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Research on Mathematical Model of Emergency Response of Coal Mine Gas Overrun

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ABSTRACT. *In order to effectively prevent coal mine gas overrun accidents and realize mine safety production, this paper establishes an emergency response mode for coal mine gas overrun based on the principle of feedback control. Secondly, on this basis, applying the theory of "system algebraic state equation" and using MATLAB as the technical means to obtain the mathematical expression of the response, the mathematical model of the emergency response of coal mine gas exceeding the limit was established. Thirdly, use Origin software to draw the transition response curve when the expression takes different parameters. The results show that the operation results of the established mathematical model of coal mine gas overrun emergency response are consistent with the actual response process conditions, verifying the mathematical model built The correctness of this method provides a new working idea for coal mine gas overrun control.*

KEYWORDS: *gas overrun, emergency response, mathematical model*

1. Introduction

In these years, the whole situation of safety production in coal enterprises is becoming optimistic in our country, but the incidence of gas accident in coal enterprises still never decreases. In accordance of the associated survey, gas accident has occured 563 times totally and caused 1729 deaths in our country from 2013 to 2019, which is showed in figure 1[1-2]. However, some gas accidents(especially gas explosion) are all caused by gas overrun. The basic situations of the several gas explosions caused by gas overrun have been listed in table 1. Therefore, putting an end to gas overrun plays a key role in effectively preventing gas acciedent. That is to

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say, the safety production in coal enterprises can be implemented ultimately only in preventing gas overrun and eliminating gas overrun accident[3-4].

At present, in the field of coal mine safety, the principle of feedback control is primarily applied in: in 2004, the feedforward control, the feedback control and the self-organizing control of accidents in coal mines were put forward based on cybernetics in the first time by Miao De jun[5] according to the model and hazard identification method of coal mine accident. In 2008, Wen wei and others[6] analysed the essence and mechanism of the incidence of coal mine accident on the basis of factors of coal mine accident and researched the feedforward control, the feedback control and the self-organizing control associated with the prevention technology of coal mine accident. At the same time, they investigated the methods of every prevention technology. In 2010, comparing and combining the two different methods of feedforward control and feedback control, Li Jun and others[7] established the logistic model of the dual predicting and early-warning monitor firstly. In 2011, Cui Xiu wei[8] defined the safety control system of gas disaster in coal mines and safety countermeasure as the research object and the controller respectively and established the feedback closed-loop system by combining the research object and the controller, which made the dynamic control of gas disaster come ture. In 2013, Sun Hai min[9] summarized the modes of safety management used in our coountry’s coal enterprises universally and considered that they are short of returning results after outputting the information of safety management, so the assumption of the safety management mode in coal mines based on the feedback control was put forward at the beginning. Despite the fact that the feedback control has been applied well in the safety management of coal mines, it is used in the emergency response of coal mine accidents seldom, especially in the emergency response of gas overrun. In the meanwhile, the feedback control is never applied in the deeply quantitative research being bound up with the crisis management of coal mines. Thus, in this article, the mathematical model of emergency response of coal mine gas overrun will be considered and established in accordance of the theory of feedback control and so on, which provides a new working thought for governing coal mine gas overrun.

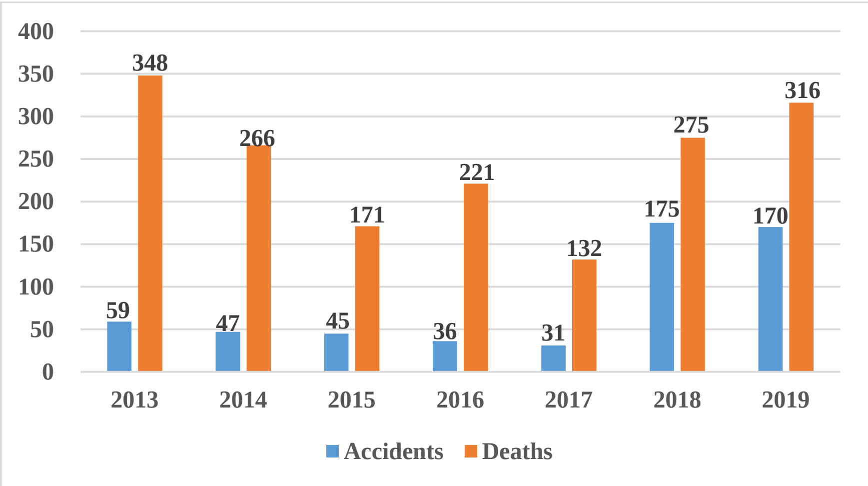

Figure. 1 The occurrence of coal mine gas accidents in my country from 2013 to 2019

Table 1 Basic overview of several coal mine gas explosion accidents caused by gas accumulation and over-limit in Guizhou Province

Year	Accident	Design production capacity of coal mine /10,000tons per year	Number of fatalities	Direct economic loss	Reasons of the accident
2013	Shi Ban po coal mine"4·12"larger gas explosion accident	30	7 persons killed, 2 persons injured	More 900 thousands yuan	Illegal cross-border mining; the cross-border mining area was not equipped with any security facilities and conditions such as safety monitoring systems; gas accumulation arised in the illegal mining area; the illegal shooting caused the gas explosion
2013	Da Shan coal mine"5·10"major accident of gas explosion	15	12 persons killed, 2 persons injured	1462.82 thousands yuan	No formal ventilation facilities; no any safety monitoring system; illegal cross-border mining caused gas accumulation; coal drills explosed and produced sparks to detonate the gas
2014	Run Feng coal mine"8·13"larger gas explosion accident	9	3persons killed, 4 persons injured	558.8 thousands yuan	No gas sensor was installed at the accident site to monitor the gas situation in the tunnel. After the ventilation was blocked, local gas accumulated and reached an explosive concentration. The miner's lamp line was damaged and short-circuited to generate electric sparks to detonate the gas.
2017	Xin Xin coal mine"8·3"larger gas explosion accident	21	5 persons killed, 3 persons injured	571.5 thousands yuan	Gas monitoring falsified and failed to effectively monitor the changes in gas where the accident occurred. When the gas accumulates and reaches the explosive concentration, the second detonation produces sparks to detonate the gas
2017	Kong Jia gou coal mine"12·13"larger gas explosion accident	9	6 persons killed, 20 persons injuered	1468 thousands yuan	The safety monitoring and monitoring system failed to operate normally. The monitors left their posts without authorization and used "one wind blow" to discharge high-concentration gas into the accident site, causing the gas to exceed the limit, and the mining face exploded and detonated the gas.

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2. Theoretical Foundation of Mathematical Model

2.1 The principle of feedback control

1) The basic principle of feedback control

Feedback control refers to the process that the output from a system effects(return) the same system through a link. That is to say, the amount of the input will be determined by detecting the system's situation or output. Feedback signal makes the input of setting value reduce, which is defined as negative feedback control[10-12] showed in figure 2. Feedback control consists of the decision making process, executive mechanism, controlled object, feedback loop and so on[13].

2) The basic parameter of feedback control

Controlled variable: the physical quantity that should be permanent and is marked with y in feedback control.

Disturbance: the external factor making controlled variable change and being marked with f.

Regulating quantity: when the deviation arises, there is a controlling means, changing a variable through the decision making process, of making the controlled variable become the expected value. The variable is described as regulating quantity and marked with u.

Setting value: it is the specified value of controlled variable and marked with r. If we hope that the controlled variable is permanent, r will be a constant and its value depends on the request of a production.

Deviation: the difference , between the specified value and the actual value, is marked with e.

Operation: the inventory or energy put into an object or exported from the object through governing mechanism so as to make controlled variable become a stable vable when it is disturbed.

Feedback quantity: the actual value of controlled variable returned in the feedback loop.

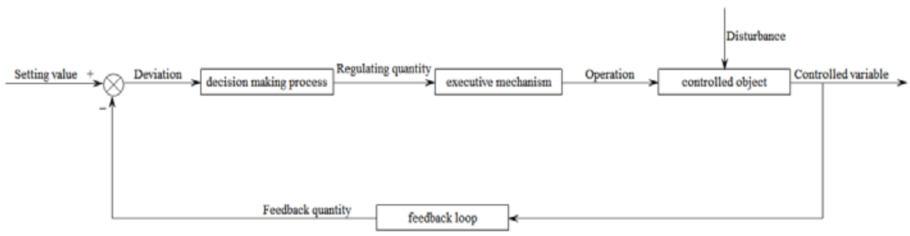

Figure. 2 Basic principle diagram of feedback control

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2.2 Transfer function of a system

The study of linear steady feedback control is maturest among all feedback controls and linear steady feedback control can be represented as a linear differential equation with constant coefficients which is as follows:

$$a_n \frac{d^n y}{dt^n} + a_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_1 \frac{dy}{dt} + a_0 y = b_m \frac{d^m x}{dt^m} + b_{m-1} \frac{d^{m-1} x}{dt^{m-1}} + \cdots + b_1 \frac{dx}{dt} + b_0 x \quad (1)$$

Transfer function of a system is the ratio of the Laplace transform of the output of the system to the Laplace transform of the input of the system under the condition of zero initial. Getting the Laplace transform of the formula (1), we are able to understand[14]:

$$\begin{aligned} & a_n s^n Y(s) + a_{n-1} s^{n-1} Y(s) + \cdots + a_1 s Y(s) + a_0 Y(s) \\ & = b_m s^m X(s) + b_{m-1} s^{m-1} X(s) + \cdots + b_1 s X(s) + b_0 X(s) \end{aligned} \quad (2)$$

So, the transfer function of the system is:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0} = \frac{B(s)}{A(s)} \quad (3)$$

2.3 The dynamic characteristics of typical links

The dynamic characteristics of typical links that are seen frequently are as follows[15]:

1) Proportion component(The output is proportional to the input, and this component can also be amplification section or inertialess link)

It can be described as an algebraic equation which is as follows:

$$y = Kx \quad (4)$$

In the equation: y —the output;

x —the input;

K —proportional coefficient.

The transfer function is

$$G(s) = \frac{Y(s)}{X(s)} = K \quad (5)$$

2)First-order process(The effect of the input can’t reflect completely at the output end because it has the inertia)

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It can be represented as a first order differential equation which is as follows:

$$T\frac{dy}{dt}+y=Kx \tag{6}$$

In the equation: K—proportional coefficient;

T—time constant, s.

The transfer function is

$$G(s)=\frac{Y(s)}{X(s)}=\frac{K}{Ts+1} \tag{7}$$

2.4 System algebra state equation

From the figure 3, we can understand that the dynamic process of a system can be divided into two parts: one equation which is used of describing the phenomenon that the change of the input can cause the change of the system's condition is called state equation and the other one which is used of describing the phenomenon that the changes of the condition and the input can cause the change of the output is called output equation.

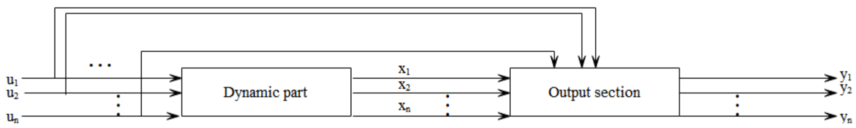

Figure. 3 shows the structure of the system

The state equation and the output equation constitute the system algebra state equation which can describe the state space of the system. The algebra state equation of a linear system is:

$$\begin{cases}\dot{x}=Ax+Bu\\ y=Cx+Du\end{cases},\quad t\geq t_0 \tag{8}$$

In the equation, the coefficient matrices A, B, C and D are n×n dimensions, n×r dimensions, m×n dimensions and m×r dimensions respectively. In other words, for the linear steady system, the coefficient matrices A, B, C and D are all constant matrices and the initial time t_0 is usually defined as 0 under the condition. At the same time, the output of the system can't be influenced directly by the input. That is to say, the matrix D is a zero matrix.

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3. Research on mathematical model of emergency response to coal mine gas overrun

The essence of the emergency response to coal mine gas overrun is the fact that the abnormal gas concentration in the mine is able to be returned and we take intervention measures to make the gas concentration normal when gas overrun arises, which prevents the gas overrun from causing the gas accident[16]. The study of the mathematical model in this article focuses on the fact that how to make response so immediate that prevent the gas accident from happening via containing the gas concentration when the gas overrun arises.

3.1 The establishment of the mathematical model of emergency response

Mathematical model of emergency response to coal mine gas overrun will be established according to the principle of feedback control, system algebra state equation and so on, the steps are as follows:

1)From the principle of feedback control, the gas concentration and the coal mine or one section of the coal mine are defined as the controlled variable and the controlled object respectively and the mode of emergency response to coal mine gas overrun showed in figure 4 will be constructed;

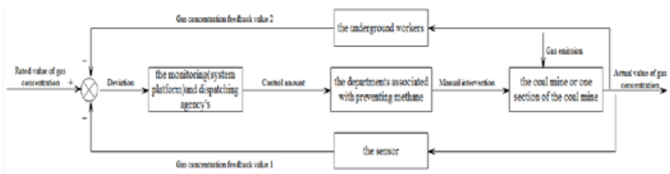

Figure. 4 Emergency response mode of coal mine gas exceeding limit

2) Based on the figure 4, the total structure block diagram will be built in accordance with the principle of feedback control and so on and the meanings of symbols in the diagram are reflected in the table 2;

Table 2 Structural block diagram symbols and meanings

Symbol	Meaning	Symbol	Meaning
U	Rated value of gas concentration	M_1	Gas emission situation
Y	Actual value of gas concentration	x_1	Control amount
G_1	the monitoring(system platform)and dispatching agency's	x_2	Manual intervention
G_2	the departments associated with preventing methane	x_3	Actual value of gas concentration
G_3	the coal mine or one section of the coal mine	x_4	Gas concentration feedback value 1
H_1	the underground workers	x_5	Gas concentration feedback value 2
H_2	the sensor	x_6	Gas emission
w_1	Gas emission factor		

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3)According to the arrow in the block diagram, outputs of all blocks in the block diagram are marked with x_1, x_2,…,x_6 and they are all state variables, which is showed in figure 5;

4)Decompose the total structure block diagram of the system and establish sub-structure block diagrams that are showed in figure 6 and figure 7;

5)Write the state equation for figure 6 according to the theory of system algebra state equation, it is:

$$\begin{cases} x = Ax + bU + fw_1 \\ Y = cx + DU + gw_1 \end{cases} \quad (9)$$

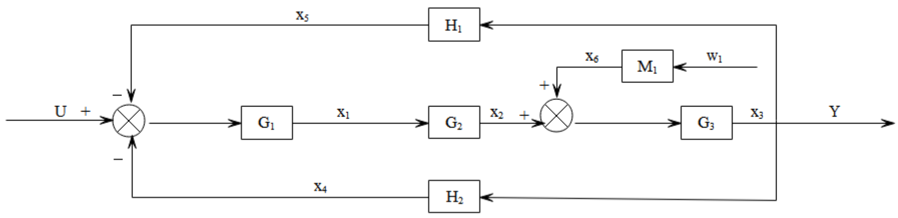

Figure. 5 Block diagram of the overall structure of the mathematical model of coal mine gas emergency response

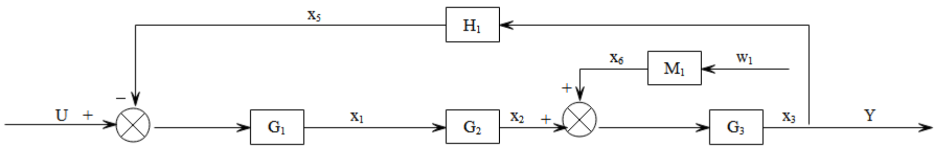

Figure. 6 The structure diagram of the feedback response mechanism of downhole operators

6)In accordance with figure 6, fill the elements of matrices A,b,f,c,D,g in the formula (9). That is to say, make the embodiment of the state equation of the structure block diagram of the system, which is as follows:

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$$\begin{cases} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_5 \\ x_6 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -G_1 & 0 \\ G_2 & 0 & 0 & 0 & 0 \\ 0 & G_3 & 0 & 0 & G_3 \\ 0 & 0 & H_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \bullet \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_5 \\ x_6 \end{pmatrix} + \begin{pmatrix} G_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \bullet U + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ M_1 \end{pmatrix} \bullet w_1 \\ Y = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \end{pmatrix} \bullet \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_5 \\ x_6 \end{pmatrix} + 0 \bullet U + 0 \bullet w_1 \end{cases} \quad (10)$$

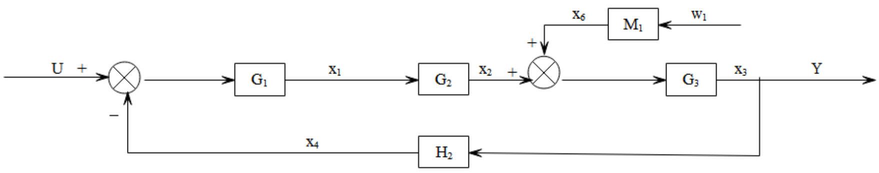

Figure. 7 The structure diagram of the sensor feedback response mechanism

7)From the formula(10), make use of MATLAB to programme and calculate according to the above derivation, which is as follows:

```
syms G1 G2 G3 H1 M1            % define symbol variables
A=[0,0,0,-G1,0;
G2,0,0,0,0;
    0,G3,0,0,G3;
    0,0,H1,0,0;
    0,0,0,0,0];
b=[G1;0;0;0;0];f=[0;0;0;0;M1 ];
c=[0,0,1,0,0];D=0;g=0;     % enter the elements of matrices A,b,f,c,D,g
R=c/(eye(size(A))-A);                        % calculate the middle variable R
Y2U=R*b+D;                                   % calculate the transfer function Y/U
Y2w1=R*f+g;                                  % calculate the transfer functionY/w1
disp(['the transfer function Y/U is']),pretty(Y2U)
disp(['the transfer function Y/w1 is']),pretty(Y2w1)       % show the result
```

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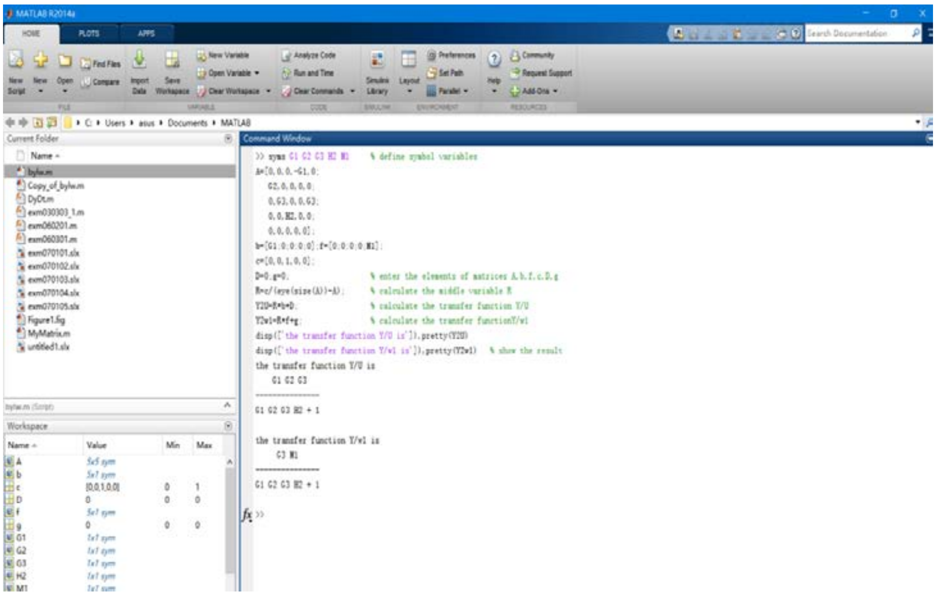
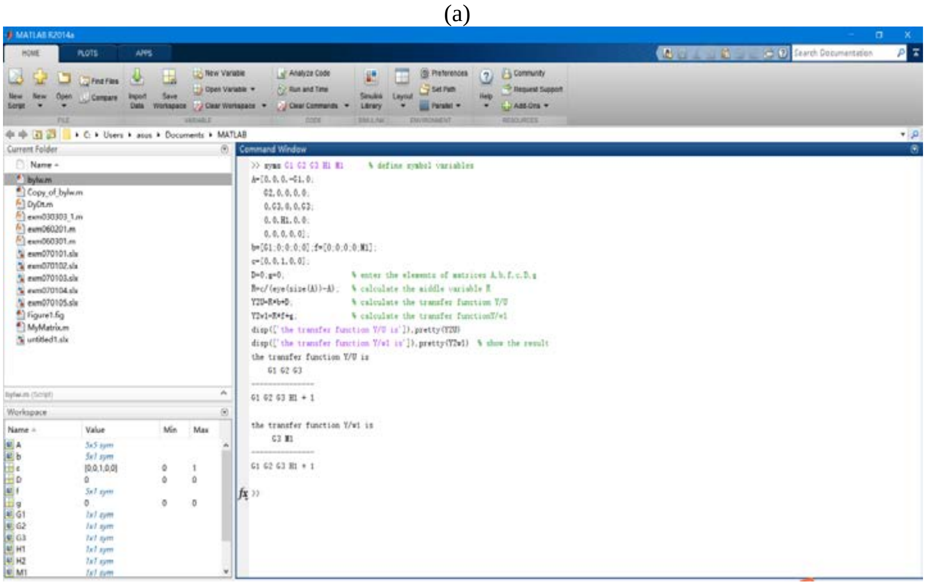


(a)



(b)

Figure. 8 MATLAB running results

The transfer function in the figure 6 can be calculated via MATLAB, which is as follows and showed in the figure 8(a):

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$$\begin{cases} \dfrac{Y}{U} = \dfrac{G_1 G_2 G_3}{1 + G_1 G_2 G_3 H_1} \\ \dfrac{Y}{w_1} = \dfrac{G_3 M_1}{1 + G_1 G_2 G_3 H_1} \end{cases} \quad (11)$$

So, the transfer function in the figure 7 can be calculated, which is as follows and showed in the figure 8(b):

$$\begin{cases} \dfrac{Y}{U} = \dfrac{G_1 G_2 G_3}{1 + G_1 G_2 G_3 H_2} \\ \dfrac{Y}{w_1} = \dfrac{G_3 M_1}{1 + G_1 G_2 G_3 H_2} \end{cases} \quad (12)$$

8)Transfer functions of all links in the figure 5 can be determined according to the mechanism of emergency response and the dynamic characteristics of the typical links:

$$\begin{cases} G_1(s) = K_c \\ G_2(s) = K_o \\ G_3(s) = \dfrac{K_a}{T_a s + 1} \\ M_1(s) = K_f \\ H_1(s) = \dfrac{K_1}{T_1 s + 1} \\ H_2(s) = \dfrac{K_2}{T_2 s + 1} \end{cases} \quad (13)$$

In the formula: K_c —the monitoring(system platform)and dispatching agency's decision coefficient which describes the agency's decision-making capacity;

K_o —the execution coefficient of the departments associated with preventing methane and the coefficient can describe the departments' execution capacity;

K_a —the structure coefficient of the coal mine or one section of the coal mine and the coefficient can describe the complexity of the coal mine or one section of the coal mine, %/%;

T_a —the time constant of the coal mine or one section of the coal mine and the time constant can reflect the adjustment capacity of the coal mine or one section of the coal mine, min;

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K_f —the emission coefficient of the methane which describes the degree of the gas emission;

K_1—the working capacity coefficient of underground workers, which decribes the workers' working capacity, %/%;

T_1—the time constant of the underground workers' feedback which describes the efficiency of the underground workers' feedback, min;

K_2 —the reliability coefficient of the sensor which reflects the sensor's reliability, %/%;

T_2 —the time constant of the sensor's transmission which describes the efficiency of the sensor's transmission, min.

From the formula (11), it can be got as follows:

$$\frac{Y(s)}{w_1(s)}=\frac{K_aK_f(T_1s+1)}{(T_as+1)(T_1s+1)+K_cK_oK_aK_1} \quad (14)$$

Define the formula "$K=K_cK_oK_aK_1$" and the formula (14) will become:

$$\frac{Y(s)}{w_1(s)}=\frac{K_aK_f(T_1s+1)}{(T_as+1)(T_1s+1)+K} \quad (15)$$

When define $w_1$as n(step signal), $w_1(s)$ is n to s. Suppose that K_f multiplied n is M, so:

$$Y(s)=\frac{K_aM}{1+K}\left[\frac{\frac{1+K}{T_aT_1}}{s(s^2+\frac{T_a+T_1}{T_aT_1}s+\frac{1+K}{T_aT_1})}+\frac{T_1\cdot\frac{1+K}{T_aT_1}}{s^2+\frac{T_a+T_1}{T_aT_1}s+\frac{1+K}{T_aT_1}}\right] \quad (16)$$

Define the two formulas "$\omega_n=\sqrt{\frac{1+K}{T_aT_1}},\qquad \xi=\frac{T_a+T_1}{2\sqrt{T_aT_1(1+K)}}$" and the above formula can be written to:

$$Y(s)=\frac{K_aM}{1+K}\left[\frac{\omega_n{}^2}{s(s^2+2\omega_n\xi s+\omega_n{}^2)}+\frac{T_1\cdot\omega_n{}^2}{s^2+2\omega_n\xi s+\omega_n{}^2}\right] \quad (17)$$

According to the principle of Laplace transform, the formula (17) will become:

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$$y(t)=\frac{K_aM}{1+K}\left[1-\frac{1}{\sqrt{1-\xi^2}}e^{-\xi\omega_n t}\cdot\sin(\omega_n\sqrt{1-\xi^2}\cdot t+\varphi)\right.\tag{18}$$
$$\left.+T_1\cdot\frac{\omega_n}{\sqrt{1-\xi^2}}e^{-\xi\omega_n t}\cdot\sin(\omega_n\sqrt{1-\xi^2}\cdot t)\right]$$

From the formula, the formula "$\varphi=\arctan\frac{\sqrt{1-\xi^2}}{\xi}$" can be got. When simplified, the above formula will become:

$$y(t)=\frac{K_aM}{1+K}\left[1-\frac{e^{-\xi\omega_n t}}{\sin\varphi}\cdot\sin(\omega_n\sqrt{1-\xi^2}\cdot t+\varphi)\right]\tag{19}$$

From the formula, the formula "$\varphi=\arctan\frac{\sqrt{1-\xi^2}}{\xi-T_1\omega_n}$" can be got; simultaneously, the corresponding expression in the figure 7 is:

$$y(t)=\frac{K_aM}{1+K'}\left[1-\frac{e^{-\xi'\omega_n' t}}{\sin\varphi'}\cdot\sin(\omega_n'\sqrt{1-\xi'^2}\cdot t+\varphi')\right]\tag{20}$$

From the formula, the formulas "$\varphi'=\arctan\frac{\sqrt{1-\xi'^2}}{\xi'-T_2\omega_n'}$" "$K'=K_cK_oK_aK_2$" "$M=K_f n$" "$\omega_n'=\sqrt{\frac{1+K'}{T_aT_2}}$" "$\xi'=\frac{T_a+T_2}{2\sqrt{T_aT_2(1+K')}}$" can be got.

9)Take the parameters in the expression (19) and expression (20) values and draw the response curves of the two expressions via Origin software. These curves and the values of the parameters are showed in the figure 9 and in the table 3 respectively.

Table 3 Values of response curve parameters

Curve	K_1	T_1	K_2	T_2	K_c	K_o	K_a	K	K'	T_a	K_f	n(%)
a	0.6	2.5	——	——	4.5	1.8	4.0	19.44	——	5.0	3.19	1.5
b	0.9	2.5	——	——	4.5	1.8	4.0	29.16	——	5.0	3.19	1.5
c	0.6	4.5	——	——	4.5	1.8	4.0	19.44	——	5.0	3.19	1.5
d	——	——	0.7	1.5	4.5	1.8	4.0	——	22.68	5.0	3.19	1.5
e	——	——	1.2	1.5	4.5	1.8	4.0	——	38.88	5.0	3.19	1.5
f	——	——	0.7	3.5	4.5	1.8	4.0	——	22.68	5.0	3.19	1.5
g	0.6	2.5	——	——	5.0	1.8	4.0	21.60	——	5.0	3.19	1.5
h	0.6	2.5	——	——	4.5	2.5	4.0	27.00	——	5.0	3.19	1.5
i	0.6	2.5	——	——	4.5	1.8	4.0	19.44	——	5.0	3.50	1.5

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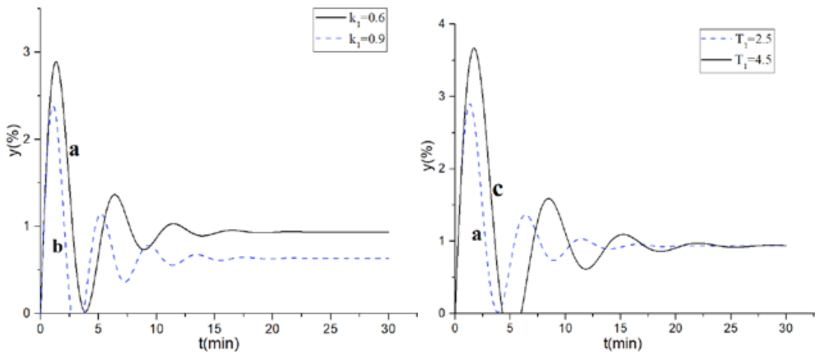
3.2 The analysis and verification of the mathematical model of emergency response

Under the condition that the structure coefficient K_a and the time constant T_a of the coal mine or one section of the coal mine are permanent, for the same disturbance n, when the working capacity coefficient K_1 of underground workers is larger or the time constant T_1 of the underground workers' feedback is smaller or when the reliability coefficient K_2 of the sensor is larger and the time constant T_2 of the sensor's transmission is smaller or when the monitoring(system platform)and dispatching agency's decision coefficient K_c and the execution coefficient K_0 of the departments associated with preventing methane are larger, when the emission coefficient K_f of the methane is smaller, the maxium of the methane concentration will decrease and it takes the methane concentration little time to attenuate and oscillate. The above situation has been showed in the figure 9.

In the process of the response to gas overrun and under the condition that the internal conditions of the coal mine or one section of the coal mine are steady, if underground workers or sensors are able to return the abnormal signal of the methane concentration to the monitoring and dispatching platform and the monitoring and dispatching platform can make decisions in a minute according to the abnormal situaiton and the departments associated with preventing methane can take intervension in accordance with the decisions, the development of gas overrun will be restrained effectively and prevent the tragedy that the gas accident happens because the gas overrun expands further. In addition, for the same and holistic capability level, the gas overrun will be contained effectively and easily when the emission of the mine methane isn't serious.

To sum up, the running result of the mathematical model of emergency response to coal mine gas overrun established in this article matches with the practical process of the response, which has verificated the correctness of the mathematical model established in this article. They are reflected in the figure 10.



(a)Different K_1 (b)Different T_1

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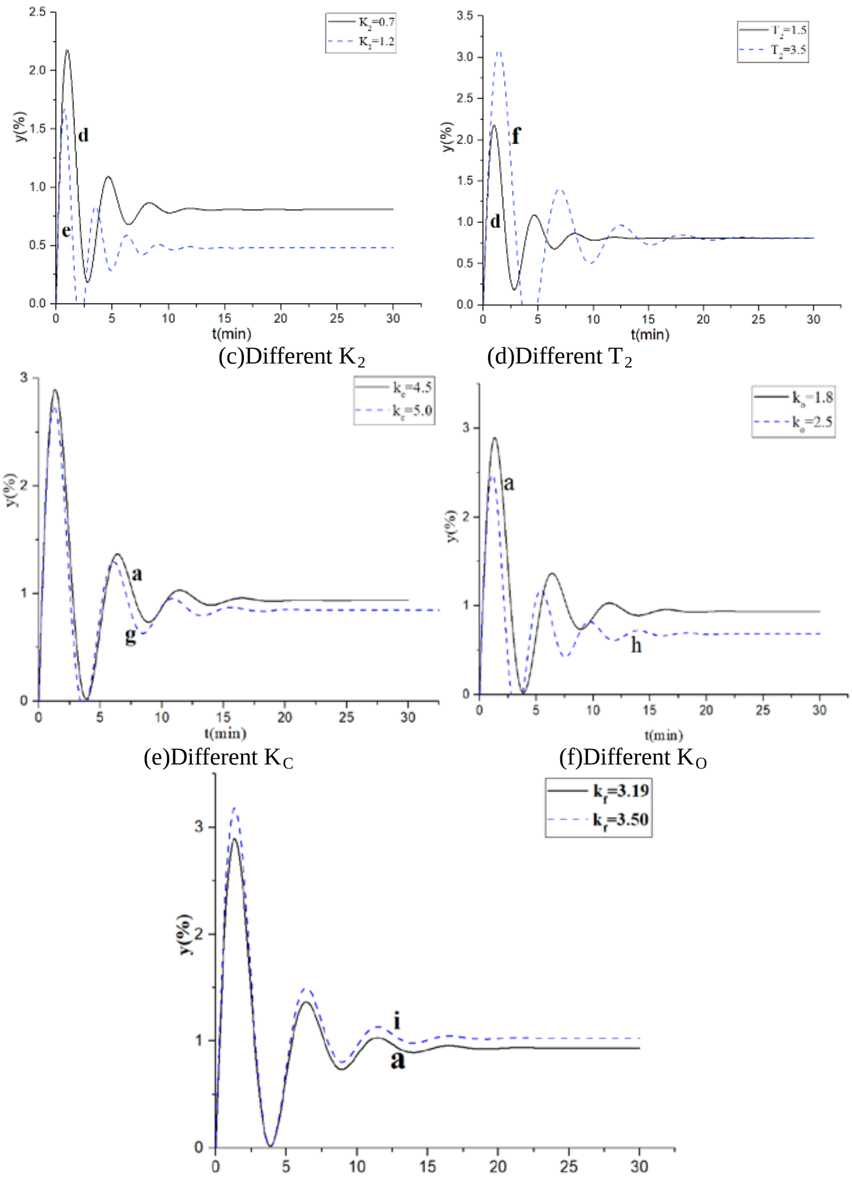

(c)Different K_2 (d)Different T_2

(e)Different K_C (f)Different K_O

(g)Different K_f

Figure. 9 Response curve

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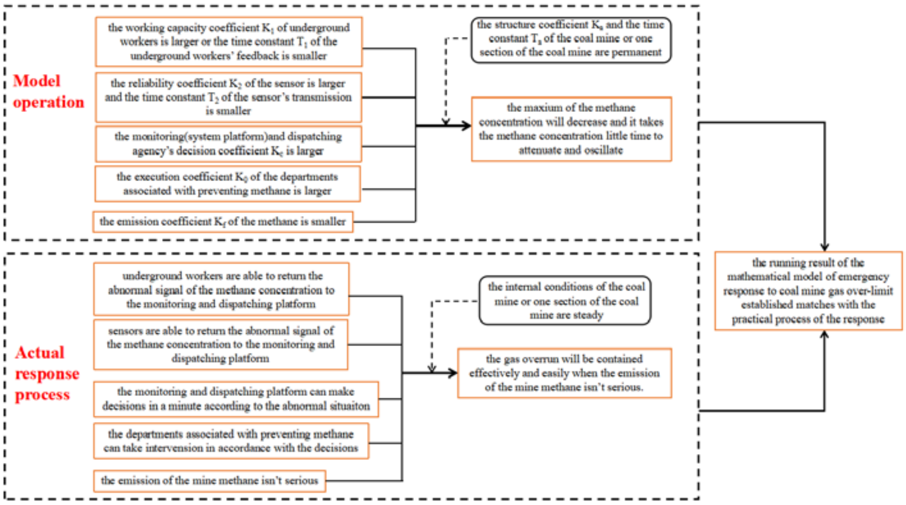

Figure. 10 Comparison of model operation and actual response process

4. Conclusion

1) From the principle of feedback control, the gas concentration and the coal mine or one section of the coal mine are defined as the controlled variable and the controlled object respectively and the model of emergency response to coal mine gas overrun will be constructed and based on the model, the structure block diagram of the mathematical mode of emergency response to coal mine gas overrun is established.

2) On the basis of the structure block diagram of the mathematical model of emergency response, the transfer functions of the structure block diagram of the mathematical model of emergency response to coal mine gas overrun, all links and the total transfer function will be determined. At the same time, the mathematical expression of the response has been calculated and the mathematical model of emergency response to coal mine gas overrun has been established.

3) Make use of Origin software to draw all response curves calculated by all different parameters such as time constant and draw a conclusion that: under the condition that the structure coefficient K_a and the time constant T_a of the coal mine or one section of the coal mine are permanent, that is to say, under the condition that the internal conditions of the coal mine or one section of the coal mine are steady, for the same disturbance n, when the working capacity coefficient K_1 of underground workers is larger or the time constant T_1 of the underground workers' feedback is smaller or when the reliability coefficient K_2 of the sensor is larger and the time constant T_2 of the sensor's transmission is smaller or when the monitoring(system platform)and dispatching agency's decision coefficient K_c and the execution coefficient K_0 of the departments associated with preventing methane

are larger, when the emission coefficient K_f of the methane is smaller, the maxium of the methane concentration will decrease and it takes the methane concentration little time to attenuate and oscillate.

4) The running result of the mathematical model of emergency response to coal mine gas overrun established in this article matches with the practical process of the response, which has verificated the correctness of the mathematical model established in this article and provide a new working thought for governing the coal gas overrun.

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