Change Characteristics of Negative Drainage Pressure along the Drill Hole: Theoretical Analyses and Field Tests

Jun Liu, Zhikuan Liu, Yanzhao Wei,* and Xiangjun Chen

ABSTRACT: A proper understanding of the change characteristics of negative drainage pressure along a drilling hole is essential since gas drainage parameters are the key parameters that influence the efficiency of gas drainage. In this study, based on the coupling of gas seepage from coal seams and the gas flow along the drilling hole, a theoretical model was established to calculate the gas pressure change law along the drilling hole with different influencing factors. Subsequently, a multibranch method was applied to test the negative pressure at different drilling holes. Finally, a field test was conducted in the Jiulishan coal mine to analyze the changed characteristics of the negative drainage pressure along the drilling hole. The results show that at a constant negative drainage pressure in the borehole, the negative pressure gradually decreased with increasing depth. With an increase in negative drainage pressure at the borehole, the negative pressure loss for every 100 m substantially increased. The gas flux had the most obvious influence on the negative pressure in the drilling hole, and the pressure loss rapidly increased with increasing gas flux. When the diameter of the borehole was small, the negative pressure loss was significant; when the drilling hole was deep, the negative pressure decreased more significantly. This study has important theoretical and practical significance for improving the gas drainage effect.

1. INTRODUCTION

Continuous fluid inflow along the pipe network causes changes in the dynamic and laminar boundary, and this state inside the pipe is a variable mass flow. The pressure and flow caused by a variable mass flow have been of interest in oil exploitation. Dikken1 and Doan2 investigated the severity of the pressure reduction in the process of a variable mass flow. Su3–5 found that the pressure drop of a variable mass flow primarily consists of four parts: friction pressure drop of the tube wall, acceleration, hole roughness, and mixed pressure drop. Schukles,6 Yuan,6 and Zhou7 revealed that the pressure drop is related to the hole diameter, hole density, velocity, and angle of injection and obtained empirical formulas for the mixed pressure drop. Qu,8 Le,9 Shi,10 and Li11 studied two-phase transition mass flow and established a pressure drop model for multibranch wells.

Only a few studies have focused on the variable mass flow in coal mining and gas drainage. When the depth of the extraction borehole increases, the gas flow in a borehole becomes a variable mass flow due to the influence of the resistance along the hole wall and gushing gas, and the negative pressure of the borehole gradually decreases along the direction of the borehole depth until the negative pressure disappears or the bottom hole pressure becomes positive. This phenomenon causes the desorption, diffusion, and seepage of coal gas along the depth of the hole under different pressures; it also results in the zoned drainage effect phenomenon (Wang,12 Lin13), which is one of the main problems that restricts the exploration of the gas flow regularity in coal seams and extraction boreholes. Mastering the dynamic change characteristics of negative pressure along the hole length and determining reasonable gas extraction parameters have been an unmet challenge (Wang,14 Duan15). Qin16 believed that the distribution of the negative pressure in an extraction borehole corresponds to a logarithmic relationship. Wang17 studied the negative pressure distribution in bedding boreholes under three types of borehole wall gas inflows and obtained the limit length of the bedding boreholes through numerical calculations. Li18 established a coal-body borehole gas flow model, analyzed the negative pressure distribution in a long borehole along with the bedding, verified the model in-field practice, obtained the negative pressure distribution in a borehole formula, and expanded the negative pressure distribution formula in the central and branch holes of a long feather-shaped borehole.

In recent years, with the rapid development of drilling rigs and drilling tools to construct underground coal mines, long gas drainage boreholes along beddings have been widely used...
A longer borehole length has a better gas drainage effect. When the length of the borehole increases, the pressure drop caused by the gas flow along the length cannot be ignored. The negative pressure of the drainage is transmitted along the borehole. There is attenuation in the drainage process, and the negative pressure of drainage has an important impact on the drainage effect. Bai calculated negative pressure values in boreholes under creep conditions. A simulation study showed that the negative borehole pressure was approximately linearly distributed along the length of the borehole. A higher negative pressure corresponds to greater borehole resistance loss along the length cannot be ignored. The negative pressure of the drainage is transmitted along the length of borehole holes. Song analyzed the influence of the negative pressure of the orifice, gas flow, and other parameters on the negative pressure distribution in the borehole. The length gradually decreased. Liu measured the borehole negative pressure loss on-site with numerical analysis and found that the negative borehole pressure was distributed in a parabolic shape along the hole length, and the negative pressure loss in the gas drainage borehole had a negligible effect. Zhang discovered that the negative drainage pressure was approximately linearly distributed along the length of the hole, and the negative pressure loss was relatively small. The negative pressure at different parts of the borehole was closed, and the drainage flow of the borehole was roughly linearly distributed along the length of the borehole. A higher orifice negative pressure corresponds to greater borehole drainage flow and borehole negative pressure loss. Wang established a coal-seam gas diffusion—seepage model and obtained a formula to calculate the resistance loss along each borehole section. COMSOL Multiphysics finite element analysis software was used to numerically simulate the factors that affect the negative pressure attenuation in the drainage boreholes.

In this study, based on the coupling of gas seepage from coal seams and gas flow along the drill hole, a theoretical model was established to calculate the gas pressure change law along the drilling hole with different influencing factors. Subsequently, a multibranch method was applied to test the negative pressure of different drilling holes. Finally, a field test was conducted in the Juilishan coal mine to analyze the change characteristics of the negative drainage pressure along the drill hole.

2. THEORETICAL ANALYSIS

2.1. Radial Gas Flow Model of Coal. Assuming that the borehole length is L and the diameter is D, the thickness of r → r + dr from the center of the borehole and per unit length of the coal seam along the length of the borehole were used as control bodies. The gas mass entering the control body at time dt is ρvdr · 2πr, and the outflow at time dt is ρvdr · 2πr.

According to the principle of mass conservation, the net gas outflow mass in a body controlled by time dt must be equal to the mass of the gas reduction in the controlled body (Zhou) and is described as

\[ \int (\rho v + \frac{\partial (\rho v)}{\partial r}) dr dt \cdot 2\pi r - \rho v dr \cdot 2\pi r dt = -\frac{dM}{dt} \cdot 2\pi r dr dt \]

Equation 1 can be simplified as

\[ \frac{\partial (\rho v)}{\partial r} = -\frac{dM}{dt} \]

where ρ is the coal gas density (kg/m³), V is the coal gas seepage velocity (Pa s), and M is the unit coal gas quality (kg), which can be calculated using the Langmuir formula as

\[ v = \frac{K \rho}{\mu} \]

2.2. Negative Pressure Changes along the Hole Length. Let the number of holes of different aperture types per unit area be n₁ large pores (pore volume V₁, diameter d₁), n₂ medium pores (pore volume V₂, diameter d₂), n₃ small pores (pore volume V₃, diameter d₃), and n₄ micro pores (pore capacity V₄, diameter d₄), and the density of coal is ρ_c. Assuming that the mass of coal per unit area with thickness dr is 1 g and the pores with different diameters penetrate through a slightly thick dr, then

\[ dl = 1 \times 10^{-3} \rho_c \]

\[ \frac{\pi d^2}{4} n_i dl = v_i \]

The gas seepage at the hole bottom is ignored, and the total amount of gas seepage through the sidewall to the interior of the borehole is Q as shown in Figure 1.

\[ Q = \int_0^L v_i n_i A_i dX dx \]
According to Fang, \(^{(27)}\) when the gas flows from a hole to the borehole, energy loss \(h_j\) of the outflow gas through a single hole is
\[
h_j = \frac{v^2}{2g}
\]
(10)
Gas flow \(Q_x\) at hole \(x\) is
\[
Q_x = \int_0^x n A_x \sqrt{\pi} \frac{D}{Dx} dx
\]
(11)
Gas flow velocity \(u_x\) at hole \(x\) is
\[
u_x = \frac{4Q_x}{\pi D^2}
\]
(12)
Gas seepage flow \(q_{x \rightarrow L}\) from section \(x\) to \(L\) is
\[
q_{x \rightarrow L} = \int_x^L v_n A_x \sqrt{\pi} \frac{D}{Dx} dx
\]
(13)

The control unit of the gas flow and wall gas seepage in the borehole can be arbitrarily selected, as shown in Figure 2. The

![Figure 2. Control body of gas flow and gas seepage.](image)

suction port is Section 1, borehole \(x\) is Section 2, and the \(x \rightarrow L\) gas seepage is Section 2’. According to the fluid energy and Bernoulli equations, the gas seepage field equation can be expressed as
\[
z_2 + \frac{p_2}{\rho_g} + \frac{u_x^2}{2g} = z_1 + \frac{p_1}{\rho_g} + \frac{u_1^2}{2g} + h_{w2-1}
\]
(14)
\[
z_2' + \frac{p_2'}{\rho_g} + \frac{v_2^2}{2g} = z_1' + \frac{p_1'}{\rho_g} + \frac{u_1^2}{2g} + h_{w2'-1}
\]
(15)
where \(z_1, z_2,\) and \(z_1', z_2'\) are the heights of control body Sections 1, 2, and 2’, respectively; \(u_1, u_2\) and \(v_1, v_2\) are the controlled gas drainage speeds at Cross-section 1, gas flow velocity at Cross-section 2, and gas seepage velocity at Cross-section 2’, respectively; \(h_{w2-1}\) is the energy loss from Cross-section 2 to Cross-section 1; \(h_{w2'-1}\) is the energy loss from Cross-section 2’ to Cross-section 1; and \(\rho_g\) is the gas density in the borehole.

Equations 14 and 15 were multiplied by \(\rho_g Q_x\) and \(\rho_g Q_{x'}\) respectively, and the products were added to obtain the total energy equation as
\[
\rho_g Q_x \left( z_2 + \frac{p_2}{\rho_g} + \frac{u_x^2}{2g} \right) + \rho_g Q_{x'} \left( z_2' + \frac{p_2'}{\rho_g} + \frac{v_2^2}{2g} \right) = \rho_g Q_x \left( z_1 + \frac{p_1}{\rho_g} + \frac{u_1^2}{2g} \right) + \rho_g Q_{x'} \left( z_1' + \frac{p_1'}{\rho_g} + \frac{u_1^2}{2g} \right) + \rho_g Q_{x} h_{w2-1} + \rho_g Q_{x'} h_{w2'-1}
\]
(16)

According to the hydrodynamic energy equation, the heights \(z_1, z_2,\) and \(z_1', z_2'\) at this location can be ignored, the distance from Section 2’ to the borehole was small, and it can be assumed that the pressure in Section 2’ was approximately equal to that in the borehole. Therefore, at any position in borehole \(x\), the gas pressure is
\[
\frac{q_{x} + Q_{x'}}{\rho_g} = Q_x \left( \frac{p_1}{\rho_g} + \frac{u_1^2}{2g} \right) + Q_{x'} h_{w2-1} + q_{x} h_{w2'-1} - Q_x \frac{u_x^2}{2g} - q_{x'} \frac{v_2^2}{2g}
\]
(17)

3. PORE CHARACTERISTICS OF COAL

Low-pressure nitrogen gas adsorption and mercury intrusion porosimetry have a high measurement speed, low sample requirement, and low cost and are currently the most extensively used methods to characterize coal pore structures. Common pore classification schemes are listed in Table 1.

An ASAP 2020 automatic rapid specific surface area, a micropore analyzer, and an AUTOPORE9505 mercury intrusion analyzer were used to examine three types of coal samples (damaged, strongly damaged, and crushed coal) from the Jiliushan coal mine in Jiaozuo. The pore structure parameters of the coal are listed in Table 2. According to the pore structure parameters of different coals, using eqs 7 and 8,

| serial number | classified scheme and year | division of pores (diameter, nm) |
|---------------|---------------------------|---------------------------------|
| division of pores | | fractures | macropores | mesopores | transitional holes | micropores | supermicropores |
| 1 | Hodot (1961) | | 1000 | 1000–100 | 100–10 | | 10 |
| 2 | Dubinin (1966) | | 100 | 100-100 | 10–100 | | 2 |
| 3 | IUPAC (1966) | | 500 | 50–500 | 5–50 | | 5 |
| 4 | Gan (1972) | | 1000 | 50–750 | 10–50 | | 10 |
| 5 | Fushun Coal Research Institute (1985) | | 100 | 10–100 | 1–1.5 | | 1 |
| 6 | Jiaozuo Institute of Mining (1990) | | 1000 | 100–100 | 10–200 | | 200 |
| 7 | Jun Wu (1991) | | 500–7500 | 50–500 | 5–50 | | 5 |
| 8 | Simin Yang (1991) | | 1000 | 50–750 | 10–50 | | 10 |
| 9 | Qixiang Yu (1992) | | 1000–10000 | 100–1000 | 10–100 | | 100 |
| 10 | Dazeng Wang (1992) | | 10000 | 10000–20000 | 10000–20000 | | 200 |
| 11 | Yong Qin (1994) | | 450 | 50–450 | 15–50 | | 15 |
4. FACTORS INFLUENCING THE NEGATIVE PRESSURE IN A HOLE

Different negative drainage pressures and gas flows inevitably affect the gas pressure change in a borehole, and the gas seepage velocity of a coal body is related to the borehole gas pressure distribution and coal body permeability. Therefore, the radial flow of the coalbed gas and the gas pressure distribution of the borehole were coupled in this study. We used the method of mutual coupling of coal seam gas in radial flow (eq 16) and borehole gas pressure (eq 17) to calculate and analyze the variation in the law of negative pressure along the length of a gas drainage borehole with a seal depth of 13 m. According to the analysis of the coal sample from the Jiuilshan Coal Mine in Jiaozuo, the relevant physical property parameters were selected and are shown in Table 4. We used C language for programming and selected the negative pressure of different drainage boreholes, drainage borehole diameter, borehole gas flow, and influence of the negative pressure and flow rate in the drainage borehole for numerical calculations. After construction drilling, the original coal body formed holes, so the coal body around the drill hole is no longer subject to drilling direction stress, the stress balance is destroyed, resulting in the coal body around the drill hole to the drilling direction of expansion and deformation, and then the internal pore fissure system of the expanded coal body will be expanded, and even through each other, forming a more fluent gas flow channel so that the gas pressure and permeability of the coal body around the drill hole are changed. This will have a direct impact on gas transportation in the coal body around the borehole. The amount of gas gushing from the borehole gradually increases as the diameter of the borehole increases. At the same time, the hole diameter is too large due to the field drilling technique, which frequently causes the hole to collapse, spray hole, and other phenomena, affecting the extraction effect. Figure 3 is obtained after calculations and analyses.

As shown in Figure 3a, when the negative pressure of the orifice was 30 kPa and the aperture was 89 mm, the negative pressure loss continuously increased with the gas flow, mainly because of the greater flow rate, higher gas velocity, greater frictional and local resistance, and more significant negative pressure loss. As shown in Figure 3b, when the negative pressure of the orifice was 30 kPa and the flow rate was 0.1 m³/s, the negative pressure loss increased with decreasing diameter of the borehole. The primary reason is that for the same flow rate, a smaller diameter corresponds to a higher gas velocity, a greater frictional and local resistance, and a greater corresponding negative pressure loss. As shown in Figure 3c, when the negative pressure of the orifice was 30 kPa, the flow rate was 0.1 m³/s, the aperture was 89 mm, and a longer drill hole had a more pronounced decrease in negative pressure. The reason for this is that as the depth of the borehole increases, the inner wall of the borehole cracks, the number of pores gradually increases, the total local resistance of gas seepage via fractures and pores into the borehole gradually increases, and the negative pressure along the length of the borehole gradually decreases. At 120 m, the negative pressure loss increased from 6 to 9 kPa. Figure 3d shows that different negative suction pressures in the orifice had consistent characteristics; in the range of 0–20 m, the negative pressure remained unchanged; in the range of 20–80 m, the negative pressure dropped faster; and in the range of 80–100 m, it decreased more slowly. This is because the negative pressure was approximately equal in the range of 0–20 m; in the range of 20–40 m, the coal body was affected by regional antisurge measures and the gas content was low, resulting in low gas flow and small negative pressure loss in this range; and in the range of 40–80 m, the negative pressure decreased rapidly, implying that the negative pressure loss was larger in this range. The reason for

### Table 2. Pore Volume and Porosity about Different Pore Size of Different Failure Type in Coal

| aperture type | crushed coal | porosity (%) | strongly damaged coal | porosity (%) | damaged coal | porosity (%) |
|---------------|-------------|-------------|-----------------------|-------------|-------------|-------------|
|              | pore volume (cm³ g⁻¹) |             | pore volume (cm³ g⁻¹) |             | pore volume (cm³ g⁻¹) |             |
| fracture     | 0.0116      | 0.35258587  | 0.0197                | 0.474698795 | 0.0272      | 0.611235955 |
| macropore    | 0.0044      | 0.13373602  | 0.0048                | 0.115662651 | 0.0016      | 0.035955056 |
| mesoporous   | 0.0092      | 0.27963558  | 0.0092                | 0.221686747 | 0.0081      | 0.182022472 |
| micropore    | 0.0077      | 0.23404255  | 0.0078                | 0.187951807 | 0.0076      | 0.170786517 |
|              | 0.0329      | 0.0415      |                       |             | 0.0445      |             |

### Table 3. Aperture Number for Different Destroy Type Coal in Profile Section

| aperture type | equivalent diameter (nm) | hole number (crushed coal), m² | hole number (strongly damaged coal), m² | hole number (damaged coal), m² |
|---------------|--------------------------|-------------------------------|----------------------------------------|-------------------------------|
| fracture      | 2200.34                  | 4.272 × 10⁷                   | 7.255 × 10⁹                            | 1.002 × 10¹⁰                 |
| macropore     | 350.08                   | 6.402 × 10¹⁰                 | 6.984 × 10¹⁰                          | 2.328 × 10¹⁰                 |
| mesoporous    | 46.46                    | 7.750 × 10¹²                 | 7.550 × 10¹²                          | 6.823 × 10¹²                 |
| micropore     | 6.27                     | 3.813 × 10¹⁴                 | 3.862 × 10¹⁴                          | 3.763 × 1⁴                  |

### Table 4. Parameter Table of Numerical Calculations

| symbol | parameter name | value | unit | parameter name | value | unit |
|--------|----------------|-------|------|----------------|-------|------|
| ρc     | coal density   | 1.481 × 1⁷ | kg/m³ | Ac            | 0.1525 |      |
| φ      | coal porosity  | 0.0385 |       | Wf            | 0.0356 |      |
| K      | coal permeability | 2.94 × 10⁻¹⁸ | m² | ps            | 1.74 | MPa |
| ρg     | CH₄ standard density | 0.717 | kg/m³ | a             | 0.03876 | m³/kg |
| β      | gas compression factor | 0.9982 × 10⁻⁵ | kg/(m³ Pa) | g             | 9.8 | m²/s |
| μ      | dynamic viscosity coefficient of CH₄ | 1.08 × 10⁻⁵ | Pa s | b | Langmuir constant of CH₄ | 1.57 | 1/MPa |
this is that as the length of the borehole increases, the resistance along the way and the local resistance increase, causing the negative pressure loss to increase. At the same time, the site is affected by borehole deformation. In the deep part of the borehole, the deformation is larger and even the hole collapses, which is also one of the reasons for the increase of negative pressure loss after 40 m. The gas in the coal seam pumped out and decreased the gas pressure in the matrix pores, and the original adsorption balance was broken. Gas was desorbed from the surface of the matrix pores, diffused into the cracks, and entered the gas drainage boreholes from the borehole wall through seepage. Under the action of negative suction pressure, the gas flowed along the borehole and finally flowed out from the orifice. When gas flowed in a borehole, it rubbed against the rough borehole wall, and there was a loss of negative drainage pressure along the direction of the drainage borehole. The amount of gas flowing into the borehole from the bottom of the hole to the orifice gradually increased. As the gas approached the orifice, the gas velocity increased, the attenuation rate of the negative pressure along the length of the hole increased, and the gas attenuation rate away from the orifice decreased. At ~100 m, the negative pressure slowly decreased.

5. RESULTS AND DISCUSSION

5.1. Field Test Scheme of Changing Regularity of Negative Drainage Pressure. Both the beam tube method and the pressure sensor method can be used to test the negative pressure in the extraction borehole. The pressure sensor method is affected by the temperature and humidity at the site, and the measured data are inaccurate. Moreover, the negative pressure sensor is larger, resulting in higher local resistance in the extraction borehole, which has a greater impact on the extraction negative pressure data. The beam tube method is a simple test method that produces accurate data. Finally, we decided to use the beam tube method in conjunction with the mine’s actual situation.

Combined with the actual situation of the Jiulishan Coal Mine in Jiaozuo, in the 16031 air-return lane test area, a hole was drilled into the coal body with a diameter of 89 mm, a depth of 100 m, and an inclination angle of −12°. Copper tubes were used for pressure measurements, and the negative drainage pressures at 90, 80, 70, and 30 m from the orifice were separately tested using the beam tube method. To prepare for the measurements, the hole was first carefully swept to discharge the slag after the drilling was completed. Then, the longest copper tube was inserted into the hole at 20 m and the second-longest
tube was attached to the first tube, which ensured that the inner edges of the two pipe holes were 20 m apart. Using this method, the remaining sections of the copper pipe were sequentially fed into the hole. The outer end of the copper pipe was exposed to a thickness of 30 mm, as shown in Figure 4. A construction eyelet that was wrapped with a window screen to prevent coal particles from clogging the pressure-measurement channel was placed within 1 m of the bottom end, the sealing tube was used to seal the hole with polyurethane at a depth of 13 m, and the orifice was closed with yellow mud. The outer end of the copper pipe was closed with a rubber pipe, a confluence tube was installed at the opening of the extraction hole, and the extraction pipe was merged into the extraction network.

To overcome the space conditions of borehole deflection and reduce the gap between the hole walls, the method of full-hole drilling and casing centralizer was adopted by increasing the strength of the drill bit, changing its force, and increasing its contact area. The deflection of the borehole was reduced.

Due to the limitations of hole diameter, borehole deflection, coal quality conditions, and pressure-measurement materials, it was impossible to test all negative suction pressures at different depths (30, 40, ..., and 90 m) in the same borehole. Within the experimental area, the coal body belonged to a coal-forming period without isolation by geological structures and thus belonged to the same geological unit. The same borehole construction process was used for each hole with a diameter of 89 mm, a length of 100 m, and an inclination angle of $-12^\circ$, and drilling maintained a straight anti-inclination path to ensure a hole inclination of $-12^\circ$. The negative pressure of hole A was tested at 90 and 70 m from the orifice, and that of hole B was tested at depths of 50, 40, and 30 m. The negative pressure of hole C was tested at depths of 80 and 60 m. The results can be considered the approximate negative pressure at different hole depths for the same 89 mm borehole.

5.2. Results and Analyses of the Field Tests. The predrainage hole was connected to an underground extraction pipeline. After the extraction stabilized, the negative pressure of each copper tube was tested with a mercury column meter, and the data were recorded. The negative pressure values at different

| negative pressure at different distances from the orifice (kPa) | 90 m | 80 m | 70 m | 60 m | 50 m | 40 m | 30 m | 0 m |
|---------------------------------------------------------------|------|------|------|------|------|------|------|-----|
| 19.584                                                       | 20.4 | 21.488 | 22.44 | 23.392 | 23.664 | 23.664 | 23.664 | 23.936 |
| 19.856                                                       | 20.808 | 21.768 | 22.712 | 23.392 | 23.936 | 23.936 | 24.208 |
| 22.128                                                       | 23.4 | 24.488 | 25.48 | 26.384 | 26.656 | 27.2 | 27.472 |
| 22.712                                                       | 24.664 | 26.384 | 27.472 | 28.832 | 29.104 | 29.104 | 29.104 |
| 22.712                                                       | 24.528 | 26.384 | 27.2 | 28.696 | 29.104 | 29.104 | 29.104 |
| 22.576                                                       | 24.472 | 26.384 | 27.064 | 28.424 | 29.104 | 29.104 | 29.104 |
| 22.952                                                       | 24.664 | 26.656 | 27.88 | 28.968 | 29.92 | 29.92 | 29.92 |
| 23.936                                                       | 24.208 | 27.472 | 28.832 | 29.648 | 30.192 | 30.192 | 30.192 |
| 22.848                                                       | 24.072 | 26.384 | 28.832 | 29.92 | 30.192 | 30.192 | 30.192 |
| 23.768                                                       | 25.84 | 27.608 | 28.968 | 29.92 | 30.192 | 30.192 | 30.192 |
| 22.727                                                       | 24.208 | 26.938 | 28.88 | 29.92 | 30.192 | 30.192 | 30.192 |
| 22.136                                                       | 25.024 | 27.046 | 28.968 | 29.92 | 30.192 | 30.192 | 30.192 |
| 23.768                                                       | 25.568 | 27.2 | 28.288 | 29.92 | 30.192 | 30.192 | 30.192 |
| 22.856                                                       | 24.072 | 26.792 | 28.152 | 30.192 | 30.192 | 30.192 | 30.192 |
| 21.768                                                       | 24.664 | 26.394 | 28.288 | 29.92 | 30.192 | 30.192 | 30.192 |
| 23.768                                                       | 25.84 | 27.608 | 29.648 | 30.192 | 30.192 | 30.192 | 30.192 |
| 23.256                                                       | 25.296 | 27.2 | 28.424 | 29.92 | 30.192 | 30.192 | 30.192 |
| 23.392                                                       | 25.432 | 27.59 | 28.832 | 29.92 | 30.464 | 30.464 | 30.464 |
| 23.768                                                       | 25.84 | 27.454 | 28.696 | 30.464 | 30.736 | 30.736 | 30.736 |
| 23.496                                                       | 25.568 | 27.454 | 28.6 | 30.192 | 30.736 | 30.736 | 30.736 |
| 23.678                                                       | 25.024 | 27.454 | 28.696 | 30.192 | 30.464 | 30.464 | 30.464 |
| 24.312                                                       | 26.394 | 27.88 | 29.104 | 30.192 | 31.28 | 31.28 | 31.28 |
| 24.448                                                       | 26.53 | 28.016 | 29.24 | 30.736 | 31.28 | 31.28 | 31.28 |
| 33.048                                                       | 35.224 | 36.584 | 38.352 | 39.712 | 40.528 | 40.528 | 40.8 |
| 33.592                                                       | 35.496 | 37.264 | 39.576 | 41.208 | 41.344 | 41.344 | 41.344 |
distances between the predrilled borehole and the orifice are listed in Table 5.

As shown in Table 5, within the 30 day study period, for predrained gas drilling with a hole diameter of 89 mm and a length of 90 m, the difference between the borehole and bottom negative suction pressures was 4.35–8.42 kPa and the negative pressure loss along the 100 m borehole was 4.72–9.36 kPa.

Figure 5. Negative pressure change with hole length.
5.3. Comparative Analysis of the Variation Regularity of the Borehole Extraction Negative Pressure. Using C language, the negative pressure, diameter, gas flow, and influence of the negative pressure and flow rate of different drainage boreholes were numerically calculated. The average values under the same orifice negative pressure condition are listed in Table 5. As shown in Figure 5, the negative pressure inside a hole that changed with the length of the hole was considered.

As shown in Figure 5, at different negative orifice extraction pressures, the changing trend of the negative pressure in a hole was approximately the same, whereas at the same negative orifice extraction pressure, the depth of the borehole deepened. The negative pressure gradually decreased; with an increase in negative pressure at the orifice, the loss of negative pressure at 100 m generally increased. If human errors and precision errors of instruments are excluded, within the range of negative suction pressure and time, the loss of negative pressure in a hole did not change with the change in negative suction pressure.

6. CONCLUSIONS

In this study, based on the coupling of the gas seepage from coal seams and the gas flow along a drill hole, a theoretical model was established to calculate the gas pressure change law along a drill hole with different influencing factors. Subsequently, a multi-branched method was applied to test the negative pressure of different drill holes. Finally, a field test was conducted in the Jiuilshan Coal Mine to analyze the change characteristics of the negative drainage pressure along a drill hole. Based on the aforementioned results, the main conclusions are as follows:

1. The gas flow, borehole diameter, borehole depth, and orifice negative pressure influenced the variation in the negative pressure in the borehole. When the drainage negative pressure was 30 kPa, with an increase in gas flow, the negative pressure loss was sharp and increased; a smaller borehole diameter corresponded to a greater loss of negative pressure; a longer borehole corresponded to a more obvious decrease in negative pressure. The variation characteristics of the negative suction pressure in different holes were identical: in the range of 0−20 m, the negative pressure basically remained unchanged; in the range of 20−80 m, the negative pressure dropped faster; and in the range of 80−100 m, the negative pressure slowly dropped.

2. Under a constant negative extraction pressure condition, the negative extraction pressure in a hole gradually decreased when the drilling depth deepened; with an increase in extraction pressure at the orifice, the loss of negative pressure at 100 m roughly increased if human errors and precision errors of instruments were excluded. It could be approximated that within the negative pressure and time range of the test in this study, the loss of negative pressure in a hole per 100 m basically does not change with the change in negative pressure. This study of the change characteristics of negative drainage pressure along a drilling hole has important theoretical and practical significance for improving the gas drainage effect.

AUTHOR INFORMATION

Corresponding Author
Yanzhao Wei — School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000 Henan, China; orcid.org/0000-0002-1858-3123; Email: weiyz0309@163.com

Authors
Jun Liu — School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000 Henan, China; State Key Laboratory Cultivation Base for Gas Geology and Gas Control and The Collaborative Innovation Center of Coal Safety Production of Henan, Henan Polytechnic University, Jiaozuo 454000 Henan, China; orcid.org/0000-0002-8229-7172
Zhiyuan Liu — School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000 Henan, China
Xiangjun Chen — School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000 Henan, China; State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo 454000 Henan, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c01753

Notes
The authors declare no competing financial interest.

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