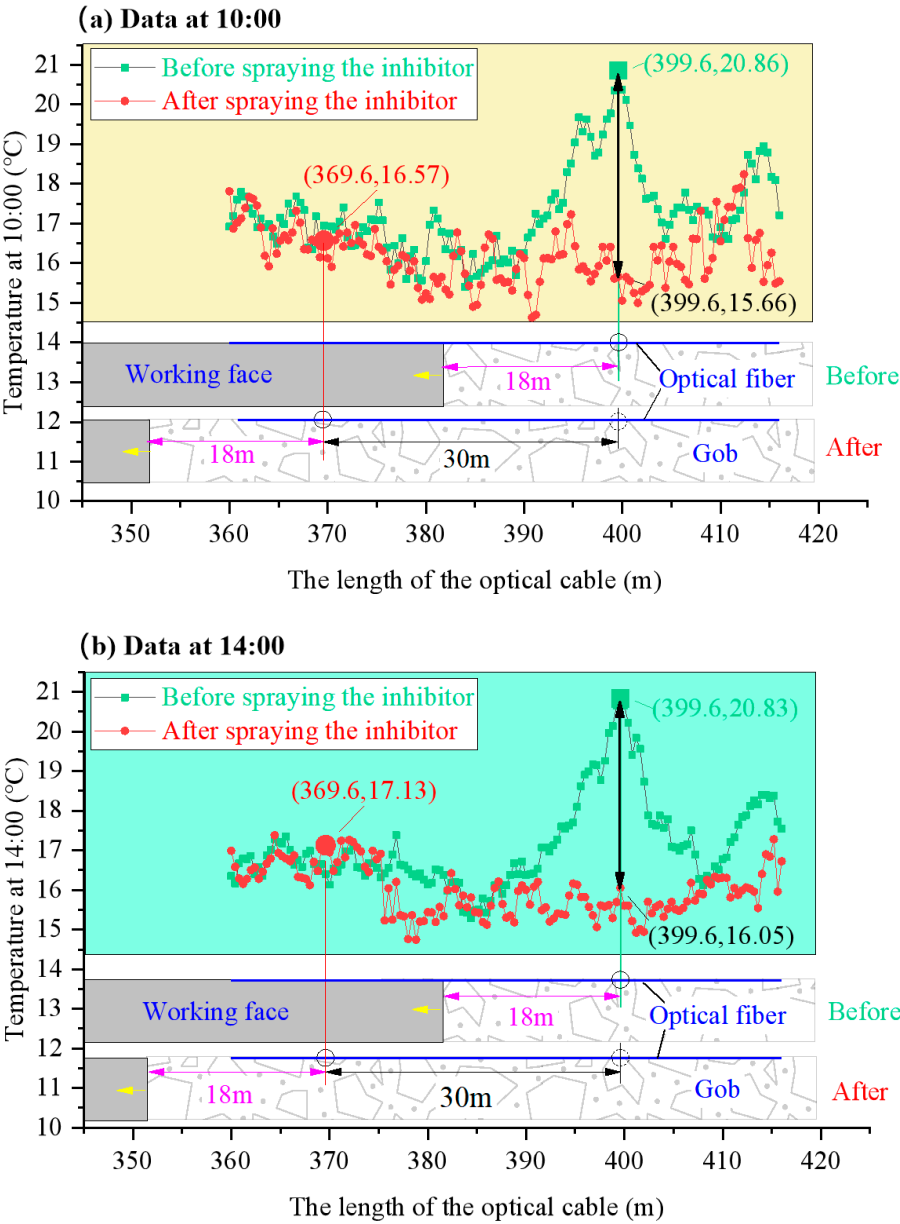


Figure 11. Cont.

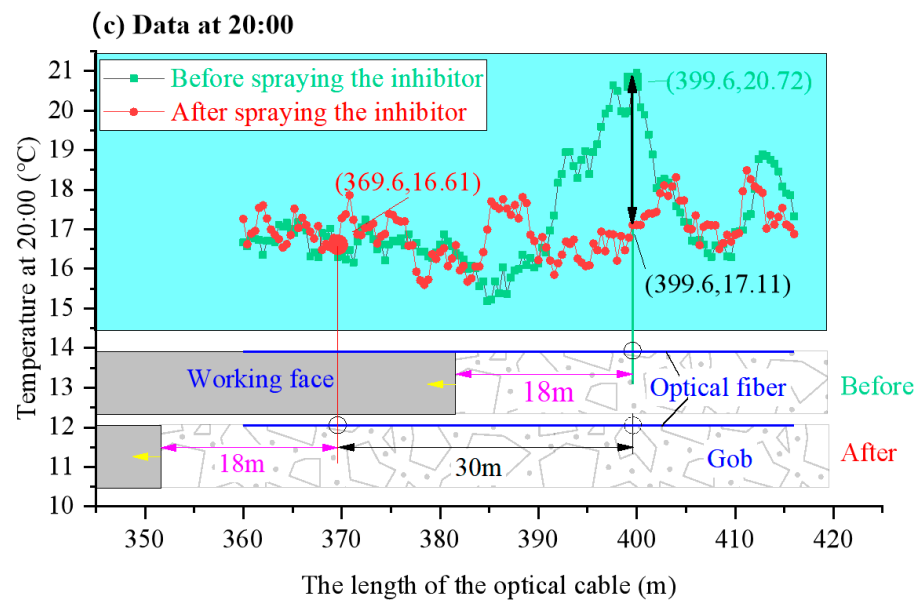


Figure 11. Comparison of temperature before and after spraying the inhibitors after 65 days. (a) Data at 10:00. (b) Data at 14:00. (c) Data at 20:00.

What can be seen from Figure 11 is the following: ① Before spraying the inhibitor solution, the temperature of the gob at the position 18 m behind the working face (optical cable length 399.6 m) increased to 20.86 °C, 20.83 °C, and 20.72 °C, respectively. After using the inhibitor solution, the temperature of the gob with a relative delay of 18 m (cable length 369.6 m) was 16.57 °C, 17.13 °C, and 16.61 °C, respectively, decreasing by 4.29 °C, 3.7 °C, and 4.11 °C, respectively. The average temperature decreased from 20.8 °C to 16.77 °C, with a decrease of 19.38%. This means that the temperature of the gob behind the working face returned to a normal temperature. ② After 65 days of advancing the working face, the point at 399.6 m of the optical cable changed from 18 m to 48 m behind the working face, and the temperature at this position also decreased to 16.05 °C, 15.66 °C, and 17.11 °C, respectively. The average temperature at this point decreased from 20.8 °C to 16.27 °C, with a decrease of 21.78%. This indicates that the risk of coal spontaneous combustion in this area was eliminated. ③ These temperature changes indicate that the adopted inhibitor spray measures effectively suppressed the oxidation and exothermic effect of residual coal, and the DTSS used strongly supports the safety of production work in the coal mine.

This product and technology have greatly improved the monitoring and warning capabilities of CSC hazards in gob.

5. Conclusions

In this work, a monitoring and early warning system suitable for harsh environments in gob, called the distributed optical fiber temperature sensing system, was developed and successfully applied to monitoring and evaluating the degree of CSC in a coal mine in China. The main conclusions are summarized below:

1. The internal parallel steel cables and the external protective pipe improved the anti-damage ability of the optical cables. The technology of the protective pipe only increases the time required for detecting the actual temperature and does not affect the accuracy of temperature measurement. The temperature difference before and after use of the protective pipe is only 0.87 °C, 0.67 °C, and 0.24 °C, respectively. So, the protective pipe can be used with confidence.
2. The technology of the DTSS could improve early warning ability for preventing the risk of CSC in gob. This technology can detect abnormal temperature conditions in gob in a timely manner. Through the monitoring and evaluation of the DTSS, the average temperature at the same location in the gob after spraying the inhibitor

returned from 20.8 °C to 16.27 °C, with a decrease of 21.78%, which means the risk of CSC in the gob was eliminated.

3. This study only analyzes the application effect of DTSS technology in coal mine gob, which is not comprehensive enough. So, in the future, to enrich these research findings, comparative research on other measurement methods, such as temperature measurement methods of thermal resistance, will be carried out. In addition, we also hope to use the DTSS for in-depth research in different scenarios.

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