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# Research of inversion problem of coal mine fire hidden based on the method of regularization

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**ABSTRACT**

*The spontaneous combustion of coal mine is one of the five natural disasters in coal mine, and the coal spontaneous combustion concealed fire location is the key to solve the problem of coal spontaneous combustion. The theory of heat transfer and fluid flow in porous media theory, combined with the actual fire location problem is reduced to the heat conduction equation of the search for the source of the inverse problem in this paper. The mathematic model was established to analyze the source point. The mine hidden fire location for inversion and numerical simulation, reduce the occurrence of coal spontaneous combustion. Firstly, according to the characteristics of mine concealed fire, attributing the problem to determine the fire location for the heat conduction equation for source identification. Secondly, we suppose fire as line fire in the ideal situation and using the discrete regularization method to mine the hidden line source inversion. The inversion results show that: this method can accurately show the characteristics of anti fire and method by solving the heat source inversion is an effective way to solve the mine concealed fire ignition characteristics of mine fire prevention and it has high research value both in theory and practice.*

**Keywords:** Inverse problem, Regularization, Coal Mine Fire Hidden, Spontaneous combustion

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## INTRODUCTION

### 1.Background

The spontaneous combustion of coal mine fire has strong concealment, until now, there is no an effective detection method for determining fire. It is due to the inaccuracy of the detection method, some scholars began to study method to determine the position of fire source theoretically. Spontaneous combustion of coal seam is a very complex process. Its essence is the surface of the coal and oxygen in the air to produce a series of physical and chemical adsorption and reaction heat, which leads to the coal combustion, heating of the surrounding medium and to escape the heat. Detection of fire source of spontaneous combustion in coal mine is according to the physical and chemical changes of the spontaneous combustion process itself or the surrounding medium to achieve volume.

Determine the fire source position can be attributed to the heat conduction equation for source identification. After decades of research, scholars, experts have heat conduction in the search for the source of the inverse problem of a solution of a series of methods, there are continuous regularization method, discrete regularization method, pulse spectrum method, generalized pulse spectrum technique, the finite difference method, the quantum scattering inversion method, finite element the inversion method, which is commonly used regularization method. The regularization methods are divided into two categories: continuous regularization method and the discrete regularization method. The difference is: the continuous regularization is first normalized discrete, discrete regularization for the first discrete regularization.

### 2. The regularization algorithm

Solutions for our requirements may be too compact case. However, many practical problems it is not solvable class of compact sets and with the equation as follows:

$$Fx = y \tag{1}$$

The approximate characteristics of the right end of the changes linked to, you can make it beyond the set $FM$ . This problem is called ill-posed nature [1].

Let equation (1) in the operator F is such that the inverse operator $F^{-1}$ is not continuous within the set of FX, and possible solutions of the X set is not compact.

Let elements of $x_T \in X$ and $Fx_T = y_T$ $y_T \in Y$ is linked to relationships. If $K(y,\delta)$ has the following characteristics of operator time to call in the neighborhood of the equation $Fx = y$ $y = y_T$ is regular.

(1) The existence of such number of $\delta_1 > 0$ , the operator $K(y,\delta)$ for all $\delta$ , $0 \le \delta \le \delta_1$ and $\rho_Y(y_T, y_\delta) \le \delta$ in any $y_\delta \in Y$ sense;.

(2) For all $\varepsilon > 0$ , the existence of $\delta_0 = \delta_0(\varepsilon, y_T) \le \delta_1$ , so that inequalities $\rho_Y(y_\delta, y_T) \le \delta \le \delta_0$ can be drawn from the inequality $\rho_X(x_\delta, x_T) \le \varepsilon$ A, where $x_\delta = K(y_\delta, \delta)$ .

Note: In this definition, the general said, does not assume that operator K of the single value. It used to represent the set $y_\delta$ in any of $K(y_\delta, \delta)$ the elements. In many cases, the use of regular operator more convenient to other definitions, the above definition is included [2].

**2.1 Construction Method of Regularization**

Build on the regularization method, the long-standing guiding principle of constructing a suitable stabilization is functional, that is, functional stabilization methods. A more systematic exposition of early in the text is Groetsch spectrum theory-based work, but its methods and maneuverability is not strong, and its failure to achieve a higher regular asymptotic solutions of order. In recent years, Krisch made singular system theory is the mathematical concept of the polaron, which gives the establishment of regularization method, provides a new theoretical basis. Construction of this section will give two regularization methods: variation principle based on the stabilization of functional methods and the theory based on singular value system is the annihilator method.

Let $x_T$ and $y_T$ is the X and Y in the two fixed elements, $x_T \in X$ , $y_T \in Y$ , $Fx_T = y_T$ , $\delta$ is a fixed positive number. Any one element of $y_\delta \in Y$ , so that

$$\rho_Y(y_T, y_\delta) \le \delta$$

There

$$\rho_X(\widetilde{K}(y_\delta,\alpha), x_T) \le \rho_X(\widetilde{K}(y_\delta,\alpha), \widetilde{K}(y_T,\alpha)_T) + \rho_X(\widetilde{K}(y_T,\alpha), x_T) \tag{2}$$

Because the operator $\widetilde{K}(y,\alpha)$ at point $y_T$ on $y$ is continuous, then all sufficiently small $\delta > 0$ can be inequality

$$\rho_Y(y_T, y_\delta) \le \delta \tag{3}$$

Come inequality

$$\rho_X(\widetilde{K}(y_\delta,\alpha), \widetilde{K}(y_T,\alpha)) \le w(\delta) \tag{4}$$

When $\delta \to 0$ , $w(\delta) \to 0$ .

Because

$$\lim_{\alpha\to 0} \widetilde{K}(Ax,\alpha) = \lim_{\alpha\to 0} \widetilde{K}(y_T,\alpha) = x_T$$

So are there for $\delta > 0$ all such $\alpha = \alpha_1(\delta, x_T)$, such that when $\alpha \le \alpha_1$,

$$\rho_X(\widetilde{K}(y_\delta, \alpha), x_T) \le w(\delta) \quad (5)$$

By the inequality (2), (4), (5) can be obtained for any of the $\delta \le \delta_1$ and $\alpha \le \alpha_1$ are established inequality

$$\rho_X(\widetilde{K}(y_\delta, \alpha), x_T) \le 2w(\delta) \quad (6)$$

Because $\delta \to 0$ and $w(\delta) \to 0$ it can be pointed out that for all e such $\varepsilon > 0$, such that for $\delta(\varepsilon)$, and $\alpha = \alpha_1(\delta, x_T)$ can from the inequality (3) and (6) derived inequality

$$\rho_X(\widetilde{K}(y_\delta, \alpha), x_T) \le \varepsilon$$

**2.2 Tikhonov regularization method**

Tikhonov regularization method is theoretically the most complete and effective method in practice, the nonlinear equation:

$$Fx = y$$

Where F: $D(x) \in X \to Y$, $X, Y$ is the Hilbert space, $x^*$ located above the equation $x_0$ is $Fx = y$ the minimum distance solution (that is, the solution when the equation is not unique when the $Fx = y$, $x^*$ and $x_0$ is a minimum distance of a solution.) The introduction of the following Tikhonov functional as follows:

$$\Phi_\alpha(x) = \left\| y^\delta - F(x) \right\|^2 + \alpha \left\| x - x^* \right\|^2$$

Where $\alpha > 0$, $\left\| y - y^\delta \right\| \le \delta$, $x_0$ is an initial guess solution $x^*$. We have the global minimum of functional $\Phi_\alpha(x)$, $x_\alpha^\delta$ as $x^*$ an approximate solution. Choose the right time when the A, S D can be used as a good approximation [3].

Let $X, Y$ is a Hilber space, F: $X \to Y$ is a bounded operator, then

(1) $\Phi_\alpha(x)$ in X, there exists a unique minimizer $x^\alpha$;

(2)meet $x^\alpha \in X$

$$\alpha x^\alpha + F^* F x^\alpha = F^* y$$

Regularized solution is uniquely determined by the $\alpha x^{\alpha,\delta} + F^* F x^{\alpha,\delta} = F^* y^\delta$. Regularization parameter $\alpha = \alpha(\delta)$ as long as the $\delta \to 0$, to meet the $\alpha(\delta) \to 0, \dfrac{\delta^2}{\alpha(\delta)} \to 0$.

When the compact operator K of the singular system is known, is assumed to be $\{u_j, x_j, y_j\}$, derived from the following expression for $R_\alpha y^\delta$ can be drawn:

$$x^{\alpha,\delta} = R_\alpha y^\delta = \sum_{j=0}^{\infty} (x^{\alpha,\delta}, x_j) x_j = \sum_{j=0}^{\infty} ((F^* F + \alpha I)^{-1} F^* y, x_j) x_j$$

$$= \sum_{j=0}^{\infty} (y, F(F^* F + \alpha I)^{-1} x_j) x_j$$
$$= \sum_{j=0}^{\infty} \frac{u_j}{\alpha + u_j^2} (y, y_j) x_j \qquad (7)$$

Consider the equation $Fx = y$ right there disturbances, of which the right end of $y^\delta$ satisfy the equation $\|y^\delta - y\| \le \delta$, $\delta > 0$ of the disturbance data, then (7) becomes the following form:

$$R_\alpha y^\delta = \sum_{j=0}^{\infty} \frac{u_j^2}{\alpha + u_j^2} (y^\delta, y_j) x_j$$

**3. Numerical Simulation**

In order to establish the mathematical model of heat conduction, according to the basic characteristics of coal drift close concealed fire, heat conduction hypothesis fire in accordance with the following basic assumption:

1) The fire in the surrounding rock to heat conduction to the heat transfer, the heat conduction coefficient for equivalent conduction, convection, radiation heat conduction coefficient of thermal conductivity;

2) Coal, rock around the fire area is homogeneous, isotropic;

3) Thermal physical properties of coal rock that are thermal conductivity and thermal diffusivity and specific heat are constant;

4) In the mine concealed fire position inversion for two-dimensional heat conduction problem abstract.

The conditions for determining the ideal state heat conduction, heat conduction model can be established in this ideal state of spontaneous combustion of coal seams. Model for the rectangular area shown in Figure 1, the side length of 5 m × 5 m; development of temperature field detection of fire location and detection instrument model material selection reference 1996 Shandong Mining Institute of the Ministry of coal industry average annual project. In selecting a material, considering both easy production model, and can satisfy the thermal properties with the same underground rock (usually underground rock density is $2300 \sim 2700 kg/m^3$, thermal conductivity is $1.7 \sim 4.5 W/(m \cdot K)$, thermal diffusivity is $0.4 \sim 1.5 \times 10^{-6} m^2/s$, specific heat is $0.7 \sim 0.9 kJ/(kg \cdot K)$ ). So the production model of the thermal physical parameters of the model in the data, so you can assurance and underground rock has the characteristics of heat conduction in the same. According to the requirements, selection and mine pressure simulation test of similar materials, decided to use gypsum, fine sand, fine powder. It using fine iron powder is to increase the density and improve the model of thermal conductivity and specific heat).

In order to make the model simple, the model is added with a heat insulating material layer, the model with the external thermal insulation. The parameters of the model as follows: density is $2338 kg/m^3$, specific heat is $C = 0.84 kJ/(kg \cdot K)$, thermal conductivity coefficient $a^2$ is $0.024 m^2/s$.

Assuming the spontaneous combustion is parallel to the edge of the B line fire, so the parallel to the B boundary as a step of parallel lines, parallel lines can be regarded as line fire, as shown in figure 1. For source inversion of all parallel lines, the two-dimensional problem into the one-dimensional problem. In Figure 1, where the embedded thermocouple temperature sensor, with "×" said sensor, sensitivity is $0.01°C$. By measuring the discovery, the measurement data of 5 point and 7 point, 4 point and 8 point, 3 point and 9 point, 10 point, 2 point and 1 point and 11 point is close, the inversion of L ~ 6 line of fire. Measured temperature data points are shown in table 1.

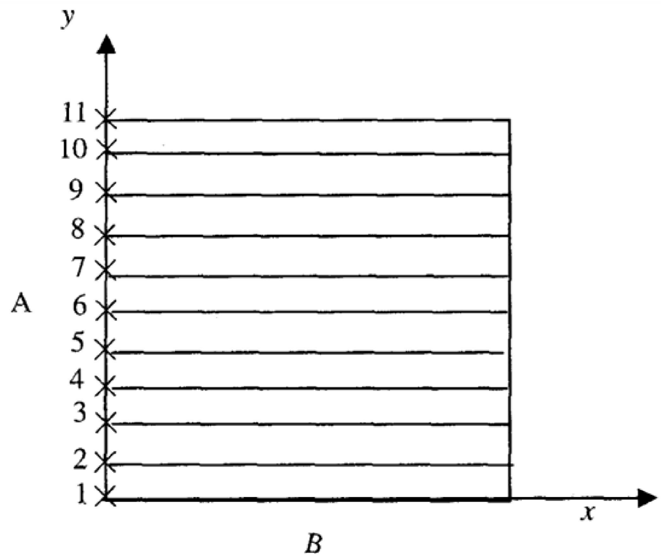


**Fig.1 Model diagram**

Assume that the parallel line temperature is uniform, mathematical model of the heat conduction equation

$$u_t(x,t) = a^2 u_{xx}(x,t) + f(t),\ \ 0 < x < 5m, 0 < t < T \tag{8}$$

**Table 1 Temperature datum**

| Days / data | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 |
| 2 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 | 24.19 |
| 3 | 24.30 | 24.30 | 24.30 | 24.30 | 24.30 | 24.30 | 24.31 | 24.31 | 24.31 | 24.31 |
| 4 | 24.23 | 24.23 | 24.24 | 24.24 | 24.24 | 24.25 | 24.25 | 24.25 | 24.25 | 24.25 |
| 5 | 24.16 | 24.16 | 24.16 | 24.17 | 24.17 | 24.19 | 24.19 | 24.19 | 24.20 | 24.21 |
| 6 | 24.30 | 24.30 | 24.30 | 24.31 | 24.31 | 24.31 | 24.32 | 24.33 | 24.34 | 24.34 |

| Days / Data | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 24.20 | 24.20 | 24.20 | 24.20 | 24.20 | 24.21 | 24.21 | 24.23 | 24.24 | 24.24 |
| 2 | 24.20 | 24.20 | 24.21 | 24.21 | 24.22 | 24.23 | 24.23 | 24.24 | 24.25 | 24.26 |
| 3 | 24.32 | 24.33 | 24.34 | 24.34 | 24.35 | 24.36 | 24.37 | 24.39 | 24.41 | 24.43 |
| 4 | 24.26 | 24.27 | 24.29 | 24.30 | 24.32 | 24.33 | 24.34 | 24.36 | 24.39 | 24.40 |
| 5 | 24.21 | 24.22 | 24.23 | 24.24 | 24.26 | 24.29 | 24.31 | 24.33 | 24.35 | 24.37 |
| 6 | 24.36 | 24.37 | 24.39 | 24.40 | 24.43 | 24.45 | 24.47 | 24.49 | 24.51 | 24.53 |

Initial conditions

$$u(x,0) = M,\ \ \ 0 < x < 5m \tag{9}$$

Boundary conditions

$$\begin{aligned} u_x(0,t) = 0,\ \ \ 0 < t < T \\ u_x(5,t) = 0,\ \ \ 0 < t < T \end{aligned} \tag{10}$$

Solution is as follows:

$$u(x,t) = M + \int_0^t f(\tau)d\tau \tag{11}$$

The value of M in Table 1 has been given, but $f(t)$ is unknown, in this case (9), (10), (11) equations which can not be solved, must add additional conditions to solve. Through the pre buried thermocouple temperature sensor, temperature variation is obtained $x = 0$ within 19 days, that is $u(0,t),\ \ 0 \le t \le 19$ , the data in table 1. As $u(0,t)$ an additional condition substitution type (11) in the following:

$$\int_0^t f(\tau)d\tau = u(0,t) - M \tag{12}$$

Let $F = u(0,t) - M$ , Then equation (12) can express as follows:

$$\int_0^t f(\tau)d\tau = F \tag{13}$$

Type (13) for the first kind of integral operator form, the solving procedure is as follows:
1) Discrete integral of the first kind operator.

Because $\int_0^t f(\tau)d\tau = F(t) - F(0)$ , $t_k = kh, k = 0,1,2,...,n,$ then as follows:

$$\int_{t_{k-1}}^{t_{k+1}} f(\tau)d\tau = F(t_{k+1}) - F(t_{k-1}), k = 1,2,...,n$$

Using the Simpson formula of discrete type and get as follows:

$$f_{k-1} + 4f_k + f_{k+1} = \frac{3}{h}[F(t_{k+1}) - F(t_{k-1})], k = 1,2,...,n$$

Discrete (13) type, get the following form

$$\begin{pmatrix} 1 & 4 & 1 & & & & \\ & 1 & 4 & 1 & & & \\ & & & \cdots\cdots & & & \\ & & & 1 & 4 & 1 & \\ & & & & 1 & 4 & 1 \end{pmatrix}_{n\times(n+2)} \begin{pmatrix} f_0 \\ f_1 \\ \cdots \\ f_n \\ f_{n+1} \end{pmatrix} = \frac{3}{h} \begin{pmatrix} F_2 - F_0 \\ F_3 - F_1 \\ \cdots \\ F_n - F_{n-2} \\ F_{n+1} - F_{n-1} \end{pmatrix}$$

The equations can be written in the following form.

$$A_h f = F$$

Obviously the above equations for the sick, and as the dimension increases, pathological characteristics gradually increased, the application of discrete regularization method to solve.

2) The input coefficient matrix $A_h, F$ and the parameters $\delta, h, \alpha_0$ and control precision $\varepsilon, \delta = 0.02, \alpha_0 = \delta^2, \varepsilon = 10^{-3}$ ;

3) Set $k = 0$ , solving Euler equation $(A_h^T A_h + \alpha C) f^h = A_h^T F^h$ get $f_{\alpha_k}^h$ ;

4) Calculation $\Delta_\eta(\alpha_k)$ . If $|\Delta_\eta(\alpha_k)| < \varepsilon$ then run the step 8;

$$\Delta_\eta(\alpha_k) = \varphi(\alpha_k) - \delta^2 \qquad \varphi(\alpha_k) = \left\| A^h f_{\alpha_k}^h - F_\delta^h \right\|_{L_2^h}^2$$

5) Solving the equation $(A_h^T A_h + \alpha_k C)(f_{\alpha_k}^h)' = -CF_{\alpha_k}^h$ , obtained $(F_{\alpha_k}^h)$ ;

6) According $\Delta'_\eta(\alpha_k) = -2\left(\frac{df_{\alpha_k}^h}{d\alpha}\right)^T f_{\alpha_k}^h \alpha_k$ to the calculation $\Delta'_\eta(\alpha_k)$ , and press the $\alpha_{k+1} = \alpha_k - \frac{\Delta_\eta(\alpha_k)}{\Delta'_\eta(\alpha_k)}$ update $\alpha_k$ ;

7) Set $k = k + 1$, run step 3;

8) Set $f_{\alpha^*}^h = f_{\alpha_k}^h$ the output, end.

Using the above process inversion 4 ~ 6 lines of fire were shown in Figure 2-4.

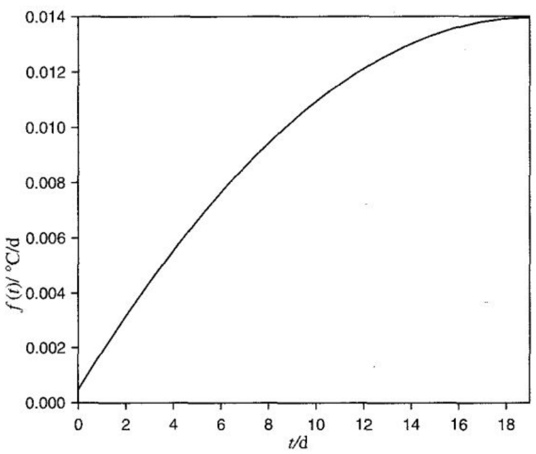


**Fig. 2 The map of $f(t)$ in the 4th line**

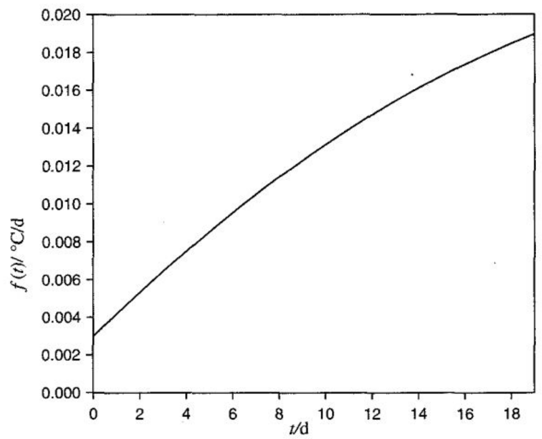


**Fig. 3 The map of $f(t)$ in the 5th line**

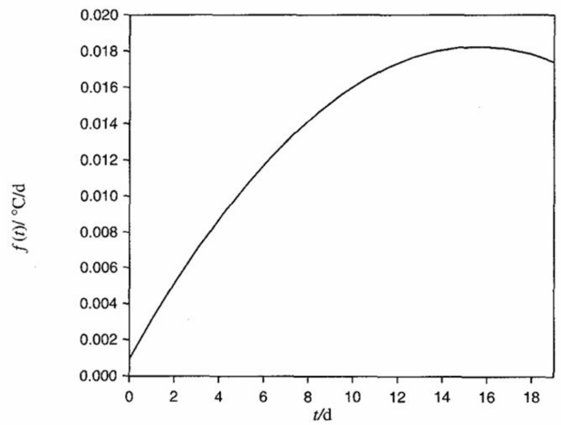


**Fig. 4 The map of $f(t)$ in the 6th line**

Figure 2-4 vividly described the 4, 5, 6 lines of source changes with time. Through the fire image observation inversion, it can be seen that the 4-6 lines of fire rate increased gradually with time, but less than. In general, the fire rate of change is not large. This is consistent with the actual situation. By comparing the 4-5, the inversion results, 6 lines can be drawn: in the initial conditions are smaller, sixth lines of temperature increase fastest, the first to reach the ignition point. This provides the basis for taking measures should be in the positions of the sixth lines near the focus for the cooling and fire prevention measures [4].

## CONCLUSION

Two dimensional temperature fields are simplified to a one-dimensional temperature field, using the discrete regularization method to mine hidden fire source inversion. The numerical simulations show that, discrete regularization method can effectively to mine hidden fire source inversion, which can effectively for fire prevention. But also should see, the method is based on the analytical solutions of the heat conduction equation is known, thus limiting the scope of use of the method.

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