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Approach to increasing the quality of pressure-relieved gas drained from protected coal seam using surface borehole and its industrial application

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Abstract　During mining of lower protective coal seam, a surface borehole can efficiently extract not only the pressure-relieved gas from the protected layer, but also the gas from the mining layer gob. If the distance between the borehole and gob is too large, the quantity of gas drained from the protected layer decreases substantially. To solve this problem, a mathematical model for extracting pressure-relieved gas from a protected coal seam using a surface borehole was established, based on the radial gas flow theory and law of conservation of energy. The key factors influencing the quantity of gas and the drainage flow network using a surface borehole were presented. The results show that the quantity of pressure-relieved gas drained from the protected layer can be significantly increased by increasing the flow resistance of the borehole bottom. Application of this method in the Wulan Coal Mine of the Shenhua Group significantly increased the flow of pure gas and the gas concentration (by factors of 1.8 and 2.0, respectively), thus demonstrating the remarkable effects of this method.

Keywords　Surface borehole · Gas drainage · Borehole bottom resistance · Pressure-relieved gas

1 Introduction

Mining a protective coal seam is the main way to achieve simultaneous extraction of coal and gas (Guo et al. 2001; Yuan 2004, 2006, 2007, 2009; Xie et al. 2014). In China, we usually drill through coal seams to extract the pressure-relieved gas from the protected layer. However, this approach has many serious defects, including the need for significant engineering, high-risk construction, and disturbance of production activities. The construction and operation of a surface borehole is not restricted by the underground space or the production configuration. A borehole can not only simultaneously extract gas from the protected layer and gob of the mining layer, but also has the advantage of achieving a large quantity of drainage and high gas concentration. It is therefore a highly efficient gas drainage technology, with good development prospects (Yuan 2009; Liu 2012). The gas quantity and concentration reach a peak rapidly in the early days of drainage via a surface borehole. As the working face advances, however, these values gradually decrease as the degree of development of bottom fractures increases. When the working face passes the borehole by about 150–200 m, the extent of connection between the borehole and gob improves and a lot of low concentration gas is extracted from the gob, correspondingly lessening the quantity of pressure-relieved gas. The capacity of the gas extraction pump is consequently wasted (Liu 2012). In addition, if the bottom of the surface borehole is improperly controlled during construction, a lot of gas from the gob is extracted, making it difficult to eliminate outbursts by extracting the pressure-relieved gas. To eliminate outbursts, effective measures must therefore be taken to improve the drainage of gas.

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Many scholars have studied the principles of pressure relief during mining, changes in permeability of coal seams, and the scope of the pressure-relief area (Sun et al. 1996; Xu and Qian 2000; Tu et al. 2004; Esterhuizen and Karacan 2005; Whittlesa et al. 2006; Zhou and Jiao 2006; Sang et al. 2010). Zhou et al. (2010) studied the proportion of gas flow from each source with a surface borehole. When the gas flow resistance between the surface borehole and the gob decreased, a lot of low concentration gas from the gob was extracted by the borehole. The most commonly used measure to solve this problem is stopping the gas drainage of the borehole. There is no effective method of increasing the quantity of pressure-relieved gas drained from the protected layer. This paper therefore establishes a mathematical model for extracting gas from pressure-relieved coal seams using a surface borehole. By analyzing the factors affecting flow of the gas from the protected layer and the flow network used for gas drainage, a method of increasing the resistance of the borehole bottom is proposed to increase the quantity of gas drained from the protected layer. This method has been successfully applied in the Wulan Coal Mine of the Shenhua Group. This offers a new approach to increasing the drainage of pressure-relieved gas during extraction of the lower protective layer.

2 Mathematical model of extraction of pressure-relieved gas using a surface borehole

2.1 Parameters of the model

Surface boreholes extract methane gas both from the protected layer and the gob of the mining layer during mining
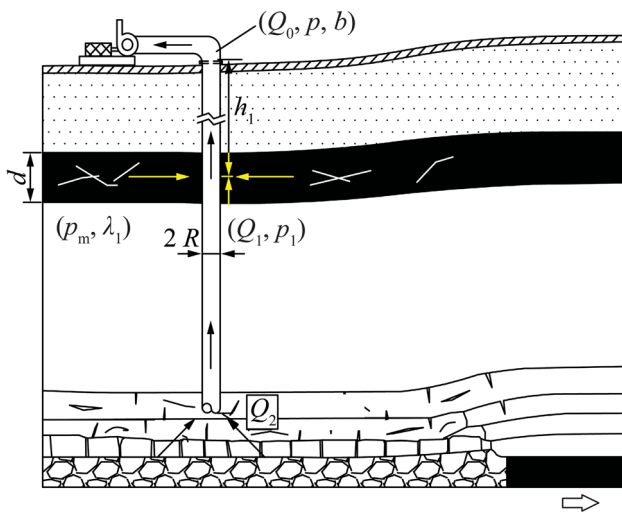

Fig. 1 Model of gas extraction by a surface borehole

of the lower protective coal seam, as shown in Fig. 1, in which Q_0 is the mixed gas extraction flow during working status, m^3/s; P is the negative pressure of gas drainage, MPa; b is the gas concentration of the mixed gas at the surface borehole wellhead, %; p_m is the pressure of the gas drainage area boundary in the overlying coal seam, MPa; d is the thickness of the overlying coal seam, m; λ_1 is the average permeability coefficient of the gas drainage area of the overlying coal seam, $m^2/(MPa^2 \cdot d)$; Q_1 is the flow of gas extracted from the overlying coal seam, m^3/s; p_1 is the absolute pressure of the gas at the junction of the surface borehole and the overlying coal seam, MPa; Q_2 is the flow of gas extracted from the gob, m^3/s; h_1 is the distance from the surface to the overlying coal seams, m; and R is the radius of the surface borehole, m.

2.2 Construction of the model

Under the effect of the negative drainage pressure, the flow of the pressure-relieved gas in the overlying coal seam can be calculated using a radial-flow model. Q_1 is calculated according to Eq. (1) (Zhou and Lin 1999):

$$Q_1 = 2\pi d\alpha_1\lambda_1 \frac{p_m^2 - p_1^2}{1440\ln(R_1/R)} \tag{1}$$

where R_1 is the radius of the gas extraction area of the overlying coal seam, m, and α_1 is the flow correction coefficient for gas extraction from the overlying coal seam.

According to the law of energy conservation, the Bernoulli equation for gas flow from the overlying coal seam to the surface borehole wellhead can be expressed as follows (because the surface borehole is a long-distance transmission pipeline and the velocity of the pressure-relieved gas into the borehole is far less than its axial velocity, local resistance can be ignored):

$$\frac{p_1 \times 10^6}{\rho_0 g} + \frac{v_0^2}{2g} = h_1 + \frac{(P_0 - P) \times 10^6}{\rho_0 g} + \frac{v_0^2}{2g} + \lambda\frac{h_1}{2R}\frac{v_0^2}{2g} \tag{2}$$

where v_0 is the flow rate of the fluid in the borehole, m/s; P_0 is the absolute atmospheric pressure at the surface, MPa; ρ_0 is the density of the gas in the borehole wellhead, kg/m^3; and λ is the loss coefficient.

Equation (2) can be further simplified as follows:

$$p_1 = (P_0 - P) + \rho_0 g h_1\left(1 + kQ_0^2\right) \times 10^{-6} \tag{3}$$

where k is the drag coefficient of the borehole, $k = \frac{\lambda}{4\pi^2 gR^5}$.

According to the relationship between density and concentration of the mixed gas, ρ_0 can be expressed as follows:

$$\rho_0 = \rho_m b + \rho_g(1 - b), \tag{4}$$

where ρ_m is the density of the pure gas, kg/m^3, and ρ_g is the density of air that does not contain methane, kg/m^3. When

ρ_m and ρ_g enter into Eq. (4), ρ_0 can be expressed as follows:

$$\rho_0 = 1.237 - 0.52b. \tag{5}$$

By simultaneous solution of Eqs. (1), (3), and (5), a mathematical model for the quantity of pressure-relieved gas drained from the protected layer, $Q1$, can be expressed as:

$$Q_1 = 2\pi d\alpha_1\lambda_1 \frac{p_m^2 - \left[(P_0 - P) + gh_1(1.237 - 0.52b)(1 + kQ_0^2) \times 10^{-6}\right]^2}{1440\ln(R_1/R)} \tag{6}$$

3 Approaches to increasing the quantity of pressure-relieved gas drained from the protected layer

3.1 Quantity of pressure-relieved gas drained

In Eq. (6), the parameter Q_1 is related to d, R_1, h_1, k, α_1, λ_1, P_m, R, P, b, and Q_0. P_0 is the local atmospheric pressure and is a constant under conditions where any change of temperature is ignored; the parameters d, R_1, and h_1 are characteristic parameters (all constants) of the protected layer, the surface borehole, and the coal bed geological conditions, respectively. When the working face pushes through the surface borehole from a greater distance (the late stage of gas drainage by the borehole) and the degree of fissure development in the protected layer is stable in the drainage area, the parameters α_1, λ_1, P_m, and R can be considered constant over a short period of time. During the late stage of gas drainage by the borehole, Q_1 is therefore mainly determined by P, b, and Q_0.

According to Eq. (6), the value of Q_1 increases with increasing P and b, but decreases as Q_0 decreases. Therefore, to increase Q_1, measures must be taken to increase the values of P and b, and decrease the value of Q_0.
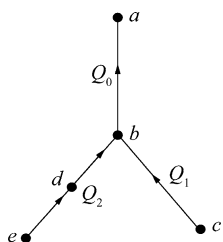
3.2 Analysis of the gas flow network

The model for gas extraction by a surface borehole is presented in Fig. 1. The flow network of the gas in the borehole and from each gas source is shown in Fig. 2, where point a is the drilling wellhead, point b is the junction of the borehole and the protected layer, point c is the gas drainage area boundary of the protected layer, point d is the drilling downhole, and point e is the gas drainage area boundary of the fissure zone. The total resistance to gas flow can be calculated by:

$$h_f = R'Q_0^2 \tag{7}$$

where R' is the equivalent wind resistance of the surface borehole, N s^2/m^8.

From the negative pressure characteristic curve of the gas extraction pump and the equivalent wind resistance curve for the borehole, we can determine the operating point of the pump, i.e., the flow of gas and the negative pressure required for gas drainage. The negative pressure characteristic curve of a 2BEC40 water-ring vacuum pump (at a rotation speed of 440 r/min), as tested at the manufacturer's Zibo factory, is shown in Fig. 3.

As shown in Fig. 4, as the parameter R' increases, the value of P increases and that of Q_0 decreases. This analysis shows that when P increases and Q_0 decreases, the value of Q_1 increases. The quantity of pressure-relieved gas drained can therefore be increased by increasing the borehole resistance.
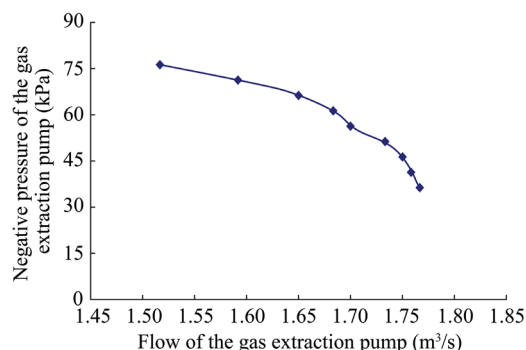

Fig. 2 Network of gas flow

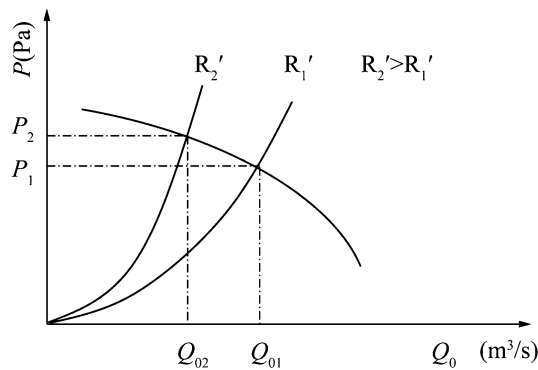Fig. 3 Negative pressure characteristic curve of a 2BEC40 water-ring vacuum pump

Fig. 4 Operational point of gas drainage pump

As shown in Fig. 2, sections bc and de are the gas flow paths in the protected layer and gob, respectively, and the values of the wind resistance R_{bc} and R_{de} do not change. Therefore, to increase the value of Q_1, we can only increase R_{ab} and R_{bd}.

When R_{ab} increases, the value of Q_1/Q_2 remains unchanged because there are no changes in R_{bc} and R_{de}, thus leaving the value of b unchanged. If the value of R_{bd} increases, then Q_2 decreases, which increases Q_1/Q_2, leading to an increase in b. Q_1 can be increased by increasing the value of b. Increasing R_{bd} is therefore a better method of improving drainage of pressure-relieved gas, compared with that achieved by increasing R_{ab}.

3.3 Increasing the resistance of the borehole bottom

Based on the above theoretical analysis, we can increase the wind resistance of the borehole bottom by throwing permeable materials (solid fragments, sandbags, etc.) into the borehole. The gas extraction conditions and the diameter of the borehole should first be used to determine the correct size and type of material to increase resistance. The prepared material is then thrown into the borehole. The stacked height of the material should be kept between 0.5 and 1 m. Finally, the pump extraction system is reconnected to continue extracting gas. If sandbags are used to increase the resistance, the use of large particle sizes of sand (diameter of 2–5 cm) is preferred.

4 Industrial application

4.1 Location of the test coal mine

One of the main mines of the Shenhua Group, the Wulan Coal Mine chiefly mines the No. 2, No. 3, No. 7, and No. 8 coal seams, and has a production capacity of 1.8 million tons per year. The No. 2 and No. 8 seams are coal and gas

outburst seams. A gas outburst accident has previously occurred in the No. 2 coal seam during mining. Because outburst problems could not be effectively solved, there was no other choice but to abandon mining from the first stage of the second level, thereby wasting a considerable high-quality coal resource. After abandoning mining of the No. 2 seam, mine production turned to the No. 3 coal seam. Excessive gas emissions, however, had a severe effect on production. To eliminate the outburst danger of the No. 2 coal seam and solve the gas emissions of the No. 3 coal seam, the traditional downward mining sequence was altered. Initially, the No. 7 coal seam was mined, which was the protective seam of the lower No. 8 coal seam. The No. 8 coal seam was then mined. The Nos. 2 and 3 coal seams were then doubly protected. Gas from the No. 2 and No. 3 coal seams was therefore extracted twice, eliminating the danger of coal and gas outbursts and substantially reducing the gas content of the seams. A surface borehole was simultaneously used to extract the gas from the protected layer and the gob. The structure of the surface boreholes is shown in Fig. 5.

4.2 Increasing the resistance of the borehole bottom

To demonstrate the effect of increasing the quantity of pressure-relieved gas that can be drained, the No. 8 surface borehole of the Wulan Coal Mine, which has adopted the method of increasing the borehole resistance, is cited as an example. In July 2009, the gas concentration drained from the borehole had reduced to about 20 %, so some sandbags were put into the borehole to increase its bottom resistance. To avoid too high a resistance, sand particles of about 2–3 mm were selected to make sandbags with a diameter
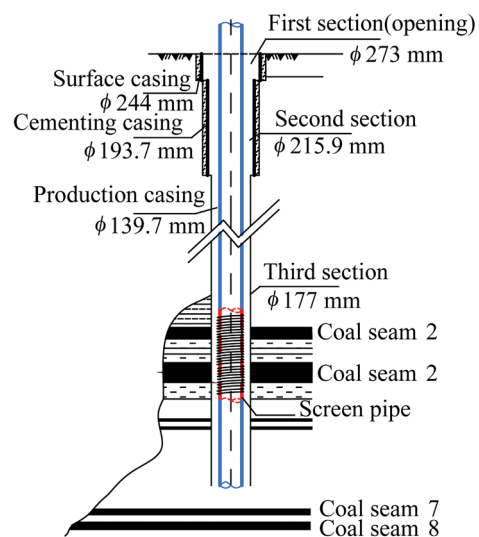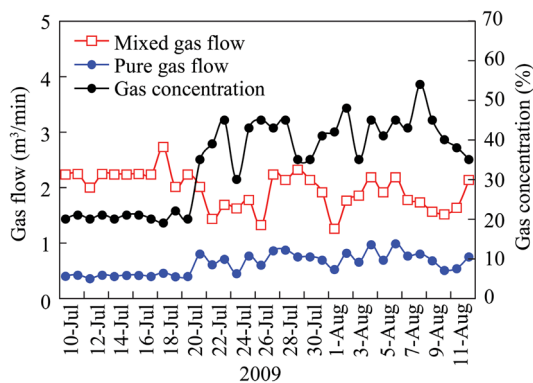

Fig. 5 Structure of surface borehole

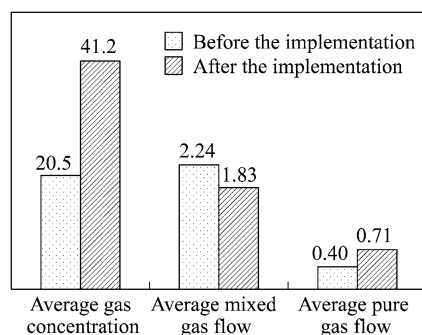**Fig. 6** Variation of gas drainage parameters with surface borehole

Fig. 7 Comparison of gas drainage parameters before and after implementing bottom resistance of the borehole

of about 5 cm. Thirty sandbags were thrown into the borehole. The variation and comparison of the gas drainage parameters before and after this implementation are shown in Figs. 6 and 7, respectively.

Analysis of Figs. 6 and 7 shows that the mixed gas flow fell slightly after implementing increased bottom resistance, but the pure gas flow and concentration increased by factors of 1.8 and 2.0, respectively. In addition, the pure gas extracted from the gob decreased because of the greater wind resistance of the borehole bottom, which increased removal of pressure-relieved gas from the protected layers. This method of increasing borehole resistance is therefore demonstrated to effectively increase the drainage of pressure-relieved gas.

5 Conclusions

(1)   Based on the theory of radial gas flow, a mathematical model for gas extraction from pressure-relieved coal seams with a surface borehole was established. This demonstrates that the quantity of pressure-relieved gas drained is related to the total flow of gas, its concentration, and the negative gas drainage pressure.

(2)   A flow network of gas drainage with a surface borehole was constructed, and the impact of changing the operating point of the gas extraction pump with the equivalent wind resistance of the borehole was studied. A method of increasing the resistance of the borehole bottom is proposed, which can increase the quantity of pressure-relieved gas drained from the protected layer.

(3)   The approach was subjected to industrial testing in the Wulan Coal Mine. The pure gas flow and concentration increased by factors of 1.8 and 2.0, respectively. These results show that increasing the resistance of the borehole bottom can significantly increase the quantity of pressure-relieved gas drained from a protective seam.

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