Study on the Response Characteristics of the Pressure and Temperature Fields of Source Gas Injection under Loading Conditions

Kan Zhou, Hongmin Yang, Jinfeng Guan, and Haoge Zheng

ABSTRACT: To study the safety of the source gas in coal seams after gas injection displacement, choosing N$_2$ as an example, the pressure and temperature field variation characteristics of the source gas in coal were studied via experimental research, numerical simulation, and theoretical analysis methods, starting from the variation characteristics of the gas pressure and temperature fields in the coal. In this work, 2−9 MPa stress was applied to the top of the coal samples. The experimental results indicated that during the coal loading process, the gas pressure and temperature in the coal generally exhibited a decreasing trend and that the pressure and temperature could increase in some areas due to pore closure and frictional heat generation, but the increase range was not significant. Based on the numerical simulation results, in the 200 min loading process, the gas pressure inside the coal body decreased by approximately 0.25 MPa and the overall temperature slightly decreased. Only the temperature near the borehole greatly changed, and the maximum decrease reached approximately 8 °C. Considering the experimental and numerical simulation results, under the condition of stress concentration, the pressure and temperature fields of the source gas injected into the coal body mainly revealed a decreasing trend and the possibility of inducing outbursts was low.

1. INTRODUCTION

Gas injection technology to displace coalbed methane includes the forcible injection of N$_2$/CO$_2$ and other source gases into a coal seam to improve the exploitation efficiency of coalbed methane and reduce greenhouse gas emissions in the coal mining process.$^1$ Because CO$_2$ poses an outburst hazard and when methane is mixed with too much CO$_2$, it will cause the combustion and explosion quality of methane to decrease,$^2−5$ and N$_2$ is often used as a source gas in the engineering practice of gas injection to displace coalbed gas in underground coal mines.$^6$

To master the pressure field effect in the process of N$_2$ injection in a coal seam, Yang$^7$ used a self-built coal seam gas injection experimental device to study the change effect and distribution of the coal seam gas pressure field with the gas injection pressure, gas injection time, and pressure relief time during the coal seam N$_2$ injection process. This is the first study to put forward a suggestion to conduct in-depth research on the outstanding danger of source gas injection. Li$^8$ conducted an experimental study on enhancing coalbed methane extraction by injecting N$_2$ underground in the No. 3. Mine of Chongqing Tianfu Mining Company and studied the variation law of the CH$_4$ volume fraction in adjacent holes during gas injection. Wang$^9$ established a mathematical model for the displacement of coal seam methane by injecting N$_2$ and used COMSOL software to simulate the gas flow in the extraction borehole at different gas injection times and pressures. Chen$^{10}$ studied the distribution of the pressure force field during gas injection and the law of residual pressure recovery after pressure relief. Previous studies have mainly focused on the displacement mechanism, parameter optimization, and effect evaluation, but there have been a few reports on the distribution characteristics of the N$_2$ pressure and temperature fields in coal seams and the possibility of inducing outbursts after gas injection displacement.

To explore the distribution characteristics of N$_2$ in coal seams after gas injection displacement, this paper adopted the method of combining experimental research with numerical simulations to study the variation trends of N$_2$ pressure and temperature fields in coal seams under loading conditions after gas injection displacement. The research results could deepen the theoretical
understanding of coal seam gas injection displacement and provide a theoretical basis for coal mine enterprises to implement this technology to control coal mine gas disasters.

2. EXPERIMENTAL STUDY

2.1. Experimental Device. The system consists of a stress loading unit, vacuum pumping unit, gas injection control unit, gas pressure monitoring unit, and coal temperature monitoring unit. The experimental device is shown in Figure 1. The effective size of the cavity in which coal samples are placed is $500 \times 500 \times 500 \text{ mm}^3$, and there occur $4 \times 4$ probe holes (64 in total) and $3 \times 5$ test holes (60 in total) across the model to meet the experimental needs.

2.2. Experimental Sample. In this experiment, briquette coal samples were used in the simulation experiment. Considering that the purpose of this experimental research was to determine whether the injected gas could result in outburst hazards under the condition of stress concentration, granular coal with a coal sample size $<1 \text{ mm}$ was selected and compacted in layers to simulate the low permeability of outburst-prone coal seams. The basic parameters of the experimental coal samples are listed in Table 1. Mad refers to the air drying base moisture of coal. Aad refers to the residue left after the coal is completely burned. Vad refers to the product of the liquid (vapor state) and gas decomposed from the coal after the coal is heated at $900 \pm 10 \degree C$ for a certain period of time in a container isolated from the air minus its moisture. It is an important index for evaluating coal quality and an important basis for coal classification.

2.3. Experimental Method. According to the characteristics of coal seam gas injection technology, the experimental process of this paper is as follows: “Layered preloading of coal samples $\rightarrow$ Vacating $\rightarrow$ $N_2$ injection adsorption balance $\rightarrow$ Drilling (release opening) $\rightarrow$ Initial stress loading $\rightarrow$ Graded loading stress $\rightarrow$ Natural pressure relief discharge at the end of loading”. The initial conditions of the experiment were 1 MPa downward stress on the top of the coal sample, which was increased by 1 MPa every 20 min until the stress reaches 9 MPa. The end time of the experiment was 200 min. An experimental flowchart is shown in Figure 2.

| Mad (%) | Aad (%) | Vad (%) | real density (kg/m$^3$) | apparent relative density (kg/m$^3$) | porosity (%) |
|---------|---------|---------|--------------------------|--------------------------------------|-------------|
| 1.01    | 13.32   | 7.95    | 1760                     | 1691                                 | 4.06        |

Table 1. Basic Parameters of the Coal Sample

Figure 1. Schematic diagram of the experimental device.

Figure 2. Experimental flowchart.

Figure 3 shows the layout of sensors inside the coal body. The drilling hole in this experiment was a round hole with a diameter.
of 16 mm. The temperature sensor type was an optical fiber temperature sensor with 10 built-in measuring points, and the distance between two adjacent measuring points was 25 mm. The measurement range was −40 to 80 °C, and the measurement accuracy was ±1‰. Four measuring points at 25, 50, 75, and 100 mm were used as temperature monitoring points. The pressure sensors were 4-fiber-optic gas pressure sensors, with round shapes and the diameter of each was 10 mm. The measurement range was 0−10 MPa, the measurement accuracy was ±1‰, and positions of 25, 50, 75, and 100 mm from the center of the borehole were selected as gas pressure monitoring points. The temperature sensor faced the center of the drilling hole, with a distance of approximately 10 mm from the edge of the drilling hole. The gas pressure sensors were directly above the temperature sensor, and the distance between the four gas pressure sensors was 15 mm so that the drilling hole, the temperature sensor, and the gas pressure sensors did not affect each other.

2.4. Results. 2.4.1. Variation Trend of the Internal Pressure of the Coal Body in the Loading Process. Figure 4 shows the data curve of the gas pressure sensor arranged in the middle of the coal body. Figure 4 shows that in the staged loading process of the test coal sample, the variation trend of the coal gas pressure at different distances from the center of the borehole differed. The gas pressure of coal at point (0, 25) first exhibited a trend of a rapid decline and then a slow decline. The rapid descending stage lasted approximately 30 min before the coal was loaded in stages. With increasing loading onto the coal, the internal coal pores quickly collapsed, and the free gas occurring near the borehole was compressed and rapidly discharged from the borehole, resulting in a rapid decrease in the gas pressure near the borehole. With a large amount of free gas discharged, driven by the concentration gradient between free and adsorbed gas, the adsorbed gas in the coal was desorbed. At this time, the coal pores were basically closed, the discharged amount of free gas and the desorbed amount of adsorbed gas in coal gradually reached a dynamic equilibrium state, and the gas pressure drop near the borehole gradually decreased. The coal gas pressures near points (0, 50) and (0, 75) exhibited a trend of an initial rapid decline and a subsequent slow rise. Compared to (0, 25), (0, 50) and (0, 75) achieved smaller decline amplitudes and rates of change at the initial stage and exhibited obvious time lags because (0, 50) and (0, 75) occur far from the borehole, the gas seepage path is longer, and the resistance is higher, so the decline amplitude and speed are low. Compared to that at point (0, 25), the gas pressure at points (0, 50) and (0, 75) began to slowly rise during the later period, which could mainly be attributed to the increase in loading stress, closure of coal pores, and permeability of free gas. Free gas could not be discharged in time due to compaction of the coal body, and the volume of free gas was reduced, so the gas pressure slowly increased at the later stage of loading. The change trend at (0, 100) was different from the above two situations, indicating a trend of an initial slow decline and a subsequent rapid decline. Because this point occurs the farthest from the borehole, the initial gas pressure drop was not obvious. At the later stage, with a large amount of free gas flowing out from the borehole, the pressure gradient of free gas near (0, 100) and that near the borehole increased. According to Darcy’s law, the gas velocity is directly proportional to the pressure gradient when the permeability remains constant or changes slightly, so the free gas occurring near (0, 100) rapidly flowed toward the borehole center, and the free gas pressure began to drop rapidly.

2.4.2. Variation Trend of the Internal Temperature of the Coal Body in the Loading Process. Temperature is an important factor affecting the occurrence of gas in coal. Based on classical thermodynamic theory, temperature is the decisive factor of the internal energy of an ideal gas. An increase in temperature could lead to intensification of the thermal movement of gas molecules, thus increasing the energy of gas molecules to overcome their bond with the coal surface. However, increased movement of gas molecules could also increase the probability of collision between gas molecules and the coal surface, so a rising temperature could increase the speed of adsorption and desorption at the same time, but the influence on desorption is far greater than that on adsorption. In the same way, with decreasing temperature, the kinetic energy of gas molecules decreases, and the speed of adsorption and desorption declines. Overall, an increase in temperature can overcome the adsorption energy increasing the desorption rate, and a decrease in temperature will increase the difficulty for the gas to overcome the adsorption energy and reduce the desorption rate. Figure 5 shows the temperature recorded by the sensors arranged at the (0,25), (0,50), (0,75), and (0,100) points in the coal body. The graph shows that the temperature change at each point in the coal body also exhibits different characteristics. Among these points, the temperature at point (0,25) closest to the center of the borehole revealed the largest change range, with a maximum temperature drop of approximately 5 °C. The overall temperature change trend demonstrated a trend of a rapid initial decrease and subsequent slow recovery. As the coal sample was loaded, the coal pores were compressed and a large amount of free gas in the coal sample was lost. Under the action of a concentration gradient, the adsorbed gas in the coal sample was desorbed. As gas desorption is an endothermic process, the coal temperature began to decrease. With further compaction of the coal sample, the coal pores basically closed, the outflow rate of free gas gradually decreased, and the desorption process decelerated. In addition, with increasing upper load, the extrusion friction of coal particles generated heat, and a coal temperature increase occurred at the later stage of loading. The temperature change trend of coal near (0,50) was basically the same as that at (0,25), both of which decreased rapidly first and
then increased slowly. Because of its long distance from the borehole, the coal temperature at (0,50) was lower than that at (0,25), both of which first decreased and then increased, revealing an obvious time lag. The change trends at (0,75) and (0,100) were basically the same, exhibiting a linear downward trend in the whole loading process. Because of the distance from the borehole, less gas loss and less gas desorption occurred, the temperature slightly changed, and there was no obvious warming stage.

3. NUMERICAL SIMULATION

In the physical experiment, monitoring of the gas pressure and temperature fields inside the coal body was mainly realized by embedding gas pressure and temperature sensors, respectively, along the middle of the coal body, but the obtained data reflect only local change in the coal body. To obtain gas pressure and temperature field distribution data in the entire coal body space, based on the theories of solid mechanics, fluid mechanics, and thermodynamics, this paper used COMSOL numerical simulation software to build a thermal–fluid–solid coupling model to describe the change in injected gas inside the coal body, and through numerical simulations, the N₂ pressure inside the coal body was analyzed.

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3.1. Basic Assumptions. As a typical heterogeneous body, the study of thermal–fluid–solid coupling with N₂ is a complex problem involving fluid mechanics, geotechnical mechanics, thermodynamics, and other disciplines. The following assumptions were made:

(1) The coupling system consists of coal and N₂, excluding gas;
(2) The coal seam is a dry porous medium;
(3) The coal body is a homogeneous and isotropic linear elastic body;
(4) N₂ is an ideal gas that conforms to the ideal gas state equation, and its dynamic viscosity remains unchanged under isothermal conditions;
(5) N₂ seepage in the coal pore space conforms to Darcy’s law;
(6) N₂ adsorption and desorption obey the Langmuir equation.

3.2. Thermal–Fluid–Solid Interaction Model. The change in temperature and pressure in coal is the result of the joint action of the physical and mechanical properties of coal, ground stress, and gas adsorption/desorption. Scholars have focused on thermal–fluid–solid coupling models of coal and gas. Tao et al. constructed a thermal–fluid–solid coupling model of gas-bearing coal and realized complete bidirectional coupling of gas-bearing coal. Fang aimed to reveal the coupling mechanism of the thermal–fluid–solid fields in the CO₂-enhanced coalbed methane recovery (ECBM) process and established numerical models of the thermal–fluid–solid fields for comparison to direct exploitation and CO₂-ECBM production practices. Fan et al. built fluid–solid coupling models of the CO₂-ECBM process to study the distribution of the gas pressure and concentration. Yang et al. established a coupled mathematical model of the thermal–fluid–solid multiphysical fields of coalbed methane seepage in the process of low-permeability coalbed methane thermal injection mining and conducted numerical simulations of the coalbed methane seepage trend in the process of thermal injection mining with multiple wells. Li et al. considered the variation in the adsorption heat of coalbed methane in the temperature field equation and established a thermal–fluid–solid coupling model for deep coalbed methane extraction. Compared to previous research results, this work mainly focuses on the study of the gas injection displacement process. This paper examines the change trend of the pressure and temperature fields of the source gas in a coal body under coal and rock stresses after gas injection displacement.

3.2.1. Stress Field Governing Equations. According to the basic assumptions in Section 3.1, the coal body is an isotropic linear elastic body, which conforms to Hooke’s law under compression. Combined with effective stress theory, the stress field governing equation is

\[
G_{\alpha\beta} + \frac{G}{(1 - 2\nu)} u_{\alpha,\beta} + F_{\alpha} - \alpha P_{,\alpha} - K\epsilon_{,\alpha} - K\epsilon = 0
\]

(1)

where, \(G\) is the shear modulus, \(P\) is the body force, \(\nu\) is Poisson’s ratio; \(F\) is the body force, \(N/m^3\); \(\alpha\) is the pore compressibility; \(P\) is the gas pressure, \(Pa\); \(K = E/3(1 - 2\nu)\); \(E\) is the elastic modulus of coal, MPa; \(T\) is the temperature, \(K\); \(\epsilon\) is the stress tensor; \(\nu\) is the deformation displacement; and \(F\) is the body force.

3.2.2. Seepage Field Governing Equation. Assuming that gas in the adsorption state exhibits single-layer adsorption, gas conforms to the Langmuir state equation, and gas seepage flow in the coal body conforms to Darcy’s law. Combined with the law of mass conservation, the seepage control equation for gas flow in a coal seam can be obtained as

\[
\left( \frac{\phi}{P} + 1 - \phi \right) \frac{\partial P}{\partial t} - \phi \frac{\partial T}{\partial t} + \frac{\partial \epsilon_{\alpha}}{\partial t} + \frac{\partial Q_{\alpha}}{\partial t} = \nabla \times \left( \frac{k}{\mu} \nabla P \right)
\]

(2)

where \(\phi\) is the porosity; \(K\) is the bulk modulus of coal, \(Pa\); \(T\) is the temperature, \(K\); \(Q_{\alpha}\) is the adsorption capacity of \(N_2\); \(k\) is the
permeability, \(m^2\); \(\mu\) is the dynamic viscosity coefficient; \(P\) is the gas pressure, Pa; and \(\varepsilon_v\) is the volumetric strain.

### 3.2.3. Temperature Field Governing Equation

The system exchanges heat with the outside environment through thermal convection and heat conduction. According to the first law of thermodynamics, the increase in the internal energy of the system is equal to the sum of the system heat exchange and the work done on the system. According to thermodynamics, the temperature field control equation can be established as follows:

\[
[(1-\phi)c_v + \phi c_l] \frac{\partial T}{\partial t} + \Delta T(\rho c_v - \rho c_l) + \nabla \times (k_v \nabla T) = W + Q
\]

where \(\rho\) is the coal density, kg/m\(^3\); \(c_v\) is the specific heat capacity of coal, J/(kg-K); \(\rho_l\) is the N\(_2\) density, kg/m\(^3\); \(c_l\) is the specific heat capacity of N\(_2\), J/(kg-K); \(k_v\) is the thermal conductivity, J/(s-m-K); \(W\) is the system heat exchange, J/m\(^3\); \(Q\) is the energy for work in the system or external work of the system, J/m\(^3\); \(\phi\) is the porosity; and \(T\) is the temperature, K.

### 3.2.4. Diffusion Field Governing Equation

Based on the assumption of dual-porosity media, it is generally believed that gas diffusion in coal is in accordance with Fick’s law of diffusion, and gas diffusion in coal is affected by various factors, such as temperature, gas characteristics, and adsorption equilibrium pressure. Combined with the mass conservation equation, the gas diffusion equation in coal particles can be obtained as:

\[
\frac{P_l}{u(P_L + u)} + \frac{c_3 c_3 (T - T_m)}{(1 + c_3 u)^2} V_l \frac{\partial u}{\partial t} + \frac{c_3 V_l}{1 + c_3 u} \frac{\partial T}{\partial t} = 0
\]

where \(V_l\) is the Langmuir volume, m\(^3\)/t; \(P_l\) is the Langmuir pressure, MPa; \(u\) is the gas pressure in the pores, MPa; \(c_3\) is the pressure coefficient, 1/MPa; \(c_3\) is the temperature coefficient, 1/K; \(T\) is the system temperature, K; \(T_m\) is the reference temperature, 293.15 K; and \(\lambda\) is the modified adsorbed gas content coefficient.

\[
\lambda = \frac{u}{P_L + u}
\]

### 3.3. Geometric Model and Boundary Conditions

According to the experimental conditions in this paper, considering the reliability and validity of the numerical simulation results, the three-dimensional model is simplified as a two-dimensional model for simulation purposes. The geometric model is shown in Figure 6. The model was a square with length and width of 500 mm. Solid mechanics under structural mechanics, Darcy’s law under fluid flow, porous media heat transfer under the heat transfer module, and the general partial differential equation under the mathematical module were selected as the main physical field modules. The simulation time was set to 200 min, the bottom edge was defined as a fixed boundary, the left and right boundaries were established as roller support boundaries, and the boundary load was set at the top. The interpolation function was used to increase the pressure by 1 MPa at 20 min intervals to simulate the stress concentration in the coal body from 2 to 9 MPa. The parameters are listed in Table 2.

### 3.4. Results

#### 3.4.1. Gas Pressure Change

Figure 7 shows the changes in gas pressure at the four points 25, 50, 75, and 100 mm away from the borehole. The figure shows that the smaller the distance from the borehole, the more the gas pressure decreases. Compared to the original pressure, the gas pressure at the four points decreases by 0.56, 0.4, 0.35, and 0.31 MPa, respectively, and the decrease amount reaches 76.1, 55.1, 47.2, and 42.4%, respectively. Based on the overall trend, in the 200 min loading process, the change in gas pressure inside the coal body can be divided into four stages: The first stage is the stage of a rapid reduction in the gas pressure. The gas pressure in the body decreases rapidly. The second stage is the slowly rising gas pressure stage, where free gas is discharged, the pore pressure decreases, the effective stress on the coal body increases, the pores in the coal body are compressed and closed, and the porosity decreases, the volume of free gas decreases, and the gas pressure begins to slowly rise. The third stage is the stage where the gas pressure more rapidly increases. As the coal sample is further compacted, the porosity is further reduced, the free gas volume...
As shown in Figure 9, the gas pressure of the entire coal body starts to rise slowly. The gas pressure near the borehole is the lowest. From the coordinate origin as the center, the figure reveals that the gas pressure near the centerline of the coal body also experienced a process of an initial rapid decline and subsequent slow recovery. At this time, gas outflow begins to play a dominant role, thus increasing the concentration gradient between free and adsorbed gas. According to Fick’s diffusion law, an increase in the concentration gradient is beneficial to promote a large amount of adsorbed gas desorption so that the gas contained in coal can be continuously discharged through boreholes.

The fourth stage is the stage with a gradual reduction in the gas pressure, and with increasing loading stress, the coal pores basically close, and the decrease in the coal porosity tends to decline. At this time, gas outflow begins to play a dominant role, and the gas pressure again begins to decrease with continuous gas outflow. Compared with the data observed in the experiment, the change trend of (100,0) gas pressure was quite different, mainly because a briquette coal sample was used in this experiment. The deformation of the raw coal body was smaller than that of the briquette because of its strong solid skeleton strength and strong compression resistance, and the change in internal pores was less than that of the briquette, so the decrease in permeability was smaller than that of the briquette coal sample.

Figure 8 shows the gas pressure change along the centerline of the coal body at 10, 20, 40, 80, 120, and 200 min with the coordinate origin as the center. The figure reveals that the gas pressure along the centerline of the coal body also experienced a process of an initial rapid decline and subsequent slow recovery. The gas pressure near the borehole was the lowest. From the center of the borehole to the vicinity of 100 mm, the gas pressure rises rapidly, and from 100 mm toward the coal boundary, the gas pressure starts to rise slowly.

Figure 9a,b shows a contour map of the gas pressure change. As shown in Figure 9, the gas pressure of the entire coal body decreased from the initial value of 0.74 MPa to approximately 0.5 MPa after 200 min of stress loading, and the gas pressure decreased by 0.24 MPa, indicating that gas adsorption/desorption was significantly affected by stress concentration, and an increase in overburden load on the upper part could obviously lead to a decrease in pores and fissures in the coal rock mass. In this case, a large amount of extruded free gas could be discharged, thus increasing the concentration gradient between free and adsorbed gas. According to Fick’s diffusion law, an increase in the concentration gradient is beneficial to promote a large amount of adsorbed gas desorption so that the gas contained in coal can be continuously discharged through boreholes.

### Table 2. Parameters of the Physical Properties of Coal and Gas

| parameter name | value |
|---------------|-------|
| coal density (kg/m³) | 1691 |
| initial porosity (%) | 4.06 |
| initial permeability of coal (mD) | 0.1 |
| N₂ density (kg/m³) | 1.25 |
| dynamic viscosity coefficient of N₂ (Pa·s) | 1.7812 |
| the molar mass of N₂ (g/mol) | 28 |
| specific heat capacity of N₂ (J/g/K) | 1038 |
| Langmuir volume constant (cm³·g⁻¹) | 25.19 |
| Langmuir pressure constant (MPa) | 1.36 |
| Young’s modulus (MPa) | 2.48 × 10³ |
| Poisson’s ratio | 0.339 |
| the initial temperature (K) | 304.65 |
| universal gas constant (J·mol⁻¹·K⁻¹) | 8.3143 |
| Reference temperature (K) | 293.15 |
| standard temperature (K) | 273 |
| coal seam initial temperature (K) | 303.15 |

Figure 7 shows the gas pressure change at each point.

Figure 8. Gas pressure change along the coal centerline.

Figure 10 shows the temperature changes at the four points 25, 50, 75, and 100 mm away from the borehole. Compared to the experimental data, the coal temperature experienced a downward trend in the numerical simulation process, and there was no temperature increase. The reason is that the numerical simulation assumes that the coal is completely linear elastic, so there is no plastic deformation throughout the loading process, which is quite different from the experimental results. The figure shows that as the coal sample was compacted, a large amount of adsorbed gas was desorbed, and the temperature of the system continued to drop, but the change rules were different. The point (0, 25) closest to the borehole exhibits the largest decline, reaching 8 °C, and the entire curve reveals a trend of a rapid initial decline and subsequent slow decline. Point (0,50) demonstrates a monotonically decreasing trend, with a decrease range of 2.99 °C. The line segment at point (0,75) exhibits a trend of a slow initial decline and a subsequent rapid decline, with a decline rate of 0.97 °C. The temperature drop at point (0,100) is the smallest, only 0.25 °C, and the overall change reveals the characteristics of a nearly horizontal line segment.

Figure 11 shows the temperature changes with the gas pressure along the centerline of the coal body at 10, 20, 40, 80, 120, and 200 min. The figure shows that in the loading process, the temperature influence range is small, and the coal body temperature in the area more than 100 mm away from the coordinate origin hardly changes.

Figure 12a,b shows a contour map of the temperature change. The figure also shows that the influence range of the coal temperature drop was limited. The temperature drop area was mainly concentrated within a range of 100 mm from the origin, and the temperature beyond 100 mm did not change significantly.
4. DISCUSSION

A comparative analysis of the numerical simulation and experimental results shows that the change trend of the gas pressure in the coal body is in good agreement with the numerical simulation results, exhibiting a trend of first rapidly decreasing, then slowly rising, and finally slowly decreasing at the last stage. Compared to the experiments, the numerical simulations of the temperature change develop no temperature rise stage, mainly because the numerical simulation assumes that the coal is a completely linear elastic body, so there will be no coal fracture friction and plastic deformation in the loading process, and the coal will generate heat via fracturing and frictional contact. Therefore, the numerical simulation results are different from the experimental data, there is no trend of temperature rise, but the overall temperature drop characteristics are the same as those of the experimental results.

According to the above results, at the early stage of coal compression, the coal pores are compressed and closed, and a large amount of N\textsubscript{2} is discharged from the coal body along the borehole, resulting in a rapid decrease in gas pressure. With decreasing free gas concentration, a large amount of adsorbed gas in coal also begins to desorb under the action of a concentration gradient. Figure 13 shows the change in the N\textsubscript{2} adsorption amount of the whole coal sample during the numerical simulation. Figure 13 also shows that at the early stage of coal compression, the adsorbed gas in coal is quickly desorbed. Because gas desorption is an endothermic process, the coal temperature near the borehole considerably decreases. As the coal body is compacted, the porosity decreases. As the free gas volume in the coal body is reduced, the gas pressure slowly rises and the coal temperature gradually decreases. With further compaction of coal, the influence of the porosity on the gas pressure is further reduced, and gas outflow again begins to play a leading role. The gas pressure in coal starts to decrease slowly during the late loading period, and the change range of the coal temperature is further reduced due to the inhibition of adsorption/desorption in coal.

5. CONCLUSIONS

Based on experimental research, numerical simulation, and theoretical analysis, this paper systematically studies the characteristics of the pressure and temperature fields of the gas in coal seams after gas injection with N\textsubscript{2} as the source gas, and the following conclusions are obtained:

(1) Under the influence of porosity and other factors, the gas in coal exhibits a trend of a rapid decline, then a slow rise, and finally a slow decline in the loading process. Throughout the loading process, the gas pressure in coal decreases by approximately 0.24 MPa.

(2) Affected by gas desorption and other factors, the coal temperature within 100 mm of the borehole decreases in the loading process, while the temperature slightly changes beyond 100 mm, and the overall cooling rate is not high.
Although the gas pressure locally rises throughout the loading process, the increase range is limited and the overall trend still indicates a decrease in the gas pressure. The decrease in coal temperature also inhibits gas desorption to a certain extent, and outbursts are a dynamic phenomenon caused by the combined action of in situ stress, gas pressure, and the structural and mechanical properties of coal. The desorption and accumulation of a large amount of gas adsorbed in the coal body and the increase in gas pressure are the necessary conditions for the occurrence and development of outbursts. According to the research results of the temperature field and pressure field in this paper, the local decrease in coal temperature and the overall decrease in gas pressure hinder the occurrence of outburst danger. Therefore, the gas injection pressure should be maintained within an appropriate range in the process of gas injection displacement, and the gas in coal slightly influences the occurrence of outbursts and other hazards.

This paper mainly studies the variation law of the pressure field and temperature field of N\textsubscript{2} after gas injection displacement and discusses the application of gas injection displacement technology in engineering practice from the perspective of safety. Limited by the test conditions, this paper studies the variation laws of the temperature and pressure fields of only N\textsubscript{2} gas and does not consider the variation laws of the CH\textsubscript{4} remaining in the coal. With the rapid development of sensor technology, especially the development of polymer\textsuperscript{28} and infrared photoconductive technology\textsuperscript{29}, it has become possible to monitor the concentration of mixed gas in coal in real time. How to apply these new gas injection technologies will be a new important topic in future research.

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K.Z. conceived the experiment, analyzed the results, and drafted the manuscript. H.Y., J.G., and H.Z. coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

Notes
The authors declare no competing financial interest.
ACKNOWLEDGMENTS

This study was financially supported by the General Program of the National Natural Science Foundation of China under grant no. 52074104 and the Guizhou Provincial Science and Technology Plan Project (Guizhou S&T Cooperation Platform Talents) under grant no. [2019] 2876. The authors also thank the reviewers and editors for their constructive comments and suggestions for manuscript improvement.

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