A multi-objective optimization model to enhance the comprehensive performance of underground gas drainage system

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Abstract: The underground gas drainage system plays a vital role in the underground drilling drainage which is widely used in Chinese coal mines. However, the pure gas drainage flow, gas concentration and energy efficiency, which together represent the comprehensive performance of gas drainage system, are generally low due to the mismatching between the drainage system and drainage objects. The optimization of gas pipeline system has been extensively investigated, but fewer studies consider the diversity and temporal correlation of drainage object characteristics and the multi-objectives of drainage system.

In this paper, a multi-objective optimization model, which fully considers the above factors, is built to achieve the match between the drainage system and drainage objects. Furthermore, the gas flow and methane transport model is established to calculate the values of multi-objectives and constraints. A derivative-free algorithm, bound optimization by quadratic approximation (BOBYQA), is proposed to solve the optimization model. Finally, the optimization model is applied to a typical modern coal mine and verified through the comparisons with field monitoring data and a

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1 recognized empirical formula. The optimization results reveal that (1) the variation
2 trends of the three objectives with decision variables are different from each other,
3 which indicates the optimal decision variables should be determined by considering
4 all three objectives; (2) the optimization model can appropriately allocate the negative
5 pressure in view of the interrelationship and different characteristics of drainage
6 objects; (3) the decision variables can be adjusted to fit the characteristics change of
7 drainage objects with time.

8 **Keywords:** Coal mine; Gas drainage system; Multi-objective optimization; Temporal
9 correlation; Bound optimization by quadratic approximation

10 **1. Introduction**

11 Gas drainage can not only eliminate gas disaster in coal mines, but also provide
12 clean energy and reduce greenhouse gas emission (Karacan et al., 2011; Pillalamarry
13 et al., 2011). The widely used gas drainage method in China is underground drilling
14 drainage (Xia et al, 2014), in which the underground gas drainage system plays a
15 significant role. From Fig. 1, the drainage system connects to various drainage objects
16 such as cross-measure boreholes, in-seam boreholes and the tube buried in gob. The
17 relationships between the drainage negative pressure and gas drainage performance
18 (i.e. gas drainage flow and concentration) are different for disparate drainage objects
19 (Pan et al., 2014). Besides, the gas drainage concentration declines with time due to
20 the air-leakage around the borehole (Liu et al., 2014; Zhou et al., 2016). Because of
21 the diversity and temporal correlation of drainage object characteristics, it is difficult
22 for gas drainage system to consistently match each drainage object without

1 optimization. The mismatching can lead to the improper negative pressure for the
2 drainage object, which further causes the low comprehensive performance of gas
3 drainage system, including low gas drainage concentration, small pure gas flow and
4 low energy efficiency. For instance, exorbitant negative pressure may result in the low
5 gas drainage concentration and energy efficiency, whereas the excessively low
6 negative pressure may induce the small gas drainage flow. According to the statistics,
7 the average underground gas drainage concentration is lower than 30%, and the
8 average pre-drained rate of coal seam gas is less than 23% in China (Zhou et al.,
9 2014a). The annual electricity consumption of gas drainage system in a medium-scale
10 coal mine normally reaches ten million kilowatt hours. Therefore, improving the
11 comprehensive performance of gas drainage system, which can be achieved by
12 optimizing the gas drainage system to match all different drainage objects, is of great
13 significance.

14

15 **Fig. 1.** The schematic diagram of gas drainage system

16 The existing researches optimized the gas drainage system mainly by regulating
17 the pipe diameters or valve opening degree. Zhai et al. (2008) and Ye et al. (2012)
18 recognized the pipe sections with excessively large flow resistance using graph theory,
19 and replaced the pipe sections with larger-diameter pipes for reducing the flow
20 resistance. Liu et al. (2010) also proposed the optimum scheme of pipe diameter
21 adjustment by using the mine ventilation simulation system to calculate the pipe
22 resistance distribution. However, the adjustment of pipe diameters needs to replace
23 the existing pipelines, which not only costs a lot in time and money but also disturbs

1 the normal gas drainage and coal production. Unlike the above optimization, Wang et
2 al. (2015) proposed to adjust the valve opening degree for improving gas drainage
3 concentration of the in-seam borehole according to the correlation between negative
4 pressure and gas drainage concentration. Nevertheless, the research only focused on
5 the gas drainage concentration but neglected the total pure gas flow and energy
6 efficiency which are also the important evaluation indicators of the drainage system.
7 In addition, without considering the interrelationship among different drainage objects,
8 the optimization research only concentrated on one drainage object. Therefore, the
9 optimization was localized and its effect on the whole drainage system was not
10 explicit.

11 The researches of underground gas drainage system optimization in coal mines
12 are relatively scant, whereas the studies on the optimization of natural gas pipeline
13 network are extensive, which can provide some reference for gas drainage system
14 optimization. In these studies, some significant performance indexes such as
15 transmission amount and operation cost are normally chosen as objective functions.
16 Some key parameters of pipeline system such as the number of compressors and the
17 compressor pressure are set as decision variables (Sun et al., 2000; Üster et al., 2014;
18 Chebouba et al., 2015). Diverse algorithms including particle swarm, ant colony,
19 genetic algorithm and so on are used to solve the optimization problem (Wu et al.,
20 2014; Zheng et al., 2012; Chebouba et al., 2009; Sanaye et al., 2013). However, there
21 also exist differences between gas drainage system and natural gas pipeline system.
22 Natural gas pipeline system connects to similar and stable gas sources which are not

1 influenced by the operating condition of pipeline system. On the contrary, gas
2 drainage system links diversified drainage objects whose gas flow and concentration
3 are remarkably different from each other. The gas flow and concentration are also
4 influenced by the negative pressure which is related to the operation condition of gas
5 drainage system. Furthermore, the gas drainage concentration can decline with time.
6 Therefore, the optimization of gas drainage system is more complicated than that of
7 the natural gas pipeline in the above aspects.

8 In this paper, we build an optimization model for underground gas drainage
9 system, which makes the drainage system consistently match each drainage object by
10 fully considering the interrelationship and different characteristics of drainage objects,
11 the characteristic change with time and the multi-objective. Pump rotate speed and
12 valve resistance coefficients are chosen as the decision variables; total pure gas flow,
13 gas drainage concentration and energy efficiency are set as the multi-objectives.
14 Moreover, the gas flow and methane transport model is established to calculate the
15 values of multi-objectives and constraints. A derivative-free algorithm, bound
16 optimization by quadratic approximation (BOBYQA), is proposed to solve the
17 optimization model. This optimization model is applied to a typical modern coal mine
18 and verified through the comparisons with field monitoring data and a recognized
19 empirical formula. This shows that this optimization model is an effective tool for
20 improving the comprehensive performance of underground gas drainage system.

21

22

2. Proposed optimization model in this study

2.1 Decision variables

From Fig.1, gas drainage pump and valves, which can remarkably influence the distribution of the drainage negative pressure, are the significant components of the gas drainage system. Therefore, the pump rotate speed r and the resistance coefficient K_i of the i th valve which controls the i th drainage object are chosen as the decision variables ($i \in \{1, 2, \dots, n\}$, n is equal to the number of drainage objects).

One gas drainage pump has several rated rotate speeds, which has different flow and power characteristic curves (see Fig. 2). The flow/power characteristic curve determines the correlation between gas drainage flow/operating power and inhalation negative pressure.

Fig.2. Flow and power characteristic curves of 2BEF-72 water ring vacuum pump

The valve resistance coefficient K_i is used to calculate the local resistance of the i th valve according to the following equation:

$$\Delta p_i = \frac{1}{2} K_i \rho u^2 \quad (1)$$

where Δp_i is the local resistance at the i th valve; K_i is the resistance coefficient of the i th valve; ρ is the gas density; u is the gas velocity.

Under a certain pipe diameter, the valve resistance coefficient K_i has one-to-one relationship with the valve relative opening degree (as shown in Fig. 3). The full range of the resistance K_i is from 0.2 (fully-open valve) to infinite (closed valve). However, the excessively small opening degree readily causes the blocking or

vibration of the control valve, thus the appropriate range of the relative opening degree is from 0.1 to 1, which also determines the reasonable range of valve resistance coefficients under a certain pipe diameter (see Fig. 3). The initial values of valve resistance coefficients in the optimization model are set to 0.2.

Fig.3. The relation curves of resistance coefficients and relative opening degree of gate valve under different pipe diameters(Wu et al., 2003)

2.2 Optimization formulation

Pure gas flow, gas drainage concentration and energy efficiency are chosen as the objective functions, which are given by Eq.(2) ~Eq.(4):

$$\max Q_{\text{CH}_4}(K_i, r) = Q(K_i, r) \cdot c_{\text{CH}_4}(K_i, r) \quad (2)$$

$$\max c_{\text{CH}_4}(K_i, r) \quad (3)$$

$$\max \eta(K_i, r) = Q_{\text{CH}_4}(K_i, r) / P(K_i, r) \quad (4)$$

where Q_{CH_4} and Q are, respectively, the total pure gas flow and mixed gas flow at the outlet (pump station) of the gas drainage system; c_{CH_4} is the gas drainage concentration at the outlet of the drainage system; η is the energy efficiency of the gas drainage system, whose physical meaning is pure gas production per unit of electricity consumption; P is the operating power of the drainage pump, which can be obtained according to the power characteristics curves (seen in Fig.2b). Q_{CH_4} , Q , c_{CH_4} , P and η are all the functions of valve resistance coefficients K_i and pump rotate speed r .

Eq.(5) gives the constraint conditions of the optimization problem:

$$\begin{cases} r = r_j, j \in \{1, 2, \dots, m\} \\ K_{\max} \geq K_i \geq K_{\min}, i \in \{1, 2, \dots, n\} \\ Q_i \cdot c_{(\text{CH}_4, i)} \geq Q_{(\min, i)}, i \in \{1, 2, \dots, n\} \end{cases} \quad (5)$$

where r_j is the rated rotate speed of a certain drainage pump, and m is equal to the number of rated rotate speeds; $K_{\max}$ and $K_{\min}$ are the upper and lower limits of the reasonable range of valve resistance coefficients, respectively; Q_i and $c_{(\text{CH}_4, i)}$ are the mixed gas drainage flow and gas drainage concentration of the i th drainage object, respectively; $Q_{(\min, i)}$ is the lower pure gas flow limit of the i th drainage object, and n is equal to the number of the drainage objects. In conclusion, in Eq.(5), the first two formulas restrict the variation range of the decision variables r and K_i , while the last formula aims to ensure the gas drainage effect to prevent the gas disaster.

Among the three objective functions of Eq.(2)~Eq.(4), the total pure gas drainage flow is the major objective for it directly matters the safety of coal mine production. In order to successfully solve the multi-objective optimization problem, the secondary objectives, namely gas drainage concentration and energy efficiency, are converted into the constraint conditions. Therefore, the above optimization formulation is transformed as follows:

$$\begin{aligned} & \text{Max } Q_{\text{CH}_4}(K_i, r) = Q(K_i, r) \cdot c_{\text{CH}_4}(K_i, r) \\ & \text{S.t } \begin{cases} c_{\text{CH}_4} \geq c_{\min} \\ \eta = Q \cdot c_{\text{CH}_4} / P \geq \eta_{\min} \\ r = r_j, j \in (1, 2, \dots, m) \\ K_{\max} \geq K_i \geq K_{\min}, i \in (1, 2, \dots, n) \\ Q_i \cdot c_{(\text{CH}_4, i)} \geq Q_{(\min, i)}, i \in (1, 2, \dots, n) \end{cases} \end{aligned} \quad (6)$$

where $c_{\min}$ and $\eta_{\min}$ are the lower limits of the secondary objectives. In order to obtain the values of $c_{\min}$ and $\eta_{\min}$, the single objective optimization problem of gas

1 drainage concentration c (Eq. (3) as the objective) or energy efficiency η (Eq.(4) as
2 the objective) should be firstly solved. The values of $c_{\min}$ and $\eta_{\min}$ are chosen
3 slightly less than the optimal values of c and η obtained through the single objective
4 optimizations.

5 **2.3 Gas flow and methane transport model of the underground gas drainage** 6 **system**

7 In order to calculate the values of the multi-objectives Eq.(2)~Eq.(4) and the last
8 constraint of Eq.(5), the gas flow and methane transport model of the underground gas
9 drainage system is proposed below.

10 Due to the huge ratio of pipe length to radius, gas flow is considered fully
11 developed in the gas drainage system, and three-dimensional pipes with finite
12 diameter are regarded as curves in the three-dimensional space for improving meshing
13 and computing efficiency. Furthermore, the following assumptions are made: (a) the
14 flow rate, pressure and concentration fields are cross-section average quantities; (b)
15 the direction of gas flow is along with the pipe axis; (c) the mixed gas in the gas
16 drainage system is ideal.

17 **2.3.1 Momentum and continuity equations**

18 Due to the great scale of gas drainage system and the complexity of theoretical
19 turbulence calculation, the widely-used empirical Darcy-Weisbach equation is used to
20 calculate the shear force in the momentum equation for simplifying the model
21 (Churchill et al., 1997; Pambour et al., 2016). Furthermore, the influence of the
22 convective term is negligible compared to the other terms in the momentum equation,

1 due to the small flow velocities($u < 40\text{m/s}$) in transport pipelines (Duan., 2001;
 2 Pambour et al., 2016). Therefore, the steady momentum equation for gas flow in a
 3 pipe is given as follows:

$$4 \quad -\nabla p \cdot \mathbf{e}_t - f_D \frac{\rho}{2d} u |u| - \rho \mathbf{g} \cdot \mathbf{e}_t = 0 \quad (7)$$

5 where p is the gas pressure in the drainage system; $\mathbf{e}_t$ is the unit tangent vector to pipe
 6 axis; f_D is the Darcy friction factor; u is the cross section average tangential velocity; $\mathbf{g}$
 7 is the acceleration of gravity; d is the diameter of gas drainage pipe; ρ is the density
 8 of mixture of methane and air, which can be described as:

$$9 \quad \rho = \frac{p(M_1 \cdot c_1 + M_2 \cdot c_2)}{RT} \quad (8)$$

10 where c_1 and c_2 are the volume concentrations of methane and air, respectively; M_1
 11 and M_2 are the molar mass of methane and air, respectively; R is the universal gas
 12 constant; T is the gas temperature in the gas drainage pipe.

13 Steel tube is normally used as the gas drainage pipeline to prevent the static
 14 electricity. The gas flow in the gas drainage system is turbulent because of its large
 15 Reynolds number. Darcy friction factor f_D of turbulent flow in steel tube can be
 16 expressed as (Ministry of construction of China, 2006)

$$17 \quad f_D = 0.11 \left(\frac{e}{d} + \frac{68}{\text{Re}} \right)^{0.25} \quad (9)$$

18 Where e is the surface roughness of the steel gas drainage pipe. Re is the
 19 Reynolds number, which can be expressed as

$$20 \quad \text{Re} = \frac{\rho u d}{\mu} \quad (10)$$

21 where μ is the dynamic viscosity of mixture of methane and air, which can be

1 calculated according to the Chapman-Enskog theory (Chapman et al., 1960) :

$$2 \quad \mu = \frac{\mu_1 M_2^{\frac{2}{3}} + \mu_2 M_1^{\frac{2}{3}}}{M_1^{\frac{2}{3}} + M_2^{\frac{2}{3}}} \quad (11)$$

3 where μ_1, μ_2 are the dynamic viscosities of methane and air, respectively.

4 The local resistance of bends and T-junctions can also be calculated according to
5 Eq.(1). The resistance coefficients of bends are equal to 0.9, while those of side and
6 main branch in T-junctions are 2.1 and 0.1, respectively (U.S. Army Corps of
7 Engineers, 1999).

8 The steady continuity equation of gas flow in the drainage system is defined as

$$9 \quad \nabla \cdot (A \rho \mathbf{u}) = 0 \quad (12)$$

10 where A is the pipe cross section area which is calculated by $A = \pi d^2 / 4$.

11 **2.3.2 Mass transport equation**

12 The mass transport equation of methane in the drainage pipe is given by

$$13 \quad \nabla \cdot (c_1 \mathbf{u}) - \nabla \cdot ((D_c + D_d) \nabla c_1) = 0 \quad (13)$$

14 where D_c and D_d are the diffusion and dispersion coefficients of methane, respectively.

15 $\mathbf{u}$ is the gas velocity vector. D_d can be calculated according to the following equation

16 (Talor et al., 1954):

$$17 \quad D_d = 10.1 \frac{d}{2} u \sqrt{\frac{f_D}{2}} \quad (14)$$

18 **2.3.3 Inlet and outlet boundary conditions**

19 From Fig.1, we can see that the drainage objects and the drainage pump are,
20 respectively, the inlets and outlet of gas drainage system.

21 The inlet conditions of gas flow and methane transport are established according

1 to the relationship between the gas drainage performance (i.e. mixed gas flow and gas
 2 concentration) and negative pressure of the drainage objects. Gas drainage
 3 concentration decreases while mixed gas flow increases with the augment of negative
 4 pressure under normal conditions. Therefore, the following exponential function (15)
 5 is set as the inlet boundary conditions:

$$6 \quad \begin{cases} q = q_0 e^{-b_1/(p_{\text{sub}}+b_2)} \\ c_1 = c_1^0 e^{-b_3 p_{\text{sub}}} \end{cases} \quad (15)$$

7 where q and c_1 are the mixed gas flow rate and the gas concentration at the inlets of
 8 the gas drainage system, respectively; p_{sub} is the negative pressure of the drainage
 9 object, which is equal to the difference of the barometric pressure and the absolute
 10 pressure; q_0 , c_1^0 , b_1 , b_2 and b_3 are the undermined coefficients which can be obtained
 11 by using Eq. (15) to fit the field monitoring data of drainage objects.

12 The outlet boundary condition of gas flow is set in terms of the flow characteristic
 13 curve of the drainage pump (see Fig.2a). By selecting sufficient data points in the flow
 14 characteristic curve for linear interpolation, the function of aspirating volume and
 15 inhalation absolute pressure is established and set as the outlet boundary condition of
 16 gas flow. In addition, the outflow condition is set as the outlet boundary condition of
 17 methane transport:

$$18 \quad -\mathbf{e}_t \cdot (D_c + D_d) \cdot \nabla c_1 = 0 \quad (16)$$

19 **2.4 Solution method and procedures of the optimization model**

20 Governing equations of gas flow and methane transport in the gas drainage
 21 system are a set of non-linear partial differential equations (PDE) and there exists the
 22 cross-coupling relationship among momentum, continuity and mass transport

equations. Therefore, these equations are difficult to solve analytically and are implemented into, and solved by using COMSOL Multiphysics, a powerful PDE-based multiphysics modeling environment.

The values of the objective functions can only be obtained by solving the complex PDEs, thus the derivatives of the objective functions are difficult to be determined. Consequently, a derivative-free optimization algorithm, namely bound optimization by quadratic approximation (BOBYQA), is proposed to solve the optimization model. The optimization algorithm possesses the global convergence and good descent property (Powell, 2009). The procedures of solving the optimization model are depicted by a flow chart as shown in Fig. 4.

Fig.4. The flow chart of solving the optimization model

3. Simulation case and model validation

3.1 Simulation case

Dingji colliery with an annual production of six million tons, affiliated with Huainan Mining Group in Anhui province of southern east China, is under the threat of coal and gas outburst. The average gas content, gas pressure and permeability of the coal seam are approximately $6.28\text{m}^3/\text{t}$, 1.2MPa and 0.013mD , respectively. The coal mine adopts 2BEF72 water ring vacuum pump as the gas drainage pump whose characteristic curves are shown in Fig.2. The gas drainage pump links various drainage objects including in-seam boreholes, cross-measure boreholes, buried tubes of gob and high suction tunnels. Dingji colliery is a typical modern coal mines in

China, whose gas drainage methods, construction form of gas drainage system and coal seam gas occurrence conditions represent the mainstream conditions of most of Chinese state-owned coal mines. Therefore, the research conclusions based on the model case have a relatively wide applicability in China.

3.2 Physical model, parameters determination and boundary conditions

The schematic diagram and physical model of gas drainage system of Dingji colliery is shown in Fig. 5. The physical model is built by simplifying the drainage objects, pump, valves, bends and T-junctions as points and simplifying pipes as curves in three-dimensional space. The gas drainage pipes can be divided into main pipelines, sub-pipelines and branch pipelines with the diameters of 630mm, 426mm and 273mm, respectively (see Fig. 5). From Fig.5b, each short pipeline section with the diameter of 273mm has 30 mesh elements, and each long pipeline section with the diameter of 426mm or 630mm has 75 mesh elements. There are 1215 mesh elements and 7316 degrees of freedom in the whole computational domain of pipeline system. Also, the calculated results do not change with the additional increase of mesh elements, which shows that the number of mesh elements can meet the accuracy requirements. According to Fig.3, the $K_{\max}$ and $K_{\min}$ in Eq.(6) are respectively set as 50 and 0.2, which corresponds to the appropriate range of relative valve opening degree from 0.1 to 1 under the pipe diameter of 273mm. The values of parameters in the gas flow and methane transport model are listed in Table 1, which are chosen according to the contemporary literature (Cussler et al., 2002; Zhang et al., 2008) and the actual field data of the coal mine. The lower pure gas flow limits $Q_{(\min,i)}$ of the i th drainage object,

1 which are different in the earlier and later stages, are listed in Table 2. The earlier and
2 latter drainage stages can be defined based on the decline of gas drainage
3 concentration with time. In this model case, the gas drainage period, during which the
4 average gas drainage concentration of most of the drainage objects remains above
5 10%, is defined as the earlier drainage stage. The later drainage stage refers to the gas
6 drainage period during which the average gas drainage concentration drops below
7 10%.

8

9 **Fig.5.** The schematic diagram and physical model of gas drainage
10 system in Dingji colliery (The red, orange and green lines in Fig.5b respectively
11 represent the pipes with the diameters of 630mm, 426mm and 273mm)

12

13 **Table 1** The parameters of the gas flow and methane transport model

14

15 **Table 2** The lower pure gas flow limits $Q_{(\min,i)}$ in the earlier and later drainage stages

16

17 From Fig.5, the gas drainage system connects to eight drainage objects numbered
18 as 1#~8#. The functional relationships between gas drainage performance and the
19 negative pressure are expressed by Eq.(15), which is set as the inlet boundary
20 condition. The undermined coefficients q_0 , b_1 , b_2 , c_1^0 and b_3 are obtained by using Eq.
21 (15) to fit the field monitoring data of drainage objects (see Fig. 6). Table 3 and Table
22 4 show the values of undetermined coefficients of Eq.(15) in the earlier and later

drainage stages, respectively. Based on the field monitoring data and the theoretical analysis (Xia et al., 2014), the gas concentration of gob gas drainage (1#, 4#, 6#) and the mixed gas flow rate of all drainage objects do not have a markedly attenuation relationship with time. Therefore, only the values of c_1^0 and b_3 of coal seam gas drainage objects (2#, 3#, 5#, 7#, 8#) in the later drainage stage are different from those in the earlier drainage stage, which are listed in Table 4.

Fig.6. Field monitoring data and fitted curves of gas drainage concentration and mixed gas flow of different drainage objects ((a) Mixed gas flow of the coal seam drainage objects; (b) Mixed gas flow of the gob drainage objects; (c) Gas drainage concentration in the earlier drainage stage; (d) Gas drainage concentration of the coal seam drainage objects in the later drainage stage)

Table 3 the values of undetermined coefficients in the earlier drainage stage (The gas concentration of 4# is considered as the constant which equals to 1%)

Table 4 the values of undetermined coefficients in the later drainage stage

From Fig. 6, the high suction tunnels (1#, 6#) have relatively large mixed gas drainage flow rate and gas concentration; the tube buried in gob (4#) has large flow rate but low gas concentration; the in-seam and cross-measure boreholes (2#, 3#, 5#, 7#, 8#) have relatively small flow rate and high gas concentration. We can also see that the gas drainage concentrations in the later drainage stage are much lower than

those in the earlier drainage stage, which is mainly attributed to the reduction of gas content and stretching of air leakage fractures in the coal seam (Zhou et al., 2012; Zhou et al., 2014b; Xia et al., 2015). In addition, the mixed gas drainage flow rate of the 6# sharply increases, while its gas concentration declines slightly with negative pressure, which indicates its high yield-increasing potential with negative pressure. In conclusion, the inlet boundary condition of Eq.(15) can reflect the characteristics of different drainage objects and the characteristic change with time.

3.3 Simulation results

Pump rotate speed is set as 300r/min and the resistance coefficients of valves is set as 0.2 based on the actual running state of gas drainage system in the Dingji colliery. Fig.7 shows the distribution of flow, velocity, absolute pressure and gas concentration in the gas drainage system. The gas volume flow rate q and velocity u are relatively large in the pipe sections AB, FG and IJ, which causes the large pressure drop in the pipe sections. It is advised to increase the pipe diameters of the pipe sections AB, FG and IJ to reduce the flow resistance.

Fig.7. The distribution diagrams of mixed gas flow, velocity, pressure and gas concentration in the gas drainage system

3.4 Model validation

According to the simulation results as shown in Fig.7, the inhalation absolute pressure, gas concentration and flow rate at the output point A corresponding to the drainage pump are 70200Pa, 10% and 556 m³/min respectively, which are in good

1 agreement with the field observations of 67000Pa, 11% and 520 m³/min.

2 To further verify the correctness of our model, we compared the calculated results
3 of our model with those of the widely-used engineering empirical formula in design
4 specification of gas drainage project (Ministry of construction of China, 2008). The
5 empirical formula is given by

$$H = 69 \times 10^5 \left(\frac{e}{d} + 192.2 \frac{\nu_0 d}{Q} \right)^{0.25} \frac{L \rho Q^2}{d^5} \frac{p_0 T}{p T_0} \quad (17)$$

7 where H is the pressure drop, Pa; L is the length of the pipe, m; d is the diameter of
8 the pipe, mm; Q is the mixture flow rate at the condition of 293K and 101.3kPa, m³/h;
9 ν_0 is the dynamic viscosity, m²/s; ρ is the density of mixture, kg/m³; e is the surface
10 roughness, mm; p and p_0 are the absolute pressure in the pipe and the atmospheric
11 pressure respectively, Pa; T and T_0 are the gas temperature and the normal temperature
12 respectively, both of which are set as 293K.

13 The pressure drop of the pipe section BF is calculated and compared. According
14 to the numerical simulation results (as shown in Fig.7), L is set as 670m; Q is set as
15 13000m³/h; ν_0 is set as 1.791×10^{-5} m²/s; the average pressure in the pipe is equal to
16 81000Pa and ρ is equal to 0.921 kg/m³; d and e are the same as those in the numerical
17 model. The pressure drop H calculated by Eq.(17) and our numerical model are equal
18 to 1175 Pa and 1240 Pa, respectively. The numerical simulation result is in good
19 agreement with the result of empirical formula Eq.(17), which proves the correctness
20 of our mathematical model.

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4. Optimization results and discussions

4.1 Results and discussions of the optimizations in the earlier drainage stage

4.1.1 Results of the single and multiple objective optimizations

According to the flow chart shown in Fig.4, three single objective optimizations of total pure gas flow, gas drainage concentration and energy efficiency at every pump rotate speed are firstly solved to obtain the optimal pump rotate speed of multi-objective optimization and the values of $c_{\min}$ and $\eta_{\min}$ in Eq.(6). Fig.8 shows the optimization results of the three single-objective values at each pump rotate speed. From Fig.8, total pure gas flow increases slightly while gas drainage concentration and energy efficiency decrease significantly when the pump rotate speed increases from 270r/min to a higher rotate speed. In order to make all three objectives remain relatively high, 270r/min is chosen as the optimal rotate speed of the multi-objective optimization. The lower limits of gas drainage concentration $c_{\min}$ and energy efficiency $\eta_{\min}$ in Eq.(6) are chosen slightly less than the single-objective optimal values of c_{CH_4} and η which are equal to 11.7% and 5.08m³/kWh at the rotate speed of 270r/min, respectively; hence, $c_{\min}$ and $\eta_{\min}$ are set as 11.5% and 4.98 m³/kWh, respectively.

Fig.8 The single-objective optimal values at each pump rotate speed

With the determination of the optimal pump rotate speed and the values of $c_{\min}$ and $\eta_{\min}$, the multi-objective optimization model Eq.(6) can be solved. Table 5 shows the multi-objective optimization results of valve resistance coefficients and the three

objectives.

Table 5 the multi-objective optimization results of valve resistance coefficients and the objective values in the earlier drainage stage

4.1.2 The changes of the gas drainage system performances with decision variables

From Fig.8, the total pure gas flow increases while gas drainage concentration and energy efficiency decrease with the pump rotate speed. Furthermore, the increment of total pure gas flow becomes smaller but the decrements of the other two indexes are constantly large with the rotate speed. For instance, the increment of total pure gas flow from 300r/min to 340r/min is $0.34\text{m}^3/\text{min}$, which is much smaller than the increment of $1.71\text{m}^3/\text{min}$ from 240r/min to 270r/min. In contrast, each level increase of rotate speed leads to a large decrement of gas drainage concentration and energy efficiency about 0.6% and $1\text{m}^3/\text{kWh}$, respectively. Therefore, blindly increasing pump rotate speeds may lead to the substantial drop of gas concentration and energy efficiency, despite the limited improvement of total pure gas flow.

Fig.9 shows the variations of the multiple objectives and the valve resistance coefficients $K_1\sim K_8$. With the iteration of optimization algorithm, the valve resistance coefficients are continuously optimized, which further changes the values of multi-objectives. From Fig.8 and Fig.9, we can obtain the effects of each decision variable on the three performance indexes of gas drainage system, as shown in Table 6. The effects are authentic on the condition that the decision variables vary within the

scope shown in Fig.8 and Fig.9.

Fig.9. The variations of (a) total pure gas flow, (b) gas drainage concentration, (c) energy efficiency and (d) the resistance coefficients $K_1 \sim K_8$

Table 6 The effects of each decision variable on the three performance indexes of gas drainage system (“+” means that the performance index increases with the decision variable, the “-” means the index decreases with the decision variable)

Moreover, during the optimization process of valve resistance coefficients shown in Fig.9, total pure gas flow and gas drainage concentration increase by 1.4% and 5% respectively, while the energy efficiency decrease rapidly by 1.7% before reaching the lower limit $4.98 \text{ m}^3/\text{kWh}$ set in Eq.(6). Therefore, considering all three objectives rather than only one objective in the optimization model is significant for preventing the excessively low performance index. For instance, according to the results of single-objective optimization of total pure gas flow, the corresponding energy efficiency at the pump rotate speed 270r/min is only $4.9 \text{ m}^3/\text{kWh}$, which is much smaller than the energy efficiency $4.98 \text{ m}^3/\text{kWh}$ of the multi-objective optimization result at the same rotate speed.

4.1.3 The proper negative pressure distribution through optimizing valve resistance coefficients

Fig.10 shows the variations of the negative pressure and pure gas drainage flow of different drainage objects. Comparing Fig.10 to Fig.9, we can see that the

1 adjustments of valve resistance coefficients lead to the distribution change of negative
2 pressure, and further improve total pure gas flow and gas drainage concentration. The
3 20th~25th and 50th~60th iterations witness the substantial changes of valve resistance
4 coefficients. During the 20th~25th iterations, the increase of K_4 from 0.2 to 22 leads to
5 the relatively small negative pressure drop of the 4# by 1.7kPa , but causes the
6 significant negative pressure increase of all other drainage objects by 1kPa~4kPa (as
7 shown in Fig.9d and Fig.10a). Ulteriorly, the negative pressure decrease of the 4#
8 with low drainage concentration reduces the gas flow of the 4#, which contributes to
9 the increase of gas drainage concentration of the whole drainage system (seen in
10 Fig.10 and Fig.9b); the negative pressure increase of the 3# and 6#, which has high
11 yield-increasing potential and relatively high gas concentration, improves the pure gas
12 flow of the 3# and 6# and further causes the large increment of the total pure gas flow
13 and gas drainage concentration of the whole system (seen in Fig.10 and Fig.9a,b).
14 During the 50th~60th iterations, the certain increase of K_1 , K_2 , K_5 , K_7 and K_8 not only
15 reduces negative pressures of the 1#, 2#, 5#, 7# and 8# to improve their gas
16 concentration but also increases negative pressure of the 3# and 6#, which eventually
17 improves the total pure gas flow and gas drainage concentration (as shown in Fig.10
18 and Fig.9a,b,d).

19 To conclude, the quantitative regulation of valve resistance coefficients through
20 the optimization model can appropriately allocate the negative pressure among
21 different drainage objects based on the interrelationship and the diverse characteristics
22 of drainage objects, which indicates that the optimization model can make the gas

drainage system match each drainage object.

Fig.10. The variations of (a) the negative pressure of different drainage objects, (b)
pure gas flow of different drainage objects

4.2 Results of the multi-objective optimization in the later drainage stage

The lower limit of pure gas drainage flow $Q_{(\min,i)}$ of Eq.(5) is difficult to meet because of the low gas drainage concentration in the later drainage stage, therefore the pump rotate speed is improved to the maximum value of 340r/min. The lower limits of gas drainage concentration $c_{\min}$ and energy efficiency $\eta_{\min}$ in the multi-objective optimization of the later stage are set to 9% and 2.66m³/kWh respectively, according to the results of the single-objective optimizations in the later drainage stage. Table 7 shows the optimal valve resistance coefficients and multi-objective values in the later drainage stage.

Table 7 the optimal valve resistance coefficients and multi-objective values in the
later drainage stage

Comparing Fig.6c to Fig.6d, we can see that the decrement of gas drainage concentration with negative pressure in the later drainage stage is much smaller than that at the earlier drainage stage. Therefore, the smaller valve resistance coefficients and the consequent larger negative pressure in the later drainage stage can result in the large improvement of mixed gas flow and the minor decrease of gas concentration, which eventually leads to the increase of total pure gas flow. For above reasons, the

optimal K_2 , K_5 , K_7 and K_8 in the later drainage stage in Table 7 become smaller than those in the earlier drainage stage in Table 5. In conclusion, the gas drainage system can be properly adjusted to fit the change of drainage object characteristics in the latter drainage stage by the optimization model.

5. Conclusions

In this study, we established the optimization model of underground gas drainage system in coal mines, which fully considers the interrelationship and different characteristics of drainage objects, multi-objectives and time effect. The optimization model can quantitatively regulate the underground gas drainage system to consistently match each drainage object, thereby improving the comprehensive performance of the drainage system. Based on these investigations, the following conclusions can be drawn:

- The variation trends of the three objectives with the decision variables are greatly different from each other. With the increase of pump rotate speed, total pure gas flow increases but the growth percentages declines, whereas gas drainage concentration and energy efficiency decrease at the constantly large rate. In addition, during the optimization process of valve resistance coefficients, total pure gas flow and gas drainage concentration increase but energy efficiency decreases. Therefore, the optimal values of decision variables should be determined by quantitatively evaluating all the three objectives, thereby improving the comprehensive performance of gas drainage system.

- The valve resistance coefficient increase from 0.2 to 22 of the drainage object

which has large flow rate can lead to the relatively small negative pressure decrease of itself by 1.7kPa, but cause significant negative pressure augment of all other drainage objects by 1kPa~4kPa. According to this interrelationship and the diverse characteristics of drainage objects, the valve resistance coefficients are quantitatively regulated to appropriately allocate the negative pressure among different drainage objects, which greatly improves the total pure gas flow and gas drainage concentration.

- The gas drainage concentration and its attenuation range with negative pressure become smaller in the later drainage stage. To fit the characteristics change of drainage objects, the gas drainage system is properly adjusted by quantitatively increasing the pump rotate speed and reducing the valve resistance coefficients of some certain drainage objects, which increases the total pure gas flow in the later drainage stage.

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References

Chapman S., Cowling T., 1960. The mathematical theory of non-uniform gases: An

1 account of the kinetic theory of viscosity, thermal conduction, and diffusion in
2 gases. Cambridge University Press, New York.

3 Chebouba A., Yalaoui F., Smati A., et al., 2009. Optimization of natural gas pipeline
4 transportation using ant colony optimization. *Comput Oper Res*, 36:1916-1923.

5 Chebouba A., 2015. Multi objective optimization of line pack management of gas
6 pipeline system. *Journal of Physics Conference Series*, 574:1-4.

7 Churchill S., 1997. Friction factor equation spans all fluid-flow regimes. *Chem.Eng.*,
8 84(24): 91-92

9 Cussler E., 2002. Diffusion: mass transfer in fluid system, Cambridge University
10 Press, New York, 63-64

11 Duan C., 2001. Gas transmission and distribution, China Building Industry Press,
12 Beijing, 87-88

13 Karacan C.Ö., Ruiz F.A., Cotè M., et al., 2011. Coal mine methane: A review of
14 capture and utilization practices with benefits to mining safety and to
15 greenhouse gas reduction. *Int J Coal Geol*, 86:121-156.

16 Liu B., Li Y., Jin P., 2010. Optimization and reformation of gas drainage system based
17 on emulation technology. In: *International Mining Forum 2010: Mine Safety
18 and Efficient Exploitation Facing Challenge of the 21st Century*, Huainan:
19 19-22 September 2010.p.32-37.

20 Liu Q., Cheng Y., Yuan L., et al., 2014. A new effective method and new materials for
21 high sealing performance of cross-measure CMM drainage boreholes. *J Nat
22 Gas Sci Eng*, 21: 805-813.

- 1 Ministry of construction of China, 2006. Design specification of city gas
2 (GB50028-2006). China Architecture and Building Press, Beijing.
- 3 Ministry of construction of China, 2008. Code for design of the gas drainage
4 engineering of coal mine (GB50471-2008). China Planning Press, Beijing.
- 5 Pambour K., Bolado-Lavin R., Dijkema G., 2016. An integrated transient model for
6 simulating the operation of natural gas transport systems. J Nat Gas Sci Eng, 28:
7 672-690
- 8 Pan R., Cheng Y., Yuan L., et al., 2014. Effect of bedding structural diversity of coal
9 on permeability evolution and gas disasters control with coal mining. Nat
10 Hazards, 73(2): 531-546
- 11 Pillalamarri M., Harpalani S., Liu S., 2011. Gas diffusion behavior of coal and its
12 impact on production from coalbed methane reservoirs. Int J Coal Geol, 86:
13 342-348
- 14 Powell M., 2009. The BOBYQA algorithm for bound constraint optimization without
15 derivatives. Report DAMTP 2009/NA06, University of Cambridge.
- 16 Sun C., Uraikul V., Chan C., et al., 2000. An integrated expert system/operations
17 research approach for the optimization of natural gas pipeline operations. Eng
18 Appl Artif Intel, 13:465-475
- 19 Sanaye S., Mahmoudimehr J., 2013. Optimal design of a natural gas transmission
20 network layout. Chem Eng Res Des, 91:2465-2476.
- 21 Talor G., 1954. The dispersion of matter in turbulent flow through a pipe.
22 Proc.Roy.Soc.A, 223:446-468

- 1 U.S. Army Corps of Engineers, 1999. Engineering and Design Liquid Process Piping,
2 Engineering Manual, No.1110-1-4008
- 3 Üster H., Dilaveroglu S., 2014. Optimization for design and operation of natural gas
4 transmission networks. *Appl Energ*, 133:56-69.
- 5 Wang Z., Zhou Y., Sun Y., et al., 2015. Drainage negative pressure optimization based
6 on negative pressure influence factor. *Safety in Coal mines*,46(2):12-16.
- 7 Wu Y, Qu S, Zhang W, et al., 2003. Local head loss caused by valves in water
8 distribution network. *Journal of Harbin Institute of Technology*, 35(11):
9 1311-1313.
- 10 Wu X., Li C., Jia W., et al., 2014. Optimal operation of trunk natural gas pipeline via
11 an inertia-adaptive particle swarm optimization algorithm. *J Nat Gas Sci Eng*,
12 21:10-18.
- 13 Xia T, Zhou F, Liu J, et al., 2014. A fully coupled coal deformation and compositional
14 flow model for the control of the pre-mining coal seam gas extraction. *Int J*
15 *Rock Mech Min Sci*, 72:138-148
- 16 Xia T., Zhou F., Gao F., et al., 2015. Simulation of coal self-heating processes in
17 underground methane-rich coal seams. *Int J Coal Geol*, 141-142: 1-12
- 18 Ye Q., Wang H., Jia Z., 2012. Graph theory and its application in optimization of gas
19 drainage system in coal mine. *Procedia Engineering*, 45:339-344.
- 20 Zhang H., Liu J., Elsworth D., 2008. How sorption-induced matrix deformation
21 affects gas flow in coal seams: a new FE model. *Int J Rock Mech Min Sci*,
22 45:1226-36.

- 1 Zhai C., Lin B., Ye Q., 2008. Application of graph theory in optimizing mine gas
2 drainage system. *J Mini Safet Engin*, 25(1): 119-122.
- 3 Zheng Z., Wu C., 2012. Power optimization of gas pipelines via an improved particle
4 swarm optimization algorithm. *Pet. Sci.*, 9:89-92
- 5 Zhou F., 2012. Study on the coexistence of gas and coal spontaneous combustion (I):
6 disaster mechanism. *J. China Coal Soc*, 37(5): 843-849
- 7 Zhou F., Wang X., Liu Y., 2014a. Gas drainage efficiency: an input-output model for
8 evaluating gas drainage projects. *Nat Hazards*, 74(2): 989-1005.
- 9 Zhou F., Wang X., Xia T., 2014b. A model of safe drainage of coal seam gas. *J. China*
10 *Coal Soc.*, 2014, 39(8): 1659-1666
- 11 Zhou F., Xia T., Wang X., et al., 2016. Recent developments in coal mine methane
12 extraction and utilization in China: A review. *J Nat Gas Sci Eng*, 31: 437-458.

Figure 1

Figure 2a

Figure 2b

Figure 3

Figure 4

Figure 5a

Figure 5b

Figure 6a

Figure 6b

Figure 6c

Figure 6d

Figure 7a

Figure 7b

Figure 7c

Figure 7d

Figure 8

Figure 9a

Figure 9b

Figure 9c

Figure 9d

Figure 10a

Figure 10b

Table 1

Table 1 The parameters of the gas flow and methane transport model

Parameter	value
Molar mass of methane, M_1 (kg/mol)	0.016
Molar mass of air, M_2 (kg/mol)	0.029
Universal gas constant, R (J/(mol·K))	8.314
Gas temperature, T (K)	293.15
Surface roughness of the steel pipe, e (mm)	0.17
Dynamic viscosity of methane, μ_1 (Pa·s)	1.1×10^{-5}
Dynamic viscosity of methane, μ_2 (Pa·s)	1.84×10^{-5}
Methane diffusion coefficient, D_c (m ² /s)	2×10^{-5}

Table 2

Table 2 Lower limits of the pure gas drainage flow in the earlier and later stages

Flow rate/(m ³ /min)	$Q_{(min,1)}$	$Q_{(min,2)}$	$Q_{(min,3)}$	$Q_{(min,4)}$	$Q_{(min,5)}$	$Q_{(min,6)}$	$Q_{(min,7)}$	$Q_{(min,8)}$
Earlier	8	0.423	0.423	0.47	0.3	13	0.5	1
Later	8	0.323	0.323	0.3	0.2	13	0.3	0.6

Table 3

Table 3 The values of undetermined coefficients in the earlier drainage stage (The gas concentration of 4# is considered as the constant which equals to 1%)

Undetermined coefficients	1#	2#	3#	4#	5#	6#	7#	8#
c_1^0	50.32	32.74	79.14	—	5.21	11.35	65.1	97.58
q_0	66.22	75.53	41.68	161.06	76.94	194.42	10.07	20.4
b_1	9694	27610	8108	1399	19942	399	4222	7860
b_2	1425	3351	-7298	-7942	-275	-3622	-3884	522
$b_3 \times 10^5$	3.19	6.2	7.7	—	4.5	1.32	8.7	9.08

Table 4

Table 4 The values of undetermined coefficients in the later drainage stage

undetermined coefficients	2#	3#	5#	7#	8#
c_1^0	17.88	18.57	6.18	11.19	14.78
$b_3\times10^5$	4.16	4.14	5.32	3.83	5.24

Table 5

Table 5 the optimal valve resistance coefficients and multi-objective values in the earlier drainage stage

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	Multi-objectives
Optimal values	7.7	30.5	0.2	22	50	0.2	49.6	50	36.14 m ³ /min, 11.56%, 4.98 m ³ /kWh

Table 6 The effects of each decision variable on the three performance indexes of gas drainage system(“+” means that the performance index increases with the decision variable, the “-” means the index decreases with the decision variable)

	<i>r</i>	<i>K</i> ₁	<i>K</i> ₂	<i>K</i> ₃	<i>K</i> ₄	<i>K</i> ₅	<i>K</i> ₆	<i>K</i> ₇	<i>K</i> ₈
Total pure gas flow	+	+	+	-	+	+	-	+	+
Gas drainage concentration	+	+	+	-	+	+	-	+	+
Energy efficiency	-	little relation	little relation	-	-	little relation	-	little relation	little relation

Table 7

Table 7 the optimal valve resistance coefficients and multi-objective values in the later drainage stage									
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	Multi-objectives
Optimal values	10.1	5.89	0.21	17.2	3	0.2	0.78	3.9	31.25 m ³ /min, 9%, 2.67 m ³ /kWh