

# Research on the Negative Pressure Distribution Law and Application within In-seam Borehole

Bing Li<sup>1, 2</sup>

<sup>1</sup>China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400039, China

<sup>2</sup>State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400039, China

## Abstract

In order to thoroughly explore the variation law of negative pressure along the length of in-seam boreholes, a negative pressure distribution formula within in-seam boreholes was derived through coupling a gas flow model in the coal mass surrounding the borehole and a gas flow model inside the borehole. Field tests were conducted to measure the negative pressure values at different depths within the boreholes, thereby obtaining the negative pressure distribution law and verifying the feasibility of the theoretical model. By applying the negative pressure distribution law, a novel gas extraction technology that alters the negative pressure distribution within the boreholes was proposed, and its superiority under certain applicable conditions was validated, providing references and guidance for the design of in-seam gas extraction.

## Keywords

In-seam gas extraction; in-seam borehole; negative pressure distribution law within boreholes; novel gas extraction technology.

## 1. Introduction

Gas extraction, as a core strategy for coal mine safety management and coalbed methane (CBM) resource development, serves not only as a fundamental measure to prevent coal mine gas disasters but also as a key approach for the efficient exploitation of CBM resources [1-2]. Within the coal mine gas control system, in-seam boreholes, due to their unique drilling layout, hold a significant position in the field of gas extraction [3-4]. With the rapid development of drilling technology, particularly the notable improvement in the performance of drilling rigs and tools, as well as the widespread application of kilometer-long drilling rigs, the technology of extracting gas through long in-seam boreholes has become the mainstream trend in coal mine gas control [5-8]. However, an undeniable phenomenon is that an increase in borehole length does not necessarily lead to a linear improvement in extraction efficiency. On the contrary, due to the significant pressure drop as gas flows along the length of the borehole, an inevitable attenuation of the extraction negative pressure occurs during its transmission, thereby affecting the overall extraction efficiency.

Currently, domestic scholars' research on gas extraction theories mostly focuses on scenarios of pre-drainage through cross-seam boreholes and shallow pre-drainage through in-seam boreholes, while lacking in-depth exploration of the viscous mechanical effects during the complex gas flow process within boreholes [9-11]. This limitation in theoretical research has, to a certain extent, restricted the further optimization and application of in-seam borehole extraction technology. Therefore, conducting in-depth research on the variation law of negative pressure along the length of in-seam boreholes not only helps to reveal the internal mechanisms of gas flow within boreholes but also provides a solid theoretical foundation for

the design optimization of in-seam borehole gas extraction, the scientific determination of key parameters, and the innovative application of the technology, which is of inestimable value for advancing coal mine gas control technology.

## 2. Theoretical Analysis of Negative Pressure Distribution Law of Long Coal Seam Hole

Bedding drilling gas extraction involves two distinct processes: the first pertains to gas flow within porous media, such as coal, while the second involves gas flow within the borehole itself. Under specific conditions, when analyzing a unit length of coal along the borehole's length direction, it is concluded that the gas flow field within the coal adheres to a radial unsteady flow pattern. By leveraging porous media theory, coal seam gas adsorption theory, and thermodynamics, the following equations can be derived:

$$\begin{cases} \text{div}(\rho\vec{v}) = -\frac{\partial X}{\partial t} \\ \vec{v} = -\frac{K}{\mu} \cdot \text{grad}p \\ X = \frac{abc p}{(1+bp)} \cdot \rho + np \\ \rho = \frac{p_n}{p_n} \cdot p \end{cases} \quad (1)$$

The four equations of Formula (1) are: gas flow continuity equation, gas motion equation, coal seam gas content equation, and gas state equation. Solution to the solution-determination formula (1) leads to the approximate analytical solution of the gas seepage model of unit length of coal, as is shown in Type (2):

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

In the process of gas flowing to the orifice, due to the constant gas emission off from the hole wall with changing quality, the inside-borehole gas flow belongs to variable mass flow. The inside-borehole gas flow will result in pressure loss, the major factors being the four aspects: on-way frictional resistance loss, acceleration pressure drop, mixing loss and local resistance loss resulted from gas in-flow of the hole wall, as is shown in Fig.1.

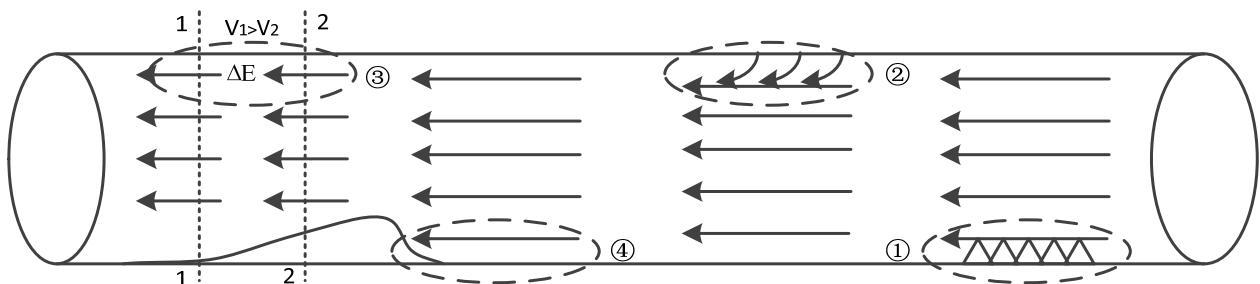
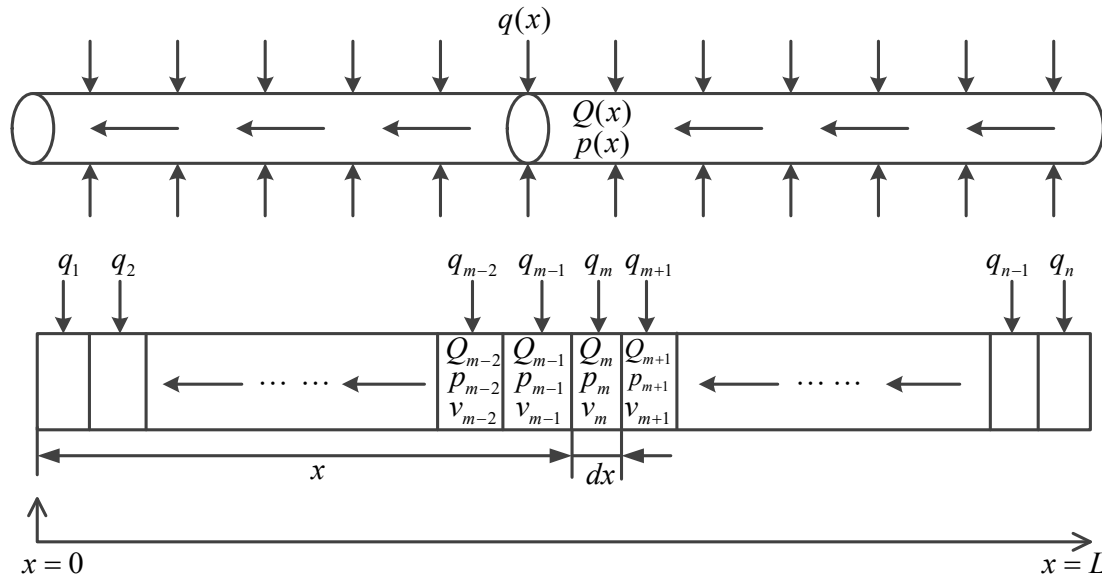


Figure 1. Classification of gas flow losses in the borehole

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



**Figure 2.** The differential schematic of coal seam borehole along the length direction

As is shown in Fig.2, disperse the coal body that is around the drilling hole 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 will not be calculated separately, instead, the on-way frictional resistance coefficient will be modified, and the mixing loss will be included in on-way frictional loss. The on-way friction formula, continuity equation and momentum equation can respectively infer on-way frictional resistance loss  $\Delta p_{fri}$  and the acceleration pressure drop  $\Delta p_{acc}$ . Make  $x$  the variable, the total pressure drop of  $dx$  infinitesimal section can be drawn:

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

Where,  $f_i$  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.

As is shown in Fig.2: 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, 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 inside-borehole flow conservation equation:

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

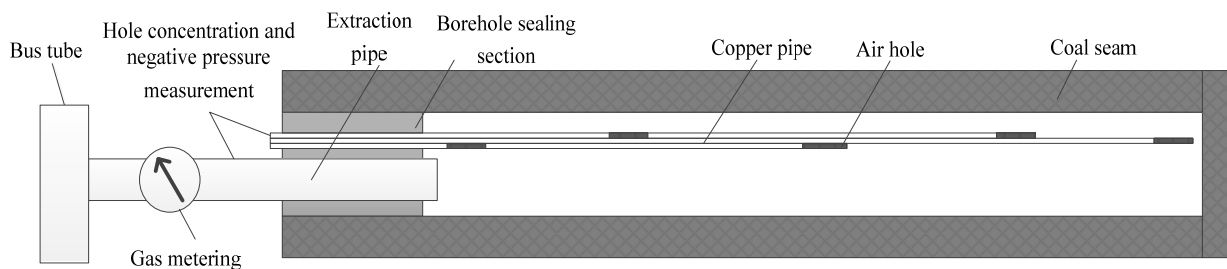
Through boundary condition:

$$x = 0, \quad p(0) = p_1, \quad x = 0, \quad Q(0,t) = Q.$$

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

### 3. Bedding Gas Extraction Borehole Negative Pressure Measurement Field Test

The borehole that is 100m deep in the N3702 transportation lane of Yuyang Coal Mine in Songzao city makes copper tube its connecting tube; combined with full-hole-section downing sieve tube process, hollow copper pipes with different lengths are sent into the borehole to determine different negative pressure values of different depths. The sealing-hole length is 10m, and the five measuring points are 10m, 40m, 70m, 90m and 100m respectively. The negative pressure field test method diagram is shown in Fig.3.



□ Borehole sealing length is 10m; there are five measuring points in the borehole, which are 10m, 30m, 60m, 80m and 90m deep respectively. □

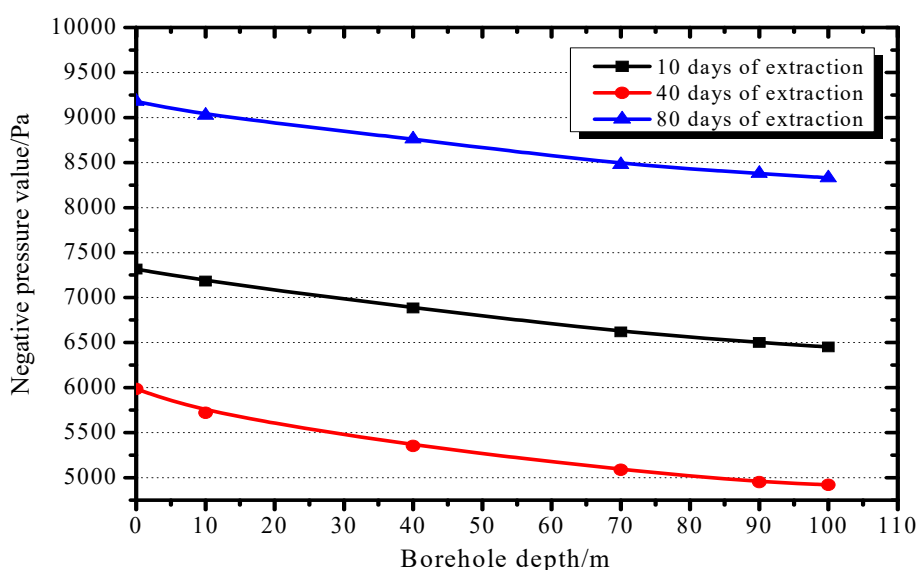
**Figure 3.** Field test method for measuring the negative pressure within the borehole

In 90 days of extraction inspection period, select three sets of representative data at three time points to analyze, that is, measure and record negative pressure values of different depths inside the borehole with extraction time of 10 days, 40 days, and 80 days respectively, as is shown in Table 1. As the extraction system of Yuyang Coal Mine is often regulated in terms of pressure, the orifice negative pressures in different time are different.

**Table 1.** Negative pressure values borehole in three drainage periods in table

Depth	Extraction time		
	10 days	40 days	80 days
0m	7315	5985	9177
10m	7182	5719	9024
40m	6883	5353	8761
70m	6617	5087	8477
90m	6501	4951	8379
100m	6451	4921	8329
Entire pressure loss	864	1064	848
100m pressure loss	960	1182	942
Pressure difference on both ends of the hole sealing section	133	266	153

There is serious leakage in the borehole when the extraction has continued 40 days, the pressure difference at the sealing-hole section has been doubled, and it returns to normal state after artificial processing. Negative pressure values of different depths at different extraction time are shown in Fig.4. From the Fig.4, The curve of negative pressure distribution of different depths inside the borehole and the whole-borehole-section pressure loss at different time shows that: inside-hole negative pressure of bedding gas extraction decays long the borehole length direction. With the extension of extraction time, the inside-borehole negative pressure attenuation change is not big. Borehole sealing quality has an impact on the negative pressure distribution, and the hole sealing quality will be decreased with the extension of extraction time. And bring the industrial parameters of No.7 coal seam of Yuyang Coal Mine into the definite-solution problem, it can be drawn that: when the orifice negative pressure is 7KPa, the entire pressure loss is 466.7Pa, while the 100m attenuation in the extracted borehole is about 800 Pa in the field measurement. However, the theoretical calculation has not considered such factors as the occupied area of copper tube, hole leakage, borehole deformation which will increase pressure loss.



**Figure 4.** Negative pressure distribution in borehole in different drainage time

## 4. Conclusion

(1) Based on the theories of coal seam gas occurrence and flow, as well as fluid dynamics, this study systematically constructed a refined model for gas flow within the coal mass surrounding the borehole and a computational model for gas flow characteristics inside the borehole. Through in-depth theoretical derivations and coupled analyses, an accurate formula for the negative pressure distribution within in-seam gas extraction boreholes was successfully derived, providing a scientific basis for understanding the gas flow behavior inside the boreholes.

(2) This study employed field testing methods to accurately measure the negative pressure values at different depth points within in-seam gas extraction boreholes. Through detailed analysis of a large amount of experimental data, the dynamic distribution law of negative pressure along the borehole length was revealed. Furthermore, computational validations using field examples demonstrated a high degree of agreement between the established theoretical model and engineering practices, fully proving its feasibility and effectiveness in practical applications. This provides strong theoretical support and practical guidance for the optimization and application of in-seam gas extraction technology.

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