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Research on the negative pressure distribution law and its application for boreholes in coal seam bedding gas extraction

Linchao Dai [a,b,*], Kai Wang [a,b]

[a] State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing, China, 400037
[b] Chongqing Research Institute Co., Ltd. of China Coal Technology and Engineering Group, Chongqing, China, 400037

ABSTRACT

Making boreholes along seams is a part of the distribution process of gas extraction in coal mines, and a fundamental measure for preventing and controlling gas disasters as well as an important means to explore coal-bed methane resources. Recently, the borehole technology along the seam has been widely applied to gas extraction with the development of borehole rigs and kilometer-borehole rig. Presently, research by domestic scholars on the extraction theory mostly focuses on pre-extraction by boreholes through beds and shallow boreholes along the seam, with few considering the influence of viscous mechanics of gas flow in boreholes. Therefore, the research on the variation of negative pressure inside the borehole along the seam is greatly important to guide the design of boreholes along the seam for gas extraction, the determination of key parameters, and the theoretical application of the technology.

This paper focuses on the distribution of negative pressure inside the boreholes along the seam and its application, with two sections: (1) The distribution of negative pressure inside the borehole along the seam in the borehole direction. Based on gas occurrence, flow theory, fluid dynamics theory, and the definite mechanism of negative pressure inside the borehole along the seam on gas extraction, both gas flow models around boreholes and inside boreholes are established. Distribution of the negative pressure inside the borehole along the seam in the borehole direction was found by classifying the pressure loss inside boreholes and coupling the flow conservation equations of two models. The distribution of negative pressure inside the borehole was technically determined via field tests to verify the feasibility of the proposed models. (2) The application of the distribution of negative pressure inside the borehole along the seam in the borehole direction. Considering the shortages of traditional extraction processes, two new ones were put forward applying the distribution of negative pressure inside the borehole along the seam in the borehole direction, and the extraction pipe reaching a certain distance or covering the whole length. Technical processes such as theory analysis, field test, and numerical simulation verified the superiority of the new extraction processes.

This study found the variation of negative pressure inside the borehole along the seam in the borehole direction and the distribution of negative pressure inside the plume borehole along the seam, derived the calculating formula of reasonable borehole length, put forward new extraction processes, and verified the superiority of the new extraction processes in some conditions.

KEYWORDS: coal mine; bedding gas extraction; bedding borehole; inside-borehole negative pressure distribution law

1. INTRODUCTION

Gas extraction is fundamental for the prevention and control of gas disasters in coal mines, and also an important means to develop coalbed methane resources. Particularly, bedding boreholes is one of the important ways to distribute boreholes in gas extraction of the coal mines (Wang, et al., 2005; Wang, et al., 2006). In recent years, with the development of the drill and borehole rig as well as the emergence of 1,000m borehole machine, the bedding long boreholes gas extraction technology has been widely used. Hu (2011) carries out a theoretical analysis, field expedition, and numerical simulation process concerning seam long boreholes used for preventing coal and gas outburst using Pan-yi mine and Pan-san mine as the experimental cases. The purpose is to reduce construction volume, improve pumping rate, shorten the cycle of outburst, and achieve safe and fast driving. Xie, et al. (2013) selected Xin'an mine as a trial zone of the gas pre-extraction technology and studied the boreholes drilled along the mining seam and the rational parameter values of the gas pre-extraction technology for coal seam.

However, with the in creasing length of the borehole, the extraction effect is not necessarily

*Corresponding author – email : dailinchao@126.com

necessarily improved (Lin, et al., 1990; Xu, et al., 2010). With the increase of borehole length, the pressure drop generated from the gas flow along the borehole length direction should not be ignored. Extraction negative pressure will decay in the transfer process. The extraction negative pressure has significant influence on the extraction effect to the extent that the extraction effect is possibly not significant when reaching a certain length. At present, the domestic research on extraction theories applies to cross-layer borehole pre-extraction and bedding borehole shallow borehole extraction, without considering the mechanical impact of viscosity on the gas flow in the borehole (Xin, 1998; Li, 2012; Li, 2013). The changing law of negative pressure along the length of long coal seam boreholes is of great significance for the theoretical guidance of the bedding borehole gas extraction design, the determination of key parameters, and technology applications. Therefore, research on the distribution of negative pressure inside the borehole along the seam in the borehole direction and its applications were studied.

2. THEORETICAL ANALYSIS

Bedding boreholegas extraction can be divided into two processes: the first process is the gas flow in porous media like coal; the second process is gas flow inside the borehole.

The surrounding-borehole coal gas flow model and the inside-borehole gas flow model can be set up to characterize these two flow processes.

2.1 Surrounding-borehole gas flow model

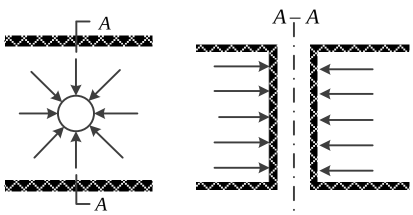


Figure 1: Radial flow in coal around the borehole.

From the Figure 1, the unit length of coal at the borehole length direction is analyzed with the conclusion that field of gas flow in the coal corresponds to a radial unsteady flow field. Gas flow speed, direction, and pressure at any point in the flow field change over time. The following equations can be derived based on porous media theory, coal seam gas adsorption theory, and thermodynamics (Zhou, et al., 1965; 1990; Yu, et al., 1989).

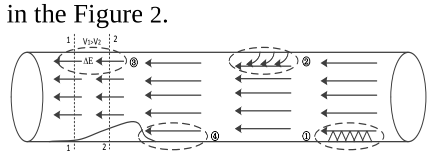
$$\begin{cases} div(\rho\vec{v}) = -\dfrac{\partial X}{\partial t} \\ \vec{v} = -\dfrac{K}{\mu}\cdot gradp \\ X = \dfrac{abcp}{(1+bp)}\cdot\rho + np \\ \rho = \dfrac{\rho_n}{p_n}\cdot p \end{cases} \tag{1}$$

(For concrete parameters refer to Sun, 1991; 1993; Wang, 2014). The solution to the solution-determination problem leads to the approximate analytical solution of the gas seepage model of unit length of coal, as is shown in formula (2).

$$q(t) = (R - r_0)\cdot(p_0^2 - p_1^2)\cdot\sqrt{\frac{\lambda\pi}{2p_n p_0 t}[n + \frac{abcp_0(2+bp_0)}{(1+bp_0)^2}]} \tag{2}$$

2.2 Inside-borehole gas flow mode

In the process of gas flowing to the orifice, the inside-borehole gas flow corresponds to variable mass flow due to the constant gas emission off from the borehole wall with the changing quality,. The inside-borehole gas flow will result in pressure loss, the four major factors being: on-way frictional resistance loss, acceleration pressure drop, mixing loss, and local resistance loss resulting from gas in-flow of the borehole wall (Ozkan, 1992; Yuan, et al., 1996; Zhou, et al., 1997; Schulkes, et al., 1997), as is shown in the Figure 2.



①On-way frictional resistance loss ②Mixing loss

③Acceleration pressure drop ④Local pressure loss

Figure 2: Classification of gas flow losses in the borehole.

In reality, due to the uncertainty of the borehole deformation, and to facilitate the theoretical analysis, it is presumed that the borehole wall is not deformed in the process of extraction; therefore, the local pressure loss is zero.

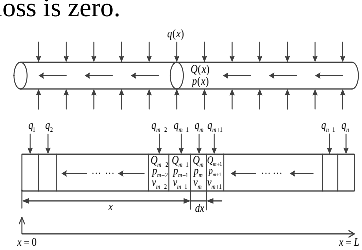


Figure 3: The differential schematic of coal seam borehole along the length direction.

It can be seen from Figure 3 that when the coal body that is around the borehole is dispersed into infinitesimal sections along the borehole length direction, each gas flow in an infinitesimal section can be represented by the previously built gas flow model around the borehole. Wall inflow mixing loss is not calculated separately. Instead, the on-way frictional resistance coefficient is modified, and the mixing loss is included in the on-way frictional loss. The on-way friction formula, continuity equation, and momentum equation can respectively infer on-way frictional resistance loss Δp_{fri} and the acceleration pressure drop Δp_{acc}. When x is the variable, the total pressure drop of dx infinitesimal section can be drawn (Ihara et al., 1994; Wu, 1999; Liu, et al., 2000).

$$\frac{dp(x)}{dx} = \Delta p_{fri} + \Delta p_{acc} = \frac{2 f_i \rho [2Q(x)+q(x)]^2}{\pi^2 D^5} + \frac{16\rho[q^2(x)+2Q(x)q(x)]}{\pi^2 D^4} \tag{3}$$

In formula (3), f_i is the frictional resistance coefficient of wall fluid when it flows into the borehole, and its size can be calculated through the borehole flow state in the infinitesimal section, that is, by calculating the Reynolds number (Re) of each infinitesimal section, determine the flow state of the fluids, and use the calculation formula of the frictional resistance coefficient f_0 when there is no wall fluids inflow to obtain the frictional coefficient. Concrete parameters can be found in Fan, et al. (2000) and Zhang (2009).

2.3 Modal coupling

According to the theory of fluid dynamics, the gas flow of the infinitesimal section x from the orifice is in line with the flow conservation equation (Ben, 1990; Liu, et al., 2006), as is shown in formula (4).

$$\frac{d[Q(x)]}{dx} = -q(x) \tag{4}$$

The gas flow model of surrounding-borehole coal and inside-borehole gas flow model can be coupled through the following inside-borehole flow conservation equation (5).

$$\begin{cases} q(x,t) = (R-r_0)\cdot(p_0^2 - p_1^2)\cdot\sqrt{\dfrac{\lambda\pi}{2p_n p_0 t}\left[n + \dfrac{abcp_0(2+bp_0)}{(1+bp_0)^2}\right]} \\ \dfrac{dp(x)}{dx} = \dfrac{2 f_i \rho[2Q(x,t)+q(x,t)]^2}{\pi^2 D^5} + \dfrac{16\rho[q^2(x,t)+2Q(x,t)q(x,t)]}{\pi^2 D^4} \\ \dfrac{d[Q(x,t)]}{dx} = -q(x,t) \end{cases}$$

Through boundary condition:

$$\begin{cases} x=0, & p(0)=p_1 \\ x=0, & Q(0,t)=Q \end{cases}$$

The inside-borehole negative pressure distribution formula of bedding borehole can be obtained from the definite-solution problem (5). However, the analytical solution to second order nonlinear partial differential equations is very complex; generally, the parameter substitution process can greatly simplify the solving process.

The Chongqing Songzao Yuyang coal mine was selected for the field test in this study. When using the industrial parameters of Yuyang No. 7 coal seam into the formula (5), it can be found that: when the orifice negative pressure is 7 KPa, the borehole pressure loss in the 100 meters process is 466.7 Pa.

3. FIELD MEASUREMENT

The borehole that is 100m deep in the N3702 transportation lane of Yuyang Coal Mine uses copper pipe as its connecting pipe. Combined with the full-hole-section downing sieve pipe process, hollow copper pipes with different lengths are sent into the borehole to determine different negative pressure values at varying depths. The negative pressure field test process diagram is shown in Figure 4.

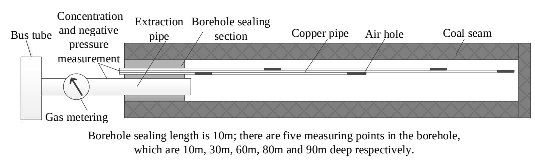


Figure 4: Field test process for measuring the negative pressure within the borehole.

In the 90 day extraction inspection period, three sets of representative data at three time points are selected for analysis. The negative pressure values at different depths inside the borehole with extraction times of 10 days, 40 days, and 80 days are measured and recorded, as is shown in Figure 5.

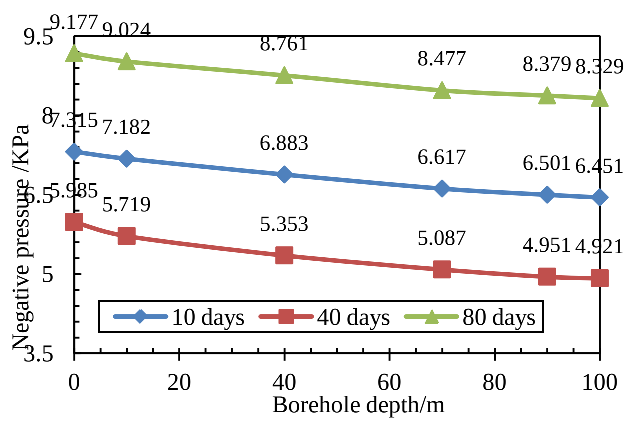


Figure 5: Negative pressure distribution in borehole in different extraction time.

From Figure 5, the curve of negative pressure distribution of different depths inside the borehole at different time shows that the inside-hole negative pressure of bedding gas extraction decays along the borehole length direction. The 100 m attenuation in the extracted borehole is about 800 Pa in the field measurement. However, the theoretical calculation does not consider factors such as the occupied area of copper pipe, borehole leakage, and borehole deformation, which will increase pressure loss. The built theoretical model is feasible and in accord with the requirements of engineering practice.

4. APPLIED RESEARCH

The traditional extraction process has many shortcomings, as shown in the negative pressure distribution law in the bedding borehole of Figure 6. (1) With longer boreholes, borehole pressure loss is more serious and the extraction effect is more and more poor along the borehole length direction. (2) The maximum negative pressure at the orifice and the formation of the differential pressure on both ends of the borehole sealing section are very big, therefore, it is easy to cause leakage that leads to low extraction concentration and a poor extraction effect. (3) Coal quality in many of China's coal mines is soft and easy to deform after forming the borehole. This increases the frictional resistance coefficient of the coal wall and causes negative pressure attenuation if the borehole collapse blocks the negative pressure in the direction of the borehole's bottom due to borehole scraps.

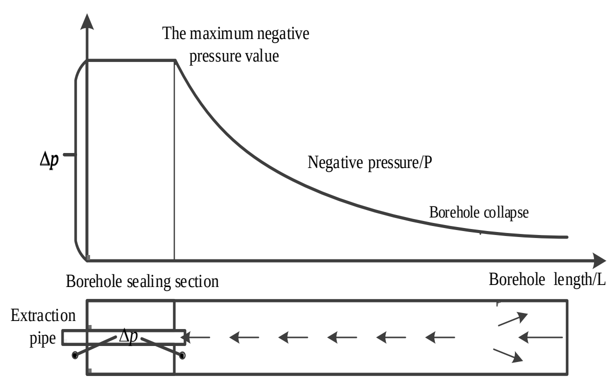


Figure 6: The traditional extraction process.

Two new extraction processes in view of the hard and soft coal quality were put forward to address the deficiency of traditional extraction processes, combined with borehole forming conditions and negative pressure distribution in the borehole.

(1) Hard coal - extending extraction pipe

As shown in Figure 7, compared with the traditional extraction process and under the same borehole length, extending the extraction pipe places the maximum negative pressure in the middle of the borehole. The distance of the maximum negative pressure on both sides in the borehole is shorter, reducing negative pressure loss and increasing the negative pressure of the whole borehole section. At the same time, because of the frictional resistance loss, the differential pressure on both ends of the borehole sealing section will be reduced and the leak situation will be improved compared to the traditional extraction process.

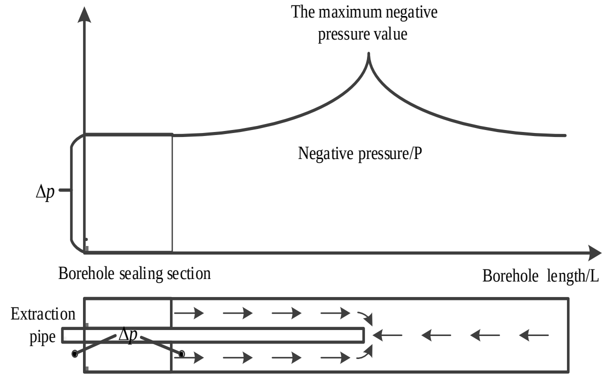


Figure 7: Extending extraction pipe process.

(2) Soft coal - using sieve pipe

As shown in Figure 8, the friction factor of the sieve pipe is much smaller than the coal wall (commonly used industrial piping equivalent roughness). New polyethylene pipe K_s (the stability against sliding coefficient) is 0 - 0.002, concrete pipe K_s is 0.3 - 3.0), reducing the negative pressure losses from orifice to bottom. At the same time, it can keep the gas flow channel clear when borehole collapse occurs, improving the extraction effect and raising the utilization rate of the borehole.

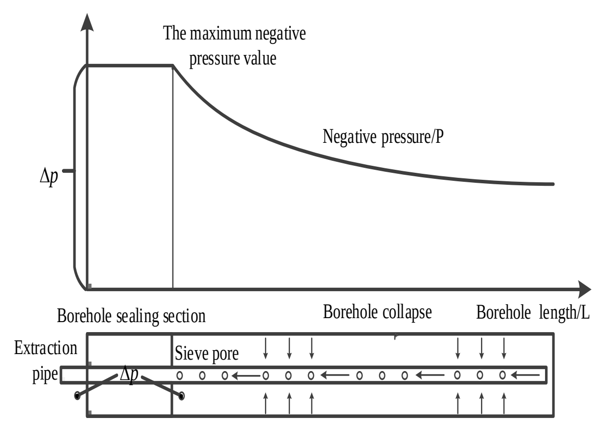


Figure 8: Using sieve pipe to replace extraction pipe.

In order to verify the superiority of the new extraction process, a field test was carried out in N3702 working face. Traditional extraction process were used for the No. 1 borehole, extending extraction pipe process was used for the No. 2 borehole, and the sieve pipe process was used for the No. 3 borehole, as shown in Figure 9.

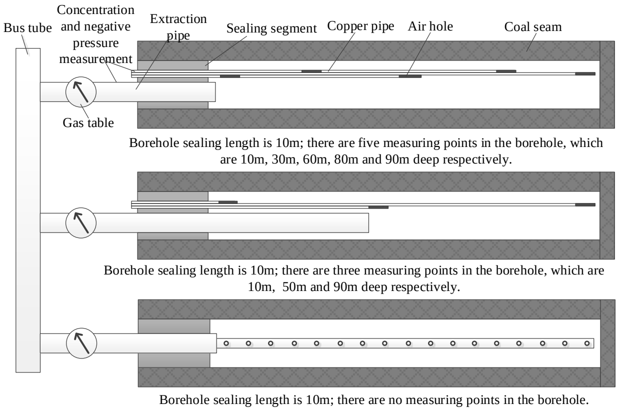
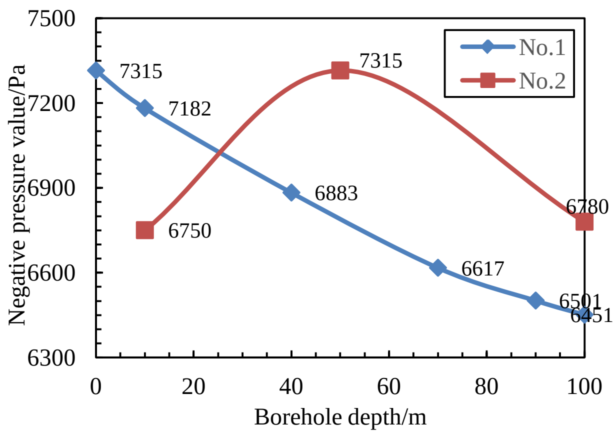
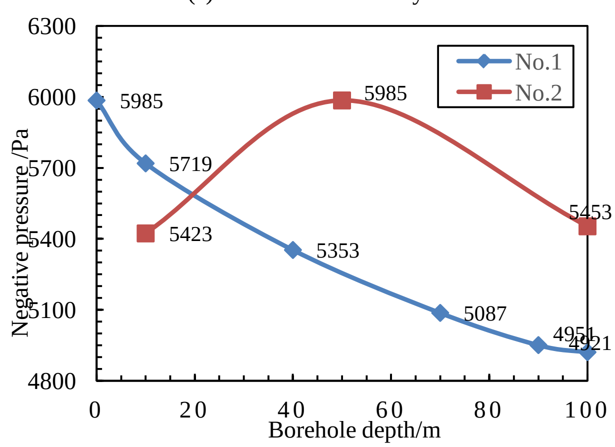


Figure 9: The compared field test of extraction effect under different extraction processes.

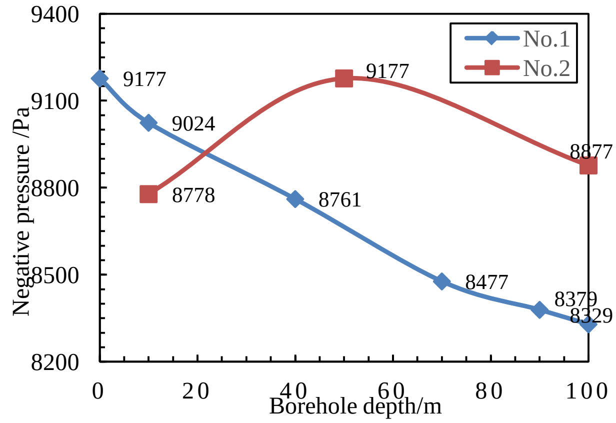
,The negative pressure distribution in the borehole of the traditional extraction process and the extending extraction pipe process were compared and studied under conditions of the same borehole sealing quality. The inspection period of extraction time was 90 days. The negative pressure values of different depths in the borehole were determined and analyzed by field measurement under the three representative stages in extraction time for 10 days, 40 days, and 80 days, as shown in Figure 10(a), (b), and (c).



(a) Extraction for 10 days



(b) Extraction for 40 days



(c) Extraction for 80 days

Figure 10: Negative pressure distribution of No. 1 and 2 borehole.

From Figure 10 (a), (b), and (c), negative pressure in the borehole presents an attenuating trend distribution along the borehole under conditions of the traditional extraction process, and negative pressure in the borehole presents a "mountain" trend distribution along the borehole under conditions of the extending extraction pipe process. The area covered by the curve in the figure shows that the average negative pressure value and full negative pressure energy of the extending extraction pipe process are bigger than for the traditional extraction process. Using the sieve pipe process in the full borehole section can not set pressure measuring points, therefore the experiment of negative pressure determination in the borehole was not carried out.

The two extraction effects (extraction concentration and flow) were taken for indexes, and compared under the different extraction processes in order to verify the superiority of the new extraction process.

The extraction concentration investigation for borehole No. 1, 2, and 3 are shown in Table 1.

Table1: Extraction concentration of borehole No.1, 2, 3.

Extraction time(d)	Extraction concentration (%)		
	No.1	No.2	No.3
0	93%	89%	90%
3	66%	95%	95%
11	89%	95%	95%
27	89%	85%	95%
37	30%	50%	90%
50	30%	50%	90%
58	30%	50%	30%
64	30%	93%	30%
78	70%	90%	80%
86	66%	80%	83%
93	65%	85%	85%

Within 90 days of extraction time, extraction effect: No.2 borehole > No.3 borehole> No.1 borehole. Under the same borehole sealing quality, the extending extraction pipe process is superior to the sieve pipe process, and the extraction effect of the traditional extraction process is the worst.

The cumulative mixed flow and the accumulative gas flow trend figures of boreholes No. 1, 2, and 3 found by field measurement are shown in Figures 11 and 12.

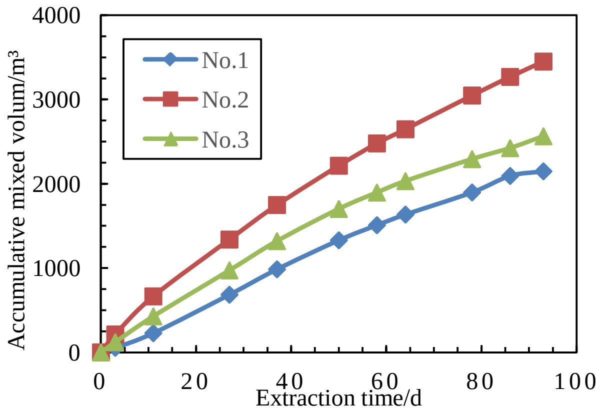


Figure 11: No. 1, 2, 3 borehole accumulative mixed flow trends.

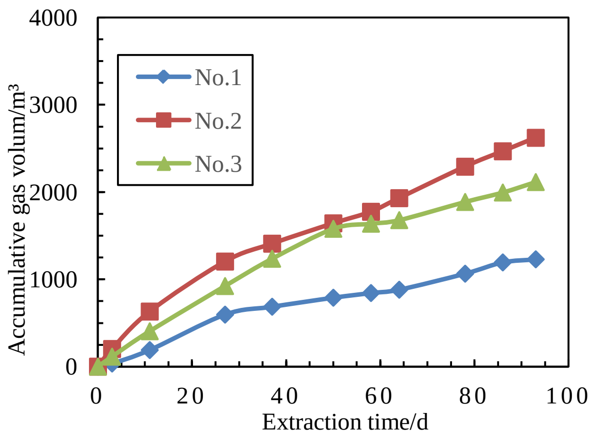


Figure 12: No. 1, 2, 3 borehole accumulative gas flow trends.

From Figures 11 and 12, the accumulative mixed flow and accumulative mixed gas flow of three boreholes show a rising trend with the increase of extraction time. The borehole extraction effect is such that No. 2 > No. 3 > No. 1. Under the same borehole sealing quality, the extending extraction pipe process is superior to the sieve pipe process, and the extraction effect of the traditional extraction process is the worst.

According to the above, it can be obtained that the extraction effect of No. 1 borehole using the traditional extraction process is the worst. Meanwhile the two indexes are the lowest and the borehole is likely to leak. Negative pressure loss is the most serious, therefore it should be improved. The concentration and flow rate for the No. 2 borehole using the extending extraction pipe process are better than that of No. 1 and 3 borehole. Implementation is simple in the field, and is worth promoting. The extension concentration and flow rate for No. 3 using the sieve pipe process are better than No. 1 borehole and smaller than No. 2 borehole. The reason is that the small sieve pore on the pipe restrains the gas flow into the pipe. When the borehole undeforms, the advantage of using the sieve pipe process is not obvious. However, using the sieve pipe process in soft coal seams has a better effect.

5. CONCLUSION

(1) The gas flow model in the coal body around the borehole and the calculation model of gas flow in the borehole were established. The pressure distribution calculation model in the bedding gas extraction borehole was found, and a field test calculation was carried out to verify the feasibility of the built model.

(2) The field test process was applied to determine the different depth points of negative pressure values in bedding gas extraction boreholes. The negative pressure distribution law along the long boreholes was summarized, Results showed that the negative pressure presents an attenuation trend distribution along the long borehole direction in the bedding gas extraction boreholes.

(3) In order to address the shortcomings of the traditional extraction process, two new extraction processes were put forward, namely the extending extraction pipe process and the sieve pipe process.

(4) Through the extraction effect contrast test under different extraction processes, the extraction effect of the new extraction process was found to be better than the traditional extraction process. In coal seams with good borehole forming conditions, it is optimal to use the extending extraction pipe process. In coal seams with bad borehole forming conditions, using the sieve pipe process is optimal.

6. ACKNOWLEDGEMENT

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