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The Longitudinal Temperature Detection System and Its Application of the Distributed Optical Fiber Freezer

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Abstract: The modeling illustrates the equation of the relation between the temperature of the freezer and the radius of the tjaele, so the horizon tjaele radius can be calculated by the temperature of the horizon freezer. Compared with the single bus temperature sensor system, the former can measure the continuous longitudinal temperature distribution at the spatial resolution of 1m, thus the relevant tjaele radius can be calculated, the same is of the whole longitudinal direction, therefore, the closure plans of ice wall can be examined by the freezer overlay. The thesis firstly gives us an introduction of the construction, working principle and methods of the distributed optical fiber freezer, and then shows some examples.

Keywords: The distributed temperature sensing; freezing method; longitudinal temperature; frozen wall; temperature field

1. INTRODUCTION

The freezing method is a special construction method in efficiently penetrating unstable stratum like deep alluvium and soft rock, which can be seen in the coal mine shaft construction. More specifically, before digging, the surrounding rock is firstly frozen into closed frozen wall through artificial refrigeration in order to resist the pressure from water and soil and cut the contact between the underground water and the shaft, secondly, the construction is started under the protection of the frozen wall, and now the freezing depth of the shaft has already surpassed seven hundred meters [1-2]. Normally, there are 4 to 7 thermometer holes distributed in the inside and outside the arranged circle of the freezer, so the situation of the frozen wall can be observed. However actually, because of the complicated geological conditions, it’s quite difficult to fully know the state of the frozen wall just through the data of these thermometer holes, especially under conditions like some special freezing constructions or the circles don’t cross each other on the frozen wall, which makes it really hard to know the state and detect the concrete location of these circles[3]. The advanced distributed temperature sensing can better reflect the temperature conduction radius of the frozen soil columns and the radius of the frozen soil itself so that we can grasp the condition of the frozen wall and find the malfunction location and then promote the freezing construction..

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2.THE LONGITUDINAL TEMPERATURE DETECTION SYSTEM DISTRIBUTED OPTICAL FIBER FREEZER

The commonly used temperature detection sensor is single bus digital temperature sensor DS18B20. When several DS18B20s are concatenated together on a cable with a certain distance and then put the cable into the thermometer hole or the freezer, we can get different temperature value. Whereas, there exist many weaknesses, such as limited sensor number, long and discontinuous temperature measuring distance; moreover, considering there is only one cable, so the fault rate is quite high; and the drive capability of the sensor is also limited because of the need of power supply.

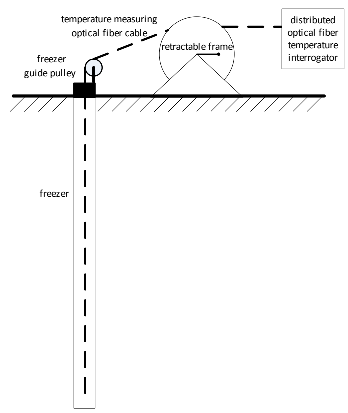

Fig. (1). Components of the detection system.

2.1 System Components

The distributed optical fiber sensing technology possesses a great sense system, a high level of spatial resolution, a continuous detection spots and a long measure distance because it is based on the scattering during the transmission of laser pulse. The system consists of a distributed optical fiber temperature interrogator, an optical fiber detection retractable frame, a freezer guide pulley and a temperature measuring optical fiber cable, seen in fig. 1. Specifically, the cable is for detecting the longitudinal temperature of the freezer, meanwhile, the pulley and frame aim at receiving and relieving the detected fiber cable, finally, the interrogator is used for observing and controlling the signal.

The structure of distributed optical fiber temperature interrogator is as fig. 2, mainly consisting of optics part and signal collection and processing part. The former is further composed of the semiconductor laser, the optical fiber directional coupler, the sensor fiber and the optical spectral components, while the latter consists of the photoelectric receiver and the data acquisition and processing computer[4-7].

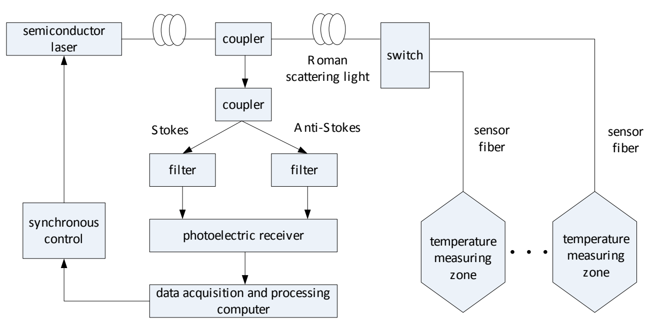

Fig. (2). Structure of the distributed optical fiber temperature interrogator.

2.2 The working principle of the distributed optical fiber temperature interrogator

The system is able to observe the longitudinal temperature change of the whole temperature field with a certain interval. The measure principle is OTDR (Optical Time Domain Reflectometry) and Raman Scattering Temperature Effect, which can not only locate the temperature measuring point but also perceive and measure the temperature.

In the perspective of energy in quantum theory, Raman Scattering is caused by the inelastic collision of photon. It is found that the Anti-Stokes scattering light is quite sensitive to temperature change; while the Stokes scattering light also has something to do with the temperature to a smaller extend; whereas, Rayleigh scattering light has nothing to do with the temperature.

The Anti-Stokes scattering photon number at optical fiber zone L

$$N_a = K_a S \nu_a{}^4 N_e \exp[-(a_0 + a_a)L] R_a(T) \qquad (1)$$

The Stokes scattering photon number at optical fiber zone L

$$N_s = K_s S \nu_s{}^4 N_e \exp[-(a_0 + a_s)L] R_s(T) \qquad (2)$$

The Rayleigh scattering photon number at optical fiber zone L

$$N_R = K_R S \nu_0{}^4 N_e \exp(-2a_0 L) \qquad (3)$$

Ne represents for the optical fiber incident light pulse photon number; *KR, Ka, Ks* respectively mean the related coefficients of the scattering cross sections of Rayleigh, Anti-Stokes and Stokes; *S* is the backward scattering factor of the optical fiber; v_0, v_a, v_s are the scattering light frequency of the three; and a_0、a_a、a_s mean the transmission loss of them; meanwhile *L* is the distance between the area to be measured and the irradiation port. $R_a(T)$、$R_s(T)$ are the related coefficient, and it is related to the temperature in the optical fiber area:

$$R_a(T) = [\exp(h\Delta\nu / kT) - 1]^{-1} \qquad (4)$$

$$R_s(T) = [1 - \exp(-h\Delta\nu / kT)]^{-1} \qquad \mathbf{(5)}$$

$\Delta\nu$ is the frequency of Raman scattering light; h is Planck constant; and k is Boltzman coefficient.

The principle of temperature demodulation method is demodulating Anti-Stokes scattering curve OTDR with Stokes scattering curve OTDR, so from (1) and (2), we can get (6):

$$\frac{N_a(T)N_s(T_0)}{N_s(T)N_a(T_0)} = \frac{\exp(-h\Delta\nu / kT)}{\exp(-h\Delta\nu / kT_0)} \qquad (6)$$

From (6), we know:

$$\frac{1}{T} = \frac{1}{T_0} - \frac{k}{h\Delta\nu} \ln \frac{N_a(T)N_s(T_0)}{N_s(T)N_a(T_0)} \qquad (7)$$

T_0, $N_a(T_0)$, $N_s(T_0)$, $N_a(T)$ and $N_s(T)$ are all known, so we can get the temperature *T*.

2.3 The longitudinal temperature measuring method and the sensor fiber structure

The longitudinal temperature measuring is action-based measuring. Firstly, stop the brine circulation, secondly, put the temperature measuring optical cable into the freezer, and then after the longitudinal detection, take out the cable and finally recover the brine circulation. And the whole process probably continues about one hour, as a result, based on the analysis, during the initial stage, temperature is quite sensitive to the size of the frozen soil column, so we should complete the detection of one freezer within four hour. Of course, we can allocate time according under different circumstances to set up each schedule and finish all the detection well.

Considering the reiterative pulling down and back, the cable needs to be quite tensile in order to avoid any mistake, and the structure is as fig. 3. We should put both the single tightly-buffered fiber and the aramid fiber together into the stainless steel flexible hose, and meanwhile add a layer of stainless steel preparation of silk onto the hose to increase the tensile ability, finally put a polyurethane sheath to resist low temperature. Besides, in order to prevent the cable from fracture during the process, we should use the colligation method together with a 1.8mm galvanized steel wire rope as the tension carrier. The concrete parameter is as following: the diameter of multimode fiber core is 62.5±2.5μm with a maximum attenuaton speed of 3.5dB/km（850nm）and 1.5dB/km（1300nm）, and the working temperature is from -50 degree to 90 degree, with a dynamic bending radius of 10D and static bending radius of 20D, together with a long-term tensile strength of 200N and a short-term tnsile strength of 300N, moreover, the long time compressive reinforcement is 3000N/100mm and short time is 5000N/100mm with a weight of 25Kg/Km.

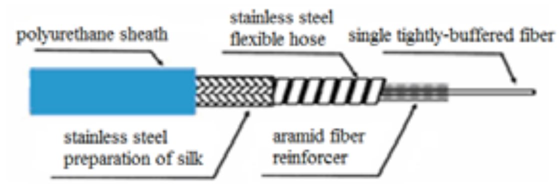

Fig. (3), The armored cable structure.

3. THE MATHEMATICAL MODEL OF TEMPERATUE RISE IN THE TEMPERATURE FIELD INSIDE THE FROZEN SOIL COLUMN[3,8-10]

The longitudinal temperature detection is to stop the brine circulation in a planned way during the freezing period and then put down the optical cable to measure the longitudinal temperature, and according to the temperature rise after freezing, we can analyze the detailed situation of the frozen wall.

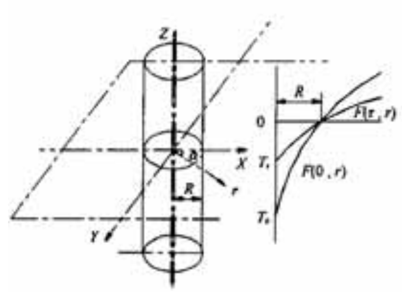

Fig. (4), The mathematical model of temperatue rise in single span frozen column

If we regard the length of freezer as infinite to build the simplified model of the frozen soil column as fig. 4, after the heat exchange for some time, the frozen soil keeps expanding to form a frozen column with, and if at a moment t, we stop the brine circulation, during this period, there is a plane tranient heat onduction, so the column has a instantaneous temperature rise. Based on the flat heat conduction principle of the diameter of the polar coordinates to the axial symmetry, and we could get the differential equation as below:

$$\frac{\partial T}{\partial \tau} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \qquad (8)$$

T is the temperature; t is time; r is radius.

If the thermal diffusivity were a parameter to reflect the heat-conducting property, and the boundary condition sets up the interface temperature of the frozen soil and melted soil as 0 degree and then stops the freezing process for a while with the frozen soil radius unchanged. Because the heat exchange between the frozen soil and melted soil mainly causes the temperature rise within the column, the frozen soil won't melt. Use $T(\tau,R)=0$ ($0 \le \tau \le \tau_0$), τ_0 is the longest unfrozen time.

The initial condition is the initial temperature field function before the temperature rise

$$F(r)=\sum_{n=1}^{N}(-1)^{n-1}\left(\frac{r}{2}-1\right)^{n}/n \quad (0<r\le 4) \tag{9}$$

$$T(0,r)=AF(r)+B \quad (r_0<r\le R) \tag{10}$$

A and *B* are the coefficients of the function, while *r0* is the outside radius of the freezing pipe.

The conditions of the initial temperature field are: $T_0|_{r=R}=0$, $T|_{r=r_0}=T_0$, normally T_0 is between -30 degree and -20 degree.

According to the principle of special function and variables separation method, we can deduce the temperature distribution inside the column at time t, and as for different frozen column R, the temperature distribution will be as:

$$T(r,R,\tau)=\sum_{n=1}^{\infty}C_n e^{-\alpha\left[\frac{q_n^{(0)}}{R}\right]^2\tau}J_0\left(\frac{q_n^{(0)}}{R}r\right) \tag{11}$$

$$C_n=\frac{2}{\left[J_0(q_n^{(0)})\right]^2R^2}\int_0^R rF(r)J_0\left(\frac{q_n^{(0)}}{R}r\right)dr \tag{12}$$

A is the thermal diffusivity of the frozen soil; J_0 the zero order Bessel function; $q_n^{(0)}$ is the positive null point of J_0. *n* could be 1, 2, 3 and so on.

The equation (11) is a series consisting of coefficient, exponential function and Bessel function compound, and because r_0 is quite small, while r approximates 0, the temperature will be quite similar to T_{r_0} of the measuring point in the freezer

$$T_{r_0}\approx T(r,R,\tau)\Big|_{r\to 0}=\sum_{n=1}^{\infty}C_n e^{-\alpha\left[\frac{q_n^{(0)}}{R}\right]^2 r} \tag{13}$$

Derivate t in (13), we can get the temperature rise speed in the freezer as

$$\dot{T}_{r_0}\Big|_{\tau}=-\frac{\alpha}{R^2}\sum_{n=1}^{\infty}C_n\left[q_n^{(0)}\right]^2 e^{-\alpha\left[\frac{q_n^{(0)}}{R}\right]^2 r} \tag{14}$$

When t=0, according to (13) and (14), we can get

$$T_{r_0}\approx\sum_{n=1}^{\infty}C_n \tag{15}$$

$$\dot{T}_{r_0}\Big|_{\tau}=-\frac{\alpha}{R^2}\sum_{n=1}^{\infty}C_n\left[q_n^{(0)}\right]^2 \tag{16}$$

As a result, Cn depends on the initial temperature field before the unfrozen period, however, the convergence value of $\sum_{n=1}^{\infty}C_n$ approximately equals to the initial temperature T_0.

According to the above equation, we know the longitudinal temperature can be used to define the radius of frozen soil surrounding the freezer, and based on the unfrozen time, we can detect the longitudinal temperature, and then use equation (13) to know the exclusive temperature of each point at different radius and moments. What's more, the radius of frozen soil can also be measured, thus we can use figure to show the relation between the size and scale of the frozen soil radius, and then add all the radius of surrounding the freezer at the same layer together, we can directly see the situation of the frozen wall.

4. APPLICATION EXAMPLES

There happened a water and sand crush accident in the auxiliary shaft, causing the shaft destruction in a coal mine in Huainna, Anhui province, so it is decided to use the ground pregrouting and freezing method to restore the accident. The auxiliary shaft is equipped with double row holes with 42 freezing holes outside and 32 inside. After 75 days' working, the water level of 4 hydrological holes all reached to the pipe orifice. The shaft was already built, so it is difficult to decide the real situation of the frozen wall either by the water from hydrological hole or by the temperature of the measuring hole, in the end, in order to know the real condition of the frozen wall, after 131 days' freezing, they decided to use the longitudinal temperature detection system of distributed optical fiber freezer.

During the detection, they used two sets of the systems at the same time with 75 time schedule of frozen and unfrozen period in three days. Therefore, each freezer could get the longitudinal temperature value from ground to underground with a spatial resolution of 1m, and they got the longitudinal temperature curve of all the freezer as fig. 5 and 6. It was concluded that the whole temperature was from -30 degree to -19 degree, so the freezing hole of the auxiliary shaft was in good condition without any abnormal phenomena. Besides, the deeper of the shaft, the lower of the longitudinal temperature, and the temperature of inside freeze was lower than that of outside, which conformed to the direct circulation of the froze brine.

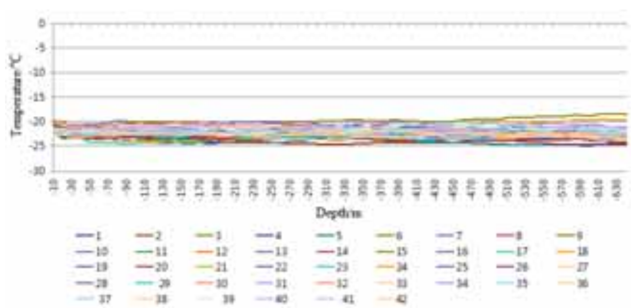

Fig. (5). The longitudinal temperature curve of outside freezer in the auxiliary shaft.

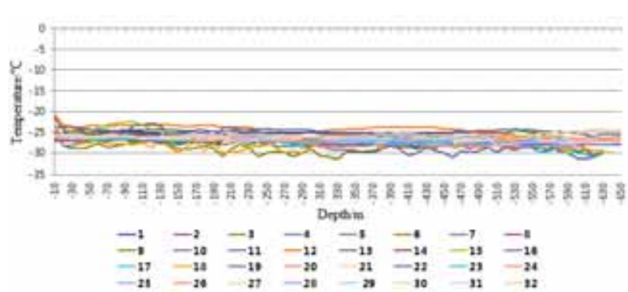

Fig. (6). The longitudinal temperature curve of inside freezer in the auxiliary shaft.

According to equation (13), we can get the frozen soil radius of each freezer. If we add the radius of a certain layer, we will know the condition of the whole frozen wall of this layer. Fig. (7) and (8) respectively gives us two circle diagrams of the frozen wall at depth of -490m and -560m, from which we can see no abnormity. The system detects each temperature value every one meter, so we can get a circle diagram every one meter, and then add all the diagrams in longitudinal directions, we can draw a solid figure to show the condition of frozen wall more directly and precisely.

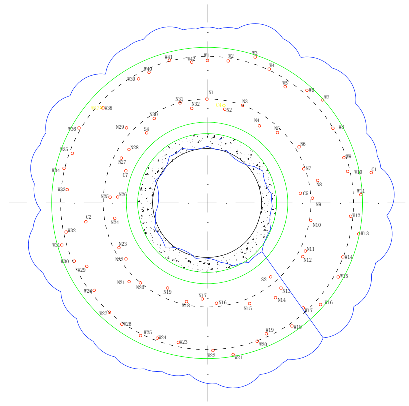

Fig.(7). The circle diagram of the frozen wall at depth of -490m.

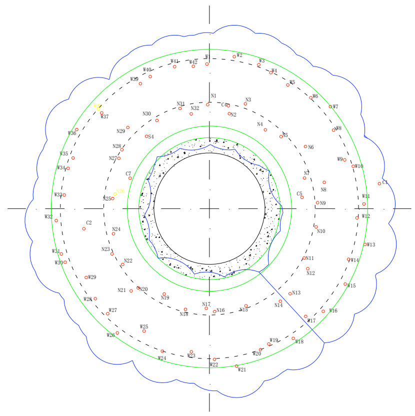

Fig.(8). The circle diagram of the frozen wall at depth of -560m.

5. CONCLUSION

Compared with the traditional single bus temperature sensor system, the distributed system is much more concrete and accurate with no blind point in detection, so we can get the continuous temperature curve to directly show the longitudinal temperature change in the freezer. According to the relation between the temperature change of the freezer and the radius of frozen soil, we can know each outside column radius of the freezer from the longitudinal temperature, thus, we can get the circle diagram of a certain layer to reflect the development condition of the frozen wall, which is much more accurate compared with the data detected from several separate temperature measuring holes. It is confirmed that the system features a better characteristic so that it serves as a new detection method to help people better control the freezing construction, therefore, the whole construction process can be much safer and faster.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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