Research on Monitoring and Regularity of Coal Mine Methane Extraction State

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Abstract. The existing gas drainage monitoring system only can measure the gas concentration of the drainage, can't dynamically predict the residual gas and the drainage cycle of the coal seam according to the drainage parameters. The mining conditions of deep coal seams have become complicated by the increasing depth of mining. The measurement of the extraction status becomes more and more difficult. It is of great practical significance to effectively predict the drainage time and the gas content of coal seam. In order to increase the gas drainage concentration of coal seam under the coal mine, combined with the actual situation at the coal mine site, a gas drainage pipeline control system was designed and developed. It is mainly composed of gas sensors, microcontroller, miniature electric valves, power conversion circuits, and wireless communication modules. In view of the non-linear, multi-coupling and hysteresis characteristics of gas flow, a fuzzy control algorithm is adopted by the controller. By measuring the gas concentration and pressure of the field extraction pipeline, the microcontroller STM8 working as the control core controls opening of the pipeline valve according to the fuzzy control law. Finally the purpose of increasing the concentration of the extracted gas is achieved. Both the fuzzy control algorithm and the system circuit is designed in detail. The system has the characteristics of long-distance wireless communication, compact structure and low power consumption. It can increase the concentration of gas extraction, which is of great significance for the gas prevention and management and coal mine gas extraction.

Keywords: Gas extraction · Gas concentration · Wireless communication · Residual gas · Drainage time

1 Introduction

Coal mine gas (Coal Mine Methane, CMM, also known as gas) extraction technology which is the main technical measure to prevent gas disaster accidents has also been continuously improved and developed with the development of coal industry technology, but the overall level is still low [1]. The informatization, intelligence and standardized and refined means of gas prevention and control technology equipment have just

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started. The collection, transmission, and intelligent identification models of information closely related to the hidden dangers of gas accidents are not complete. The keys of coal mine gas extraction parameter monitoring, engineering construction, management, effect measurement and inspection have not yet been digitized and informatized. A lot of data is still in the stage of full manual determination [2].

According to the investigation on the coal mining and discussion with on-site technical staff, The reasons for low coal gas drainage rate and the existing problems of gas drainage concentration in coal seam drilling are as follows.

Single-hole metering devices is not equipped in some coal mine pre-drainage project, so the extraction effect cannot be investigated in time [3]. The gas measuring holes and control valves is supplied for main pipeline of each roadway but not for extraction branch, so the gas in branch pipeline is out of control and the leakage of branch will affect the entire extraction system.

Sometimes the extraction system has to be shut down in order to ensure the gas concentration throughout the area. In some coal mine gas drainage systems, a regulating valve and gas measuring hole works for two boreholes and valves is supplied for the sub-pipelines. In some coal mine gas extraction systems 10 drainage drilling are connected in parallel to a sub-pipelines. The drainage drilling is provided with regulating valve and gas measuring hole and the valve is stalled for sub-pipelines so each pipeline is under control. But the operation of valve is basically manual with wrench. An air leak in one borehole is sometimes handled by shutting off the whole system which is wasteful and inefficient. The greater the density of the arranged single-hole metering device, the more complete and the higher the reference value the data obtained. The more monitoring stations are arranged, the higher the mine construction cost.

There is no effective theoretical guidance but experience for the gas concentration of drainage pipeline. So the drainage control effect is poor, and there are a lot of drill hole closing which not only causes lot waste of resources but also leaves security risks for mine. The extraction concentration of different boreholes in the same area varies greatly in some mine. There were no online monitoring of pressure, flow and concentration for branch pipeline and even there were not a flowmeter or detection hole for main pipeline of pump station. The same situation happens in most gas drainage systems and it is common to be unable to detect gas drainage volume and analyze source of gas. When the concentration of most branch pipeline does not reach the usable concentration how to take advantage of gas is big problem.

Domestic and foreign researches on gas extraction systems have mostly focused on optimization of extraction technology and systems optimization. In recent years, there have also been applications of artificial intelligence control technology for gas extraction pipelines especially branch pipelines.

Zuo Jianghong [4] and Cai Feng [5] analyzed the underground gas drainage method from the aspects of adjusting negative pressure and sealing process, Jiang Zhigang [6] found that the optimal negative pressure for drilling varies with the coal seam conditions, the extraction period, and the sealing conditions. By adjusting the negative pressure, the optimal gas concentration can be obtained. Wang Zhenfeng [7] proposed that a multi-stage negative pressure adjustment method can be used during the extraction process to ensure that the gas extraction concentration is in a safe range for a long time. The disadvantage of that system is that the branch valve is still operated by manual operation. Jiang Yuanyuan [8] introduced an intelligent system which worked by AT89C52 single-chip microcomputer as the control core and fuzzy control as algorithms to control of the gas extraction process. Kaifeng Huang [9] studied a kind of intelligent control system for coal mine gas mobile extraction system. In order to meet the need of on-line control, the system uses PLC instead of single-chip microcomputer as the main controller. Ansai [10] introduced the KJ456 adaptive gas drainage pipeline valve automatic control system which automatically controls the opening of the pipeline valve through an adaptive control strategy to achieve the maximum gas drainage concentration or pure flow. Zhou Fubao [11] designed a gas intelligent extraction system, which uses the Arduino controller to control the speed of the gas extraction pump to improve the extraction efficiency ratio and extraction pure volume. This system is relatively complicated, which is not conducive to the installation of multiple pipelines on site. Wu Yuliang [12] studied the coal mine gas drainage system based on wireless sensor network, and applied conventional control and fuzzy control to the gas drainage system. Huang Ruifeng [13] shows that the extraction concentration can be kept in a safe and available range for a long time by means of multi-level and multiple regulation.

In short, due to the complexity of gas flow law, there are the following problems in coal seam gas drainage: accurate mathematical model can not be established, conventional control method is difficult to use, gas multi parameter measurement is needs for pipeline control, field construction of traditional gas monitoring equipment adopts wired communication is complex, and the occurrence characteristics and laws of residual gas need to be further studied.

To solve the above problems, it is necessary to design a gas extraction system to achieve accurate control of pipelines. Work of the system for improving gas drainage is to control the pumping pipeline through data acquisition and control algorithm efficiency and to estimate the residual gas parameters according to the measured data. Combined with control technology and wireless sensor network and model estimation for gas drainage, the monitoring system of gas drainage branch is designed. Data parameters including gas concentration are collected by sensors, the valve operation of pumping branch can be automatically regulated. The extraction period are estimated.

2 Design of Monitoring System for Coal Seam Gas Drainage Branch Pipe

2.1 Prototype of System Model Selection

The gas drainage cycle estimation and gas concentration control of gas pre drainage in Xuyong coal mine are studied as the object. Xuyong coal mine has the following characteristics. The relative gas emission of the mine is 20.1 m^3/t, and the absolute gas emission 34.29 m^3/min, C20 main seam is coal and gas outburst whose gas content is high and permeability is poor. C20 is chosen as the first coal seam and the protective layer at the same time. The technology of cutting through coal seam strike and intercepting longhole drilling is adopted. The drilling is type of ZDY-3200 m, with 73 mm drill pipe and 120 mm hole diameter. 50 mm PVC pipe with length of 12 m and sealing length of 8 m are reserved in the hole.

2.2 System Design

The structure diagram of coal seam gas drainage system is shown in Fig. 1. In order to achieve informatization of coal mine gas drainage, gas concentration and pressure, flow, temperature and other parameters of pipe network should be collected in time to gas drainage monitoring system. The system consists of a central node and several sensor acquisition nodes. Each node includes gas flow, concentration, negative pressure and other detection devices. Each gas drainage branch pipe is installed with a sensor acquisition node. Only one central node is needed for a gas drainage face not more than 500 m in length. The monitoring for drainage branch pipe is achieved by wireless sensor technology. Fuzzy control [14] is introduced into the control method. Each branch pipeline is equipped with a controller which collects data of gas concentration, flow rate and pressure periodically and operates valve for the negative pressure of pipe to gas concentration.

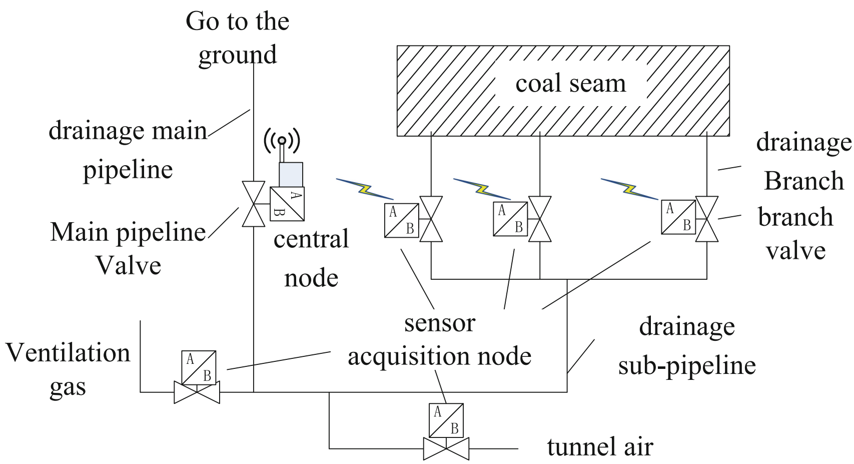

Fig. 1. Schematic diagram of coal seam gas drainage system

The function of sensor acquisition node is to collect gas drainage pipeline parameters, and transmit the data to the central node by wireless way. It is mainly composed of microcontroller, concentration sensor, flow sensor, pressure sensor, temperature sensor, micro electric valve, wireless communication circuit, etc.

Due to characteristics of the randomness, high nonlinearity and strong coupling between variables, it is unrealistic to establish an accurate mathematical model of the pumping system. It is difficult to achieve satisfactory control accuracy by traditional control algorithm. Therefore, the fuzzy control strategy is adopted for pipeline concentration control.

The node based on wireless sensor network can be combined with the inherent monitoring system. The node can be arranged according to the measuring position. The way of wireless technology networking and data transmission is fit for the complex and turbulent environment of coal mine. can avoid the influence of wired equipment wiring and pipeline movement, and facilitate the installation of equipment for central node and sensor acquisition node with the change of coal mining position. The adverse factors caused by wired equipment wiring and device movement with pipeline is avoided. It is convenient to install the node equipment as pipeline moves.

The sensor acquisition node is installed at the monitoring position of the drainage pipeline, and the gas concentration, flow rate, pressure and temperature are collected and converted by node. The intelligent control of gas concentration in the pipeline is coded by fuzzy control. The fuzzy control algorithm is designed according to staff experience so that the gas concentration is within the standard production range and the intelligent auto control of gas concentration is achieved. The acquisition node receives the command from the central node and sends the collected pipeline gas information back to the central node through wireless communication.

The central node transmits the data to the remote monitoring substation by bus communication to realize the monitoring of gas drainage pipeline parameters. The central node relays the command to the acquisition node through wireless communication, and the acquisition node transmits the collected information to the central node in order. The central node will analyze the information received, fit the change data of gas flow, predict the content and distribution of residual gas, and calculate the drainage cycle for engineering reference. The central node is mainly composed of microcontroller, wireless communication circuit, power conversion circuit and display.

When the level of gas in the main pipe is low, the main drainage pipe would be closed and the ventilation gas and roadway air valve is opened.

3 Design of Fuzzy Controller for Gas Concentration

The sensor acquisition node obtains the gas concentration of the branch pipe, and calculates the reasonable control signal through the fuzzy rule judgment. The signal is intended to opening of the drainage branch valve so as to adjust the gas drainage flow and to ensure the minimum gas concentration of the branch pipe.

The fuzzy controller is a kind of double input and single output controller. The deviation of gas concentration E and the change rate of gas concentration deviation E_c are selected as the input of fuzzy controller so called two-dimensional fuzzy controller. The regulating value U of micro electric valve is the output. Two inputs can reflect the dynamic characteristics of the process, and the control effect is much better than one-dimensional controller. The E_c is chosen to predict the trend of controlled variables which is equivalent to the derivative of PID control which is set as input in general large inertia system, such as boiler temperature control system.

The gas concentration value E_k in the branch pipe is the controlled quantity of system, E_0 is the minimum value, and E is the concentration deviation, $E = E_k - E_0$, where k for current time. $E_c = E_{k-1} - E_k$ is the change rate of concentration deviation, $k - 1$ for the previous moment. The principle is sectional multilevel negative pressure control method. Specifically, it is 4-section and 3-level. In the early stage of pumping, there is a reasonable negative pressure P_1kPa. As time goes on, the reasonable negative pressure will gradually decrease. The reasonable value of negative pressure is P_nkPa to later stage. That value is determined by on-site technicians staff. If the extraction concentration is too low, even less than 10%, the valve will be closed directly.

The pseudo code of concentration fuzzy control algorithm is as follows.

```
count_low=0
Do While time_delay=0
readSensordata()
LoraCommunication()
time_delay←5 //timer delay
if E_k < E_0 AND count_low=0
then P_1←P_1-15 count_low←count_low+1 time_delay←20
if E_k < E_0 AND count_low=1
then P_1←P_1-10 count_low←count_low+1 time_delay←15
if E_k < E_0 AND count_low=2
then P_1←P_1-5 count_low←count_low+1 time_delay←10
if E_k < E_0 AND count_low=3
then shut_vavle()
if E_c > E_cmax then alarm()
else close_alarm()
valve_adjust( P_1)
EndWhile
```

The drainage concentration of drilling branch can be expressed as follows (3 * 10 for example)

$$P_{3\times 10} = \begin{bmatrix} \rho_{1,1} & \rho_{1,2} & \cdots & \rho_{1,10} \\ \rho_{2,1} & \rho_{2,2} & \cdots & \rho_{2,10} \\ \rho_{3,1} & \rho_{m,n} & \cdots & \rho_{3,10} \end{bmatrix} \quad (1)$$

$P_{3\times 10}$ is the extraction volume concentration matrix, $\rho_{m,n}$ is the row of m and column of n extraction volume concentration.

The flow can be expressed as

$$F_{3\times 10} = \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,10} \\ f_{2,1} & f_{2,2} & \cdots & f_{2,10} \\ f_{3,1} & f_{m,n} & \cdots & f_{3,10} \end{bmatrix} \quad (2)$$

$F_{3\times 10}$ is the pumping flow matrix, and $f_{m,n}$ is the row of m and column of n drainage flow.

The pure quantity of gas drainage is the evaluation basis to investigate whether the gas drainage and drainage pipe network are efficient. The larger the pure flow is, the more gas content in the target area can be reduced as much as possible. Therefore, the gas drainage volume is the most important evaluation standard for the drainage effect of drainage pipe network. Based on the measured gas flow f and gas drainage concentration

ρ, the pure gas drainage flow PF can be expressed as $PF = \rho \times f$. The pure flow of gas drainage system is

$$PF_{3\times 10} = \begin{bmatrix} \rho_{1,1} \times f_{1,1} & \rho_{1,2} \times f_{1,2} & \cdots & \rho_{1,10} \times f_{1,10} \\ \rho_{2,1} \times f_{2,1} & \rho_{2,2} \times f_{2,2} & \cdots & \rho_{2,10} \times f_{2,10} \\ \rho_{3,1} \times f_{3,1} & \rho_{m,n} \times f_{m,n} & \cdots & \rho_{3,10} \times f_{3,10} \end{bmatrix} \tag{3}$$

where: $PF_{3\times 10}$ is the pure flow matrix of gas drainage. for example, the branch pipe in the first row and the first column is $PF_{1,1} = \rho_{11} \times f_{1,1}$. With the matrix form storage mode it is convenient for the central node to carry out three-dimensional portrait of the whole coal seam gas content, gas concentration and change trend.

4 Estimation of Gas Pre Drainage Time

It shows that the quantity of gas pre drainage every day tended to retrogress, which indicates that pre drainage time can not be extended indefinitely, and there should be a reasonable time [15]. Reasonable time is not a constant but a variable affected by many factors. Therefore, reasonable pre drainage time is different for the same coal seam, while is same for different coal seam. At present, the conventional method to predict the reasonable pre drainage time is mainly through drilling in the underground to determine the initial gas drainage amount and attenuation coefficient of the gas drainage volume, which are determined as important parameters. The precondition of this method is that the pumping quantity is exponential attenuation.

Another attenuation characteristics different from exponential attenuation is exhibited in different coal mine drainage data. Therefore, combined with the actual data characteristics, we presented a new method to determine the reasonable pre drainage time of coal seam gas.

The electromagnetic environment of coal mine is complex so sensor will be disturbed or fault, its data will be missing or abnormal. Kalman filter is taken at the central point to refine the gas flow and concentration data of the main pipe.

The process of coal seam gas drainage, can be approximately equivalent to that of water tank drainage. The coal seam is equivalent to water tank, and gas to water in a tank, all branch pipes to a pump, the residual gas content to the water volume, the drainage flow of water pump to the flow of gas drainage. The relationship between water pump drainage flow and time is very close to that of gas drainage flow and time as shows in Fig. 2.

If it is the characteristic of curve I, the initial flow rate is small, and gradually increases to the maximum value with the extension of time, and then decays. With the continuous increase of drainage time, the gas flow in the branch pipeline decreases. The rising speed is different in many mine, which may be a characteristic of low permeability outburst coal seam [16]. The measured curves in references [17] and [18] also show the characteristics of step response of underdamped second-order systems. If it is the characteristic of curve II, the decreasing rate of gas flow with time decreases continuously, and the curve shows a hyperbolic trend,

If the flow curve is close to curve I, it can be expressed by power function formula. If curve II then the step response formula of the second-order system. If the dotted line

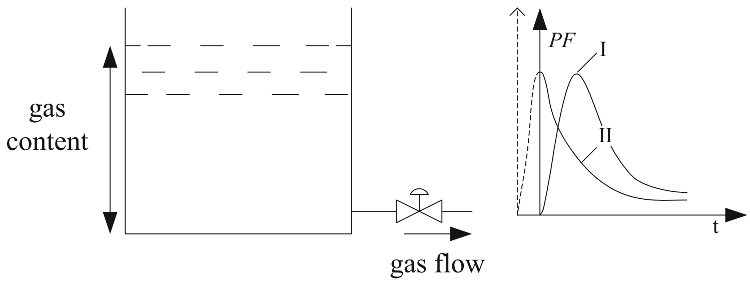

Fig. 2. Schematic diagram of the water tank pump drainage process

as shown in the Fig. 2 is added to curve I, a step response curve of the second-order system can still be obtained by translating the coordinate axis. Therefore, the model of coal seam gas drainage can be represented by a second-order system. The relationship between pumping flow and time can be approximately expressed by the step response curve of the second-order system.

The mathematical model of the second order system in Laplace transform is

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{4}$$

The model parameters ζ and ω_n are related to the gas flow of coal seam, namely both of them have a certain functional relationship with coal seam gas content. The input is step signal of $R(s) = R_0/s$, R_0 the signal amplitude. The step response expression of the second-order underdamped system is

$$c(t) = L^{-1}[R(s)G(s)] = 1 - e^{-\zeta\omega_n t}\sin(\omega_d t + \beta)/(\sqrt{1-\zeta^2}) \tag{5}$$

where L^{-1} for inverse Laplace transform.

The overshoot is

$$\sigma\% == e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \times 100\% \tag{6}$$

peak time is

$$t_p = \pi/\omega_d = \pi/(\omega_n\sqrt{1-\xi^2}) \tag{7}$$

The overshoot $\sigma\%$ is obtained by maximum value of flow $PF_{m\times n}$ which is easy to get, and the coefficient ξ can be obtained by reverse calculation. The coefficient ω_n can be calculated according to the corresponding peak time t_p. When the flow $PF_{m\times n}$ decreases to $\triangle$, the settle time can be obtained according to the step response curve. That settle time is the estimated drainage time. For example, when the steady state value is 1, the steady-state error$\triangle = 0.05$, $t_s = 3/\xi\omega_n$, the unit is day. The estimated of drainage time is not fixed, but is obtained according to the calculation dynamic of maximum gas value and steady state value. It is easy to get the maximum value through the data, while the steady state value is get under condition of the variation of gas flow $PF_{m\times n}$

within a certain range. Only when the residual gas content and drainage rate meet the requirements can the estimated of drainage time be matter.

The concrete steps to determine the reasonable pre drainage time of coal seam gas are as follows:

1) Kalman filter to the data.
2) calculate the maximum gas flow value and corresponding peak time.
3) calculate the initial gas content of coal seam.
4) calculate the residual gas content and extraction rate.
5) according to the steady state flow value, calculate the drainage time.

The average gas data acquisition interval is 1 time/5 min. There are 25920 data in three months. The first 50 days are the initial training data, the next 20 days an average sliding window period, 10 days training, another 10 days forecast and adjustment.

Considering of the geological conditions and human factors, the actual reasonable pre drainage time should be slightly larger than the theoretical calculation results.

5 Calculation of Residual Gas Content

In order to obtain the residual gas content after a period of drainage, the original coal seam gas content is required first, and the drainage amount of roadway is also considered.

$$Q = Q_T + Q_c + Q_v \tag{8}$$

where Q for original gas content of coal, m^3/t, Q_T for total amount of gas drainage per ton of coal, m^3/t. Q_c for residual gas content of coal, m^3/t. Q_v ventilation air gas, m^3/t.

The residual gas content after gas drainage is calculated according to the following formula.

$$Q_c = Q - \frac{pf_t + pf_v}{kG} \tag{9}$$

where pf_t for the amount of gas drainage, $pf_t = \rho_{main} \cdot f_{main} \cdot D_{main}$, pf_v for the amount of ventilation gas $pf_v = \rho_V \cdot f_V \cdot D_V$, v for ventilation, k for test the influence coefficient of unit gas pre drainage, k = 1.2, G for the test unit to participate in the calculation of coal reserves, t, $G = L_1 L_2 m_0 \gamma$, L1 is the length of pre pumping drilling of inspection unit, m; L2 for the width of inspection unit, m; m0 for the average thickness of coal seam in the test unit, m; γ for the bulk density (pseudo density) of coal, t/m^3, ρ for the average gas concentration and the amount of gas discharged by air, f for the air volume, m^3/min, D for the running time, d.

The gas content at different levels of C19 is calculated by indirect method.

6 Conclusion and Prospect

With the increase of mining depth, the coal seam gas drainage technology will play a more important role in coal mine gas control. Combined the theoretical research of gas flow with the practical engineering application, this paper points out some problems existing in the gas drainage of coal seam, analyzes and summarizes the existing problems. The main conclusions are as follows:

A kind of monitoring system based on wireless communication for coal seam gas drainage pipeline is designed. Through sensors, microcontrollers, micro electric valves and wireless communication modules, the gas concentration in the branch pipe is under the control which is beneficial to ensure the concentration level of gas drainage.

In this paper, the fuzzy control is applied to the monitoring system of the gas drainage branch pipe, and the sectional multilevel method is presented which improves the automation level of the gas drainage system.

In this paper, the coal seam drainage model is regarded as a second-order system. By analyzing the characteristics of the gas drainage data curve, it is concluded that the second-order system step response curve is a good choice to fit the data, and a new method for predicting the drainage time is proposed.

Gas drainage involves interdisciplinary fields, and the research to be solved in the future includes the following aspects: (1) to predict model of coal seam gas drainage based on deep learning, which provides theoretical basis for intelligent drainage and prediction of residual gas in coal seam. (2) to develop advanced sensing technology for key parameters of pumping branch pipe and main pipe, to develop intelligent pumping equipment based on industrial IOT.

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References

1. Zhu, Z., Yin, Z.: Present situation and prospect of exploitation and utilization of coalbed methane (coalbed gas) in the Sichuan province. China Min. Mag. **10**, 89–91 (2007)
2. Sun, D.: Promote informatization and intelligence of the whole process of gas prevention. China Coal News **5**(09), 3 (2020)
3. Wu, K., Shi, S.: Discussion on problems and countermeasures of gas drainage in hunan coal mine. Min. Eng. Res. **33**(03), 31–34 (2018)
4. Jianghong, Z.: Deep-hole pre-splitting blasting technology for high gassy deep complex geology area and low permeability coal seam. Saf. Coal Mines **44**(10), 69–71 (2013)
5. Cai, F., Liu, Z., Zhang, C., et al.: Numerical simulation of improving permeability by deep-hole presplitting explosion in loose-soft and low permeability coal seam. J. China Coal Soc. **32**(5), 499–503 (2007)
6. Jiang, Z., Tao, Y., Wang, F.: Research and application on automatic adjusting control system of concentration of gas extraction. Coal Technol. **10**, 34–36 (2014)
7. Wang, Z.: Study on gas extraction joint tube system and method of concentration control. Henan Polytechnic University (2009)
8. Jiang, Y.: Intelligent control and optimization of mine gas mobile pump-exhaust system. Anhui University of Science and Technology (2006)
9. Huang, K.: Mobile coalmine methane pumping-exhaust system based on online interpolation fuzzy control. Anhui University of Science and Technology (2008)

10. An, S., Zhang, H., Li, H., et al.: Design and application of automatic adjusting control system for self-adaptive gas drainage pipeline valve. Coal Eng. **48**(3), 24–26 (2016)
11. Zhou, F., Liu, C., Xia, T., et al.: Intelligent gas extraction and control strategy in coalmine. J. China Coal Soc. **44**(8), 2377–2387 (2019)
12. Wu, Y., Wu, C.: Design of mining gas drainage system based on wireless sensor network. Coal Mine Electromech. **3**, 67–70 (2015)
13. Huang, R., Zhang, Z., Bo, C.: Study on control mechanism and method of gas concentration in gas drainage borehole of underground mine. Coal Sci. Technol. **45**(05), 128–135 (2017)
14. Liu, J.: Intelligent Control. Electronic Industry Press, Beijing (2005)
15. Li, G.: Discussion on determination method of coal seam gas rational pre-drainage period. Saf. Coal Mines **43**(04), 118–120 (2012)
16. Yu, B.: Coal mine gas disaster prevention and utilization technical manual. Coal Industry Publishing House (2005)
17. Wang, L.: Study on characteristics of gas occurrence and distribution of residual gas after drainage in Hudi mine. China University of Mining and Technology (2018)
18. Ming, D.: Study on prediction model of residual gas content in protected coal seam. Shandong University of Science and Technology (2017)