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MECHANISM CONVERSION PROCESS AND TIMELINESS OF N_2-ECBM

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ABSTRACT

Purpose. Based on the technology by which methane drainage is strengthened under gas injection, to examine the process of gas injection and the mechanism of action.

Methods. Physical simulation experiment method, using the self-built coal seam and gas injection displacement experimental device, the experiment of layered pre-compression forming coal samples under vertical stress loading conditions and under the conditions of different gas injection pressures.

Findings. The experiment on N_2-ECBM is a dynamic process and has time effects. In the overall process, the rate of replacement was more than 60%, and the rate of displacement was less than 40%.

Originality. According to the behavior of nitrogen injection in the coalbed, an assessment of displacement effects under gas injection and a quantitative evaluation of the replacement effect were presented. In every stage of the process, the replacement effect is dominant, while the role of displacement is of secondary importance.

Practical implications. The experimental results have great guiding significance for optimization of gas parameters and gas source selection for gas injection flooding in underground coal seams.

Keywords: *mechanism of N_2-ECBM, timeliness, displacement effect, replacement effect, quantitative study, coal mine*

1. INTRODUCTION

Coal mine gas injection is used to promote coalbed methane drainage with such technologies as Enhanced Oil Recovery (EOR) and Carbon Capture, Utilization and Storage (CCUS). In particular, CO_2 geological storage technology not only reduces greenhouse gas emissions but also improves the recovery rate of CBM.

At the end of the 20th century, CO_2 was injected for increasing coalbed methane (CO_2-ECBM) in the United States' San Juan Basin; this approach was the prelude to CBM coalbed gas injection in the field driving the technology for methane (Reeves, 2005). In subsequent years, the United States, Canada, Japan, EU and China have started research and conducted ECBM field trials of various scale (Van Bergeb et al., 2002; Gunter, Mavor, & Robinson, 2005; Reeves, 2005; China United Coal…, 2007; Shi, Durucan, & Fujioka, 2008; Hong-min, 2010; Zhi-ming, Xiao-chun, & Hong, 2010; Oudinot et al., 2011; Godec, Koperna, & Gale, 2014; Masoudian, Airey, & El-Zein, 2014). The US carried out CO_2-ECBM field test in San Juan Basin, Black Warrior Basin, Illinois Basin, and Central Appalachian Basin. In Hokkaido (Japan), Poland, and Alberta (Canada), field trials of different sizes were also carried out. China United Coalbed Methane Co. Ltd. was the first mine that conducted CO_2 injection into the ground in Jin-Cheng, China. Next, Zhi-ming, Xiao-chun, & Hong (2010) carried out the low-pressure (< 0.6 MPa) N_2-ECBM test in Ping Dingshan Coal Mine, Yangquan Coal Mine.

To make this technology more practical and applicable to production, scientists have conducted considerable theoretical research, especially regarding the mechanisms of enhanced coalbed methane recovery under gas injection (Busch, Krooss, Gensterblum, van Bergen, & Pagnier, 2003; Fitzgerald et al., 2005) have suggested that the adsorption capacity of coal to N_2, CH_4 and CO_2 becomes stronger (Katayama, 1995) suggested that the mechanism by which CO_2 can displace CH_4 is based on the fact that coal adsorption energy to CO_2 is better than that to CH_4, because of what the seam CH_4 recovery is improved. N_2 can replace CH_4 due to the changes in the partial pressures of the two gases, thereby forming a new adsorption equilibrium (Clarkson & Bustin, 2000) assumed that when a non-CH_4 gas is injected into the coal seam, it will compete for adsorption space with CH_4 or reduce the partial pressure of CH_4 in the free gas, thus contributing to CH_4 desorption from the coal seam and

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increasing the gas production rate of CH_4 (Shi-yue & Yong-yi, 2000) studied the stimulation mechanism of exploitation of coalbed methane by gas injection based on the diffusion, percolation and multicomponent adsorption equilibrium theory. He claimed that there are three components to such mechanism of action: first, by increasing the energy of seam CH_4 flow through gas injection; second, by increasing desorption rate and desorption through the competitive adsorption and displacement effect; and third, by increasing permeability through changes in the pore structure of the coal seam (Long-jun, Cheng-lun, & Xue-fu, 2000) stated that this approach reduces the CH_4 partial pressure in the coal seam after injecting N_2, CO_2 or flue gas into coal seam and adds impetus to the flow of CH_4 to overcome the flow resistance of a coal seam with low permeability (Shu-heng, Qi, & Da-zhen, 2002) established that this technology essence is to inject energy into the coal seam, change the pressure transmission characteristics and increase or maintain the diffusion rate. In addition, the injection of gas will produce competitive adsorption, which, under high pressure, will induce the formation of new cracks, thereby increasing permeability (Xing-zhou, Yong-yi, & Shi-yue, 2000; Jian-guang & Xiao-guang,2004; Xiao-guang & Zhan-jun, 2004; Xi-jian, Li-yong, & Hao, 2007; Wen-ming & Sui-an, 2008) have suggested that N_2 reduces the partial pressure of CH_4 when it is injected into coal seam and that almost all of the CH_4 can be extracted or expelled by the N_2. When CO_2 was injected into the coal seam, because of its strong adsorptive force, it produced competitive adsorption with the CH_4, which was adsorbed in coal matrix micro pore, and, after a period of time, CO_2 could displace the CH_4 (Shang-chao & Zhi-xu, 2008; Guo-ting, 2009) supposed that ECBM increase is due to the following mechanism: first, the injection of gas reduces the partial pressure of CH_4 that promotes CH_4 desorption; second, the flow of gas expels CH_4 to production wells; third, the injected gas is maintained at a higher pressure gradient than simply pumping and this increases the effect of flow rate; and fourthly, the injection gas maintains a higher pore pressure, which increases the permeability of the coal seam (Zhi-ming, Xiao-chun, & Hong, 2010) considers that there are two mechanisms of CO_2 flooding coalbed methane: the first is replacement, by which there is adsorption competition between the displacement gas (CO_2) and CH_4, replacing CH_4 molecules and promoting CH_4 desorption, while reducing the partial pressure of CH_4 and promoting CH_4 desorption further; the second is expulsion, wherein the injected gas is maintained at a higher pressure gradient than simply pumping and this increases the effect of flow rate and expels CH_4 to production wells (Hong-min, 2010) proposed the following mechanisms by which injection gas replaces seam CH_4: the replacement adsorption – desorption effect of injection gas, the contained portable/displacement effect of airflow, dilution and diffusion and the AR expansion effect of injection gas. The carrier of gas stream and flooding effects play a dominant role, while the replaced CH_4 occupies a smaller proportion.

In summary, scholars have conducted considerable research on the mechanism of enhancing coalbed methane recovery by gas injection. These theories provide great support for the application and development of the technology, but coal seam gas injection is a dynamic process in which the contributions of a variety of mechanisms of action can also change. In engineering applications, it is important to know whether it is the choice of a different gas to increase its replacement of coalbed CH_4 or the choice of the right pressure and gas injection flow rate to improve gas flow conditions in the coal seam, which can improve the airflow displacement effect. Therefore, the roles of and quantitative research related to coal seam gas injection mechanisms are still theoretical problems to be solved. This paper aims to determine these roles through laboratory simulation experiments to analyze the replacement and displacement effect of the gas injection process and carry up quantitative research to reveal the leading mechanisms of the seam gas injection process, thereby providing an experimental and theoretical basis for the engineering application of coal seam gas injection.

2. EXPERIMENTAL METHODS

2.1. Experimental devices

The experimental platform includes the following: experimental chamber, stress loading system, gas injection system, vacuum pumping system, pressure monitoring system, gas flow monitoring and quantitative analysis systems (Fig. 1).

1. Experimental chamber. For safety purposes, the experimental chamber was milled from a single piece of rolled steel; the size of the chamber is 400×300×300 mm; the wall thickness is 40 mm, and it is fitted with a double “O” ring.

2. Stress loading system. This experimental device is a one-dimensional displacement experimental device, loading only the vertical stress by a backpressure stand and jack whose maximum force is 200KN. There is a sensor between the jack and the backpressure stand which allows for computerized control of the applied pressure.

3. Gas injection system. The gas injection system consists of cylinders, control valves, and injection gas line. The controls include a main valve and a pressure relief valve whose ranges are 0 ~ 25 MPa and 0 ~ 6 MPa, respectively. The former controls the main valve display tank pressure, while the latter can control the injection pressure.

4. Vacuum pumping system. The experimental device is connected to a vacuum pump after it passes a tightness check and is safeguarded against leaking, then the pump is started, using a gauge to monitor the system vacuum in real-time.

5. Pressure monitoring system. The chamber has test holes in the side and by varying the position of the hollow tube inserted into coal with pressure sensors, it is possible to monitor the internal pressure of coal, using computer acquisition of the pressure data.

6. Gas flow monitoring system. This system quantifies the gas injection and discharge. Injection gas was metered by a mass flow controller with a maximum of 5 l/min, and the instantaneous flow and total flow were monitored through the monitor.

7. Gas composition analysis system. During the displacement process, small gas samples were collected using 1 l sample bags at certain times from the outlet on the gas meter, while composition and concentration of the gas samples were determined by gas chromatography.

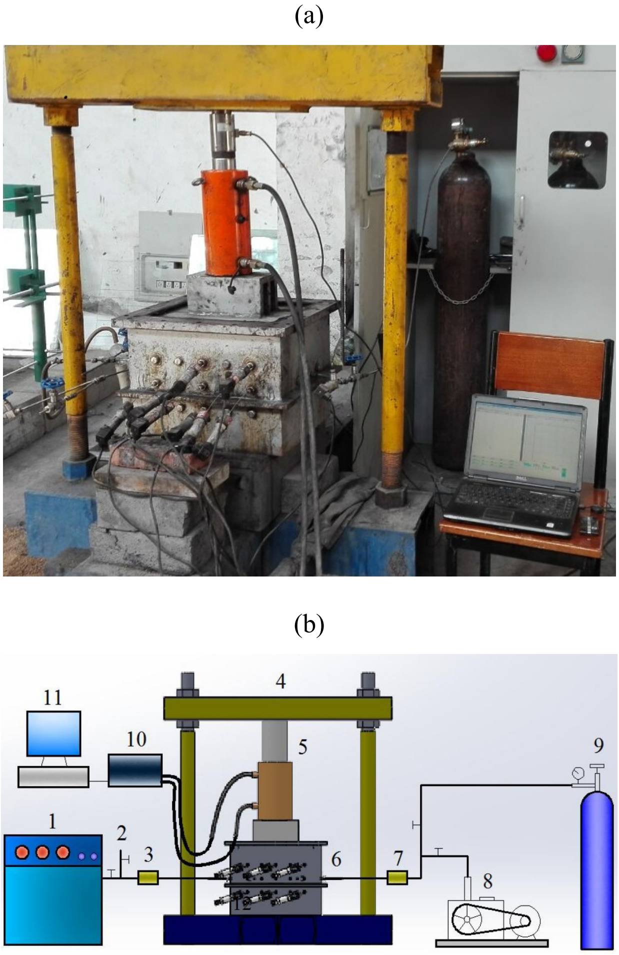

Figure 1. Experimental system: (a) general view; (b) schematic diagram; 1 – gas chromatograph; 2 – gas collecting mouth; 3 – low pressure flow meter; 4 – counterforce frame; 5 – hydraulic jack; 6 – chamber; 7 – high pressure flow meter; 8 – vacuum pump; 9 – pressure steel bottle; 10 – pressure controller; 11 – pressure monitoring computer; 12 – pressure sensor

2.2. Experimental coal sample

An experimental coal loading method was used to take granular coal-like layered loading and conduct pre-compression molding, as shown in Table 1. The characteristics of the experimental coal samples are 4.54% water, 14.66% ash, 8.43% volatile matter, 1.76 t/m^3 true density, 1.68 t/m^3 apparent density and 0.15 solidity.

2.3. Experimental procedure

1. Vacuum pumping. The system is connected to a vacuum pump and held under vacuum at 500 Pa.

2. Filling with CH_4 to adsorption equilibrium. CH_4 was provided by high-pressure cylinders; the outlet of a cylinder was connected with valve, and the coal sample was filled with CH_4 until adsorption equilibrium was achieved at 0.7 MPa. To ensure complete adsorption of methane, this process requires no less than 48 h.

3. Deflation. After achieving adsorption equilibrium, the gas injection outlet was opened, and the high-pressure free gas was released until the pressure dropped to 0.1 MPa. The volume of gas emitted was measured with a gas meter.

4. Gas injection. Upon completion of step (3), N_2 was immediately injected into the chamber using the valve to control the injection pressure, while the gas input and output were measured with a flow meter and a gas meter.

5. Outlet gas collection. Gas was collected regularly from the outlet during the displacement process, gas meter and flow readings were recorded at the time of each gas collection; these gas samples were analyzed by gas chromatography to determine the end time of the displacement process.

6. Relief of pressure. Once the concentration of methane in outlet was approximately 15%, the gas injection port was closed, stopping the gas injection. Next, the gas in the chamber was allowed to escape.

7. End of the experiment. When the gas pressure of the chamber was down to 0.1 MPa, the outlet was closed, ending the experiment. Steps (1) to (7) were then repeated for the next set of experiments.

Table 1. Experimental coal sample collection and loading method

Coal sample collection site	Coal	Granularity	Loading method	Loading level	Stratified thickness	Preliminary pressure	Preload time
No. 2 coal seam in Huatai Coal Mine, Dayugou River, Henan Province	Anthracite	< 1 mm	Layered loading preloading	4 layers	40 + 80 + 80 + + 120 mm	120 kN	2 min

3. EXPERIMENTAL RESULTS AND ANALYSIS

We carried out the experimental displacement of coal methane by N_2 injection according to the above steps. We obtained information regarding the process by monitoring the flow of N_2 pressure, pore pressure of the experiment chamber, and the flow of produced gas and by determining the gas composition.

3.1. Dependence of N_2 injection and gas discharge on the flow change

It can be seen in Figure 2 that initially, the flow of N_2 injection is larger and continues to decline. The flow of the produced gas increases rapidly and evenly across the coal seam. The higher the pressure of injection, the greater the steady state flow rates of N_2 injection and gas production. Under the same gas injection pressure, the steady state flow of the produced mixed gas is greater than that of gas injection. When the pressure of gas injection is 0.6 MPa, the steady state flow of N_2 injection is 0.33 l/min and the steady state flow of the produced mixed gas is 0.5 l/min.

When the pressure of gas injection is 1.0 MPa, the steady state flow of N_2 injection is 1.0 l/min, and the steady state flow of the produced mixed gas is 1.2 l/min. When the pressure of gas injection is 1.4 MPa, the steady state flow of N_2 injection is 2.3 l/min and the steady state flow of the produced mixed gas is 2.5 l/min.

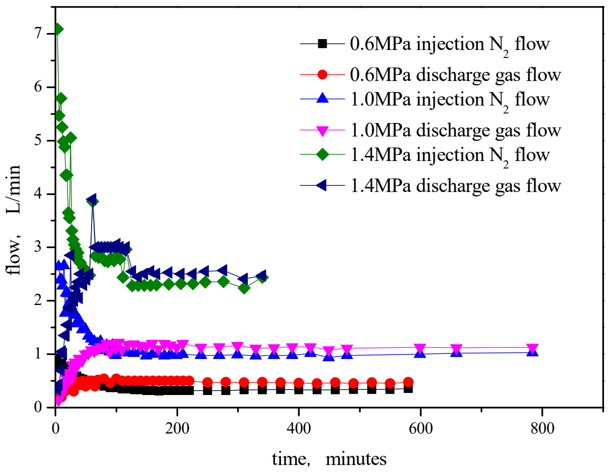

Figure 2. Dependence of N_2 injection and mixed gas discharge on the flow change with injection time

3.2. Discharge gas concentration changes the dependence and N_2 breakthrough time

The change in the discharge mixed gas concentration throughout the experiment is shown in Figure 3.

It can be seen from Figure 3 that the initial period of gas injection can only be detected in the outlet CH_4 discharge, N_2 is not discharged but retained in the coal with the continuous injection of N_2, CH_4 concentration and N_2 concentration. As the rate of change gradually slows, we will refer to the elapsed time to this point from the start of the gas injection as the N_2 breakthrough time.

When the gas injection pressure is 0.6 MPa, the breakthrough time of N_2 is 15 min. When the gas is injected for 120 min, the concentration of CH_4 is reduced to 50% and the N_2 concentration is increased to 50%. At the end of gas injection (1210 min), the concentration of CH_4 decreased to 12.27% and the N_2 concentration increased to 87.73%.

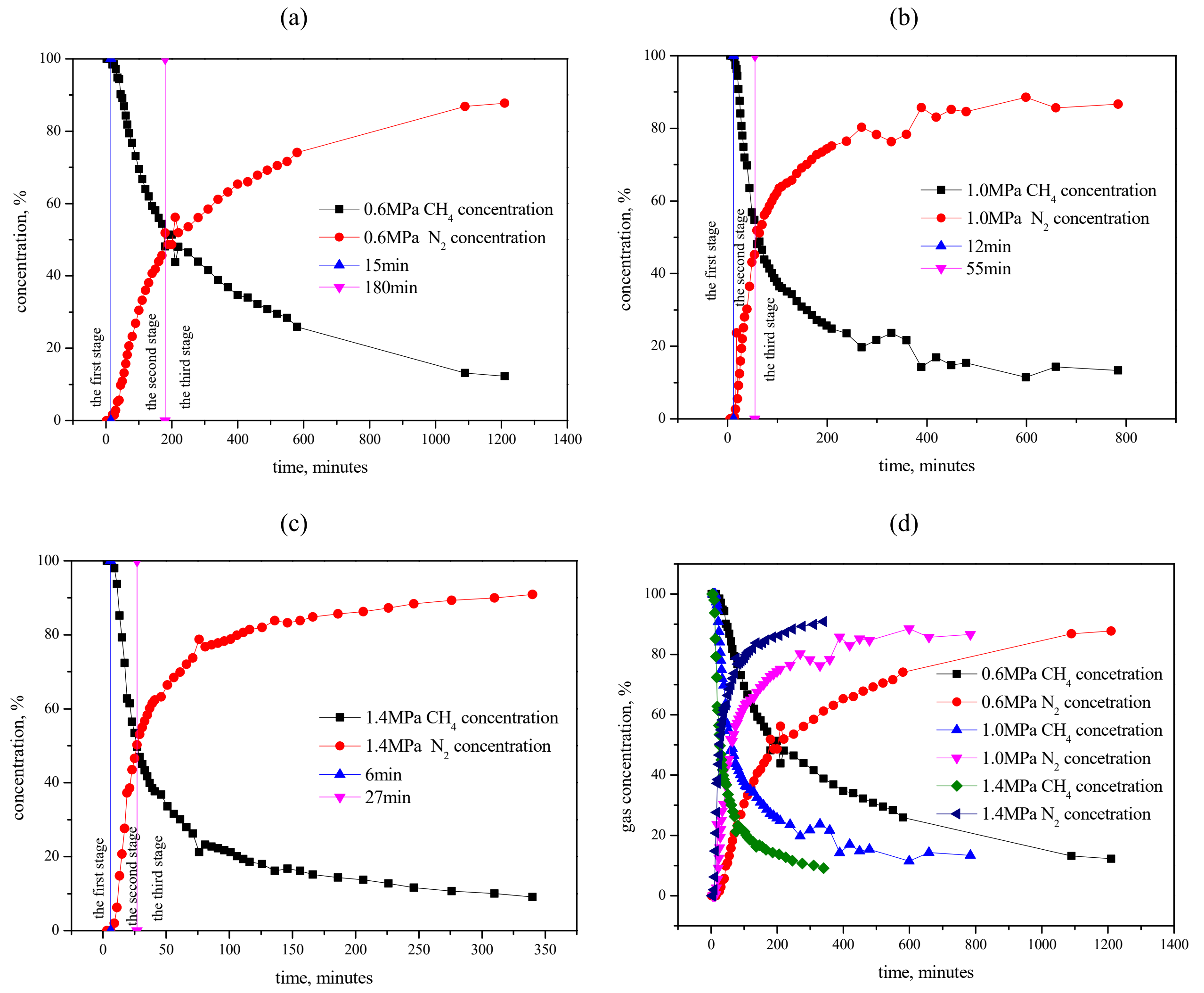

Figure 3. Dependence of discharged mixed gas concentration on the injection time: (a) 0.6 MPa; (b) 1.0 MPa; (c) 1.4 MPa; (d) 0.6 – 1.4 MPa

When the gas pressure was 1.0 MPa, the breakthrough time of N_2 was 12 min. When the gas injection time was 55 min, the concentration of CH_4 decreased to 50% and the concentration of N_2 increased to 50%. At the end of gas injection (784 min), the concentration of CH_4 decreased to 13.36% while that of N_2 increased to 86.64%. When the gas pressure was 1.4 MPa, the breakthrough time of N_2 was 6 min. When the gas was injected for 27 min, the concentration of CH_4 decreased to 50% and the concentration of N_2 increased to 50%. At the end of gas injection (340 min), the concentration of CH_4 decreased to 9.12% and that of N_2 increased to 90.88%.

3.3. Changes in the flow and volume of discharged CH_4 with injection time

The change of CH_4 flow rate over the course of the experiment is shown in Figure 4; the change of CH_4 volume is shown in Figure 5.

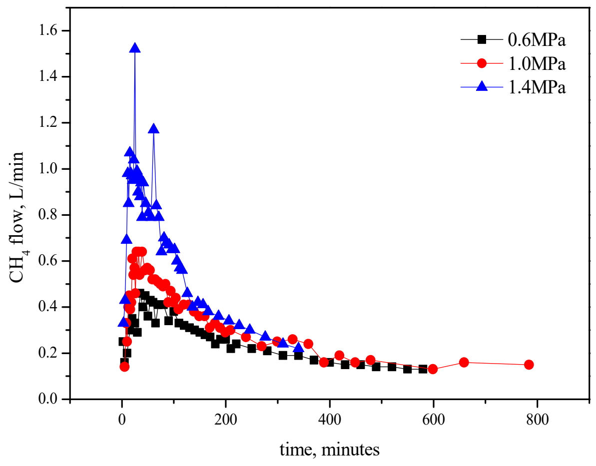

Figure 4. Dependence of flow change on CH_4 discharge with injection time

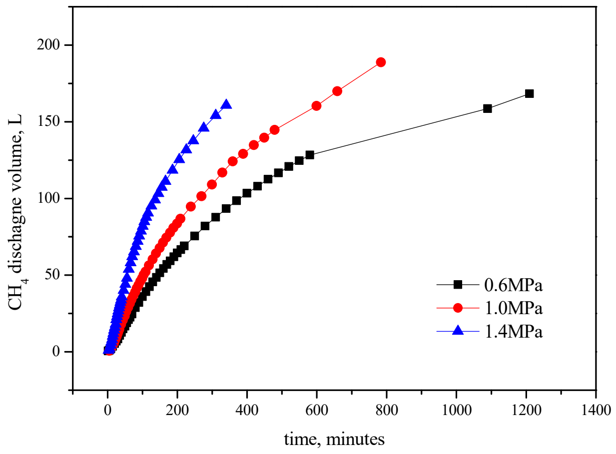

Figure 5. Dependence of volume change on CH_4 discharge with time

It can be seen from Figure 4 that the flow rate of discharged CH_4 increases at first and then declines. Under different gas pressures, the discharged CH_4 flow behaved differently. When the gas pressure was 0.6 MPa, the flow rate of CH_4 increased rapidly over 35 min from 0.25 to 0.46 l/min. Then, with the continued injection of N_2, CH_4 flow decreased slowly, and the flow rate became steady at 0.15 l/min. When the gas pressure was 1.0 MPa, the flow rate of CH_4 increased rapidly over 28 min from 0.14 to 0.64 l/min, and the flow rate became steady at approximately 0.15 l/min. When the gas pressure was 1.4 MPa, the flow rate of CH_4 increased rapidly over 28 min from 0.33 to 1.07 l/min, and the flow rate became steady at 0.22 l/min by the end of gas injection. In the initial phase of the gas injection, the higher the gas injection pressure, the higher the CH_4 flow rate. But with increased gas injection time, the CH_4 flows with various gas injection, gas pressures gradually converged to 0.2 l/min or less.

It can be seen from Figure 5, that under different gas injection pressures, the total volume of discharged CH_4 showed obvious differences. The higher the gas injection pressure, the greater the total amount of CH_4 discharged in the same time, indicating that there is a positive correlation between the injection pressure and the effect of flooding. The total volumes of discharged CH_4 were 92.5, 120.8 and 160.9 l when the gas injection pressures were 0.6, 1.0 and 1.4 MPa, respectively.

3.4. Change over time in the N_2 volume retained in coal

Under the experimental conditions, the time of gas injection in nitrogen gas, discharge of nitrogen and its retention in coal are shown in Figure 6.

It can be seen from Figure 6 that before N_2 breaking through the chamber, all the nitrogen injected into the coal (the initial gas injection) is retained in the coal. At the beginning of gas injection, the volume trapped in coal rises sharply, and then tends to be stable. The greater the pressure of gas, the greater the volume of gas retention. When the gas pressure is 0.6 MPa, and before N_2 breaking through (the 15th minute), the N_2 volume trapped in the coal is 12.21 l, and then the gas injection time is 120 mins, the N_2 volume trapped in coal is 50 l, in the end, the N_2 volume trapped in the coal is 71.10 l at the end of the gas filling (the 1210th minute).When the gas pressure is 1.0 MPa, and before N_2 breaking through the chamber (the 12th minute), the N_2 volume trapped in the coal is 29.76 l, and then the gas injection time is 120 mins, the N_2 volume trapped in the coal is 120 l, in the end, the N_2 volume trapped in the coal is 165.69 l at the end of gas filling (the 784th minute). When the gas pressure is 1.4 MPa, and before N_2 broking through the chamber (the 6th minute), the N_2 volume trapped in the coal is 37.68 l and then the gas injection is 120 mins, the N_2 volume trapped in the coal is 190 l, in the end, the N_2 volume trapped in the coal is 221.32 l at the end of gas filling (the 340th minute).

4. ANALYSIS OF THE PRINCIPAL EFFECT PRODUCED BY COAL SEAM GAS DISPLACEMENT

4.1. Quantitative determination of CH_4 in coal injection

The result of the experiment shows that the replacement of coal methane through gas injection is a dynamic process. The concentration and flow of CH_4 produced changes in N_2 injection pressure, flow and time, which shows that the process of replacement of coal seam methane by N_2 injection is time dependent. To more clearly study the mechanism of the dynamic process of coal seam methane displacement by gas injection, this paper employs two definitions. Displacement effect: when injecting gas into coal, depending on the adsorption strength, a change in the CH_4 partial pressure can turn the CH_4 adsorption state into a free state. Replacement effect: when a new gas is injected into coal, the coal seam methane will discharge even with a low gas flow rate.

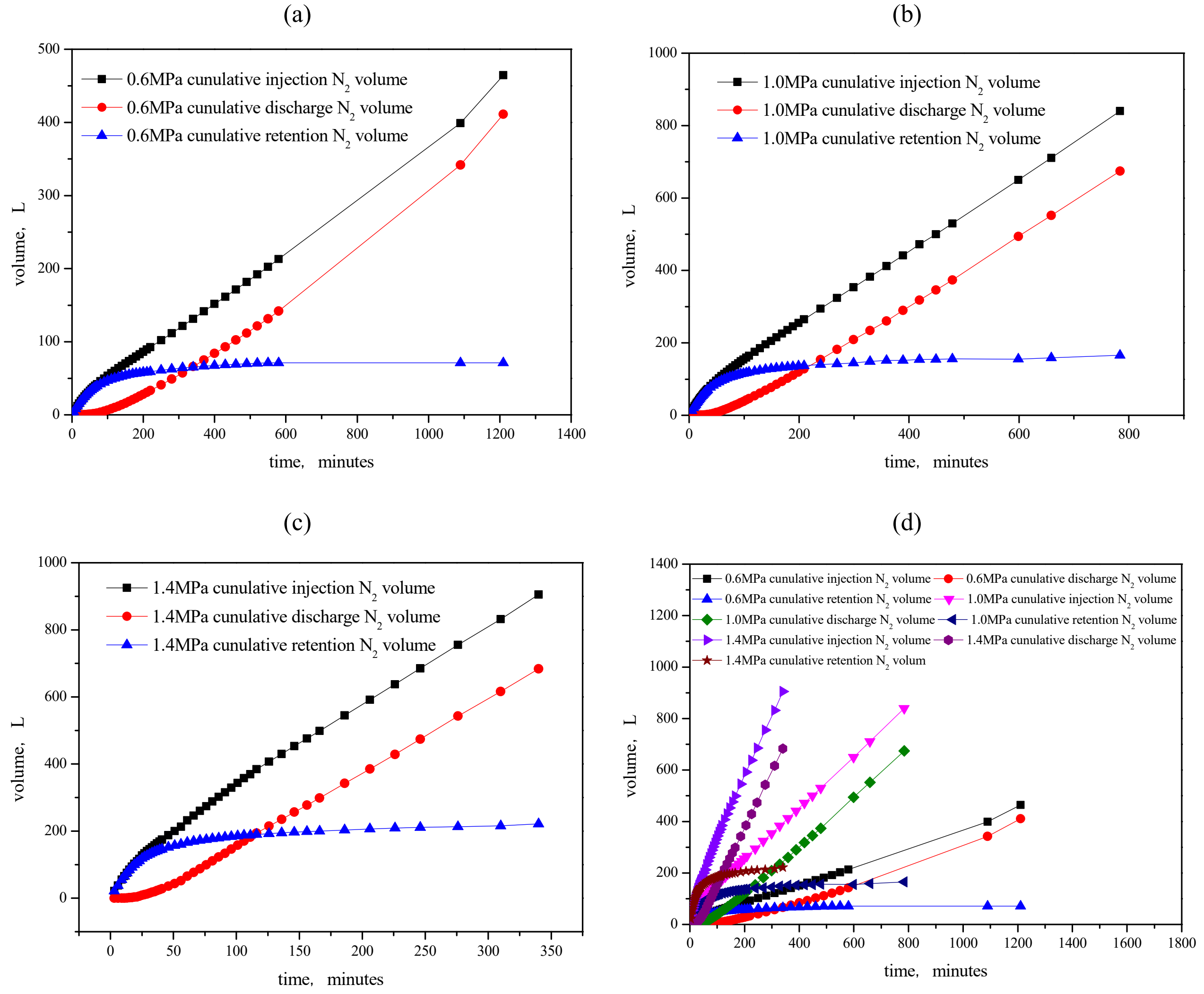

Figure 6. Cumulative volume change of injection of nitrogen, out of nitrogen, retention nitrogen in coal with time: (a) 0.6 MPa; (b) 1.0 MPa; (c) 1.4 MPa; (d) 0.6 – 1.4 MPa

This occurs because the gas injection will upset the CH_4 adsorption equilibrium, which leads to a phenomenon in which CH_4 will continue to desorb and discharge. The diagram of CO_2-ECBM mechanism is shown in Figure 7, the diagram of N_2-ECBM mechanism is shown in Figure 8.

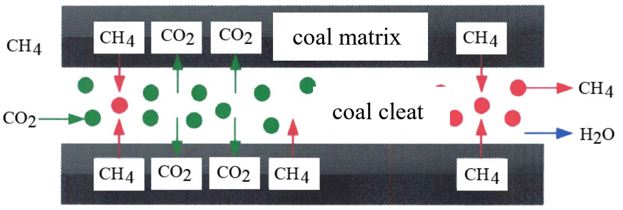

Figure 7. Diagram of CO_2-ECBM mechanism

It can be seen that initially the flow rate of N_2 injection is the same as the rate of N_2 retention in the coal. N_2 can upset the CH_4 adsorption equilibrium and CH_4 will desorb because of the partial pressure gradient, following Dalton's law during this process. The volume of N_2 retained in the coal will displace the coal methane due to the displacement effect; as the available adsorptive capacity is reduced in the coal, the volume of N_2 retained in coal also decreases rapidly.

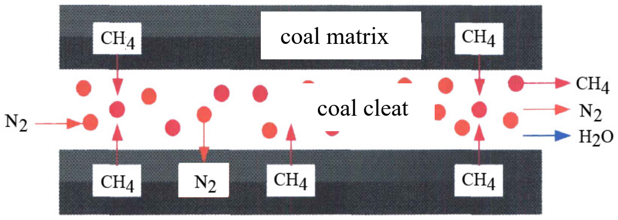

Figure 8. Diagram of N_2-ECBM mechanism

As the injection time goes on, the flow rate of N_2 injection reaches its steady state, and the CH_4 desorbs continuously. A small quantity of N_2 remains in the coal and occupies the remaining available adsorptive capacity. At this point, most of N_2 is discharged with the flow of mixed gas. The volume of N_2 discharged with the flow of gas which has replaced the coal methane can be thought of as the quantitative representation of the replacement effect.

We use the rates of displacement and replacement to quantitatively describe the changes in the balance between displacement and replacement. The rate of displacement is the ratio of N_2 retained in the coal to N_2 injected. The rate of replacement is the ratio of N_2 discharged with the flow of mixed gas to N_2 injected.

$$R_d = \frac{V_r}{V_i} \cdot 100\,\%, \quad (1)$$

where:

R_d = the rates of displacement;

V_r = 1 min volume of N_2 remained in coal;

V_i = 1 min volume of N_2 injection.

$$R_r = \frac{V_d}{V_i} \cdot 100\,\%, \quad (2)$$

where:

R_r = the rates of replacement;

V_d = 1 min volume of N_2 discharged in coal;

V_i = 1 min volume of N_2 injection.

4.2. Analysis of CH_4 conversion process mechanism in N_2 displacement coal

According to the physical simulation experiment results treated above, it can be seen that at the initial stage of N_2 injection, before the N_2 breaks through the chamber (0.6, 1.0 and 1.4 MPa correspond to 15, 12 and 6 min), the CH_4 concentration is 100%, and the N_2 concentration is 0%. Since a large amount of free CH_4 was pre-discharged before the experiment, the original adsorption equilibrium was broken, resulting in more desorption of CH_4. At this time, there was a large amount of free adsorption sites in the coal. After N_2 is injected into the coal, the N_2 first occupies these adsorption sites, and there is some free space in the coal into which N_2 continues to infuse. Meanwhile, the free space N_2 partial pressure and the system total pressure both show an upward trend. At this point, N_2 reaches the partial pressure at which it begins to sustain CH_4 desorption, but on the other hand, from the molecular motion theory applied to the coal, a large amount of N_2 adsorbs, exerting a certain hindrance on the adsorption of CH_4. During this period, it is mainly the replacement effect of N_2 which is manifest.

In the middle of the gas injection period, and N_2 having recently broken through the chamber, CH_4 and N_2 gas can be detected together. The CH_4 concentration decreases and the rate of this decrease lessens over time. On the other hand, the N_2 concentration rises from 0, rapidly at first and more slowly over time. The greater the pressure, the faster the change in gas pressure. In this process, the amount of methane adsorbed in the coal is the largest initially and the rate of desorption decreases rapidly. With the desorption, the amount of methane adsorbed in the coal decreases, and as the amount of methane available to desorb is decreasing, the amount of methane carried by N_2 is also decreasing, and the rate of this decrease is gradually reduced. The overall increase in N_2 concentration slows down over time. During this period, both the amount of N_2 adsorbed and the amount of free N_2 in the chamber are increasing. At the same time, part of the injected N_2 will replace and desorb the CH_4 which is discharged from the chamber. The carrying effect of N_2 injection becomes evident, and part of the injected N_2 begins to produce a flooding effect. As the gas injection progresses, the amount of N_2 retained in the chamber is gradually increased, during which time the concentration of each component decreases, the gas flow rate gradually stabilizes, and the pressure rise in the chamber slows as the pressure reaches its steady state. The driving effect is gradually increased. At this time, N_2 is injected, most of which carries CH_4 out of the chamber; only a small part of N_2 is adsorbed by the coal or is absorbed into the chamber free space; the cumulative retention of N_2 in the chamber is now only slowly increased. Thus, the phase replacement effect is weakened, and the flooding effect is enhanced.

At the end of the gas injection period, changes in the concentrations of the two gases are getting less and less pronounced. With the increase of the gas injection time, N_2 is gradually approaching its adsorption equilibrium state; the adsorption of N_2 is gradually slowing; gas flow at the outlet is basically stable and the chamber pressure tends to be stable. At this time, N_2 in the chamber has reached an adsorption balance, i.e., the difference between the amounts of N_2 injected and expelled is essentially constant, and the performance of the total retention of N_2 tends to be stable. Since the CH_4 partial pressure reduction rate is slowed and the total pressure in the chamber is constant, the replacement effect of N_2 is already weaker than before, and the continuous displacement effect is maintained so that the weak displacement desorption is maintained and most of CH_4 is now out of the chamber. From the three experimental sets, changes in the flow can also be observed in the late gas injection. Injection flow and discharge flow are very close to the two curves and close to the trend, and a large portion of the injected N_2 subsequently exercises a flooding effect, and in the last part of the experiment, the main effect of N_2 is observed through flooding.

4.3. Analysis of CH_4 dominant function and contribution degree in N_2-ECBM experiment

In the above section, we analyzed the mechanism of the CH_4 transformation process in N_2 flooded coal at different times of the gas injection. What are the respective contributions of replacement and displacement in the overall gas injection experiment? In this section, we will conduct a whole analysis of this subject.

Under the experimental conditions, the cumulative replacement ratio, volume and displacement ratio, volume changes with time are shown in Figures 9 – 11.

When gas injection pressure is 0.6 MPa, the whole test duration is 580 min. The replacement percentage decreased from 100% to 36.70%, while the displacement percentage increased from 0% to 63.31%. The volume of accumulated replaced gas is 47.11 l, while that of accumulated displaced gas is 87.21 l. The replacement percentage is equal to displacement percentage at 310 min. Therefore, displacement is dominant during the whole test of CH_4 replacement and displacement by N_2.

When gas injection pressure is 1.0 MPa, the whole test duration is 784 min. The replacement percentage decreased from 100% to 24.44%, while the displacement percentage increased from 0% to 75.56%. The volume of accumulated replaced gas is 46.21 l, while that of accumulated displaced gas is 142.84 l. The replacement percentage is equal to displacement percentage at 180 min. Therefore, displacement is dominant during the whole test of CH_4 replacement and displacement by N_2.

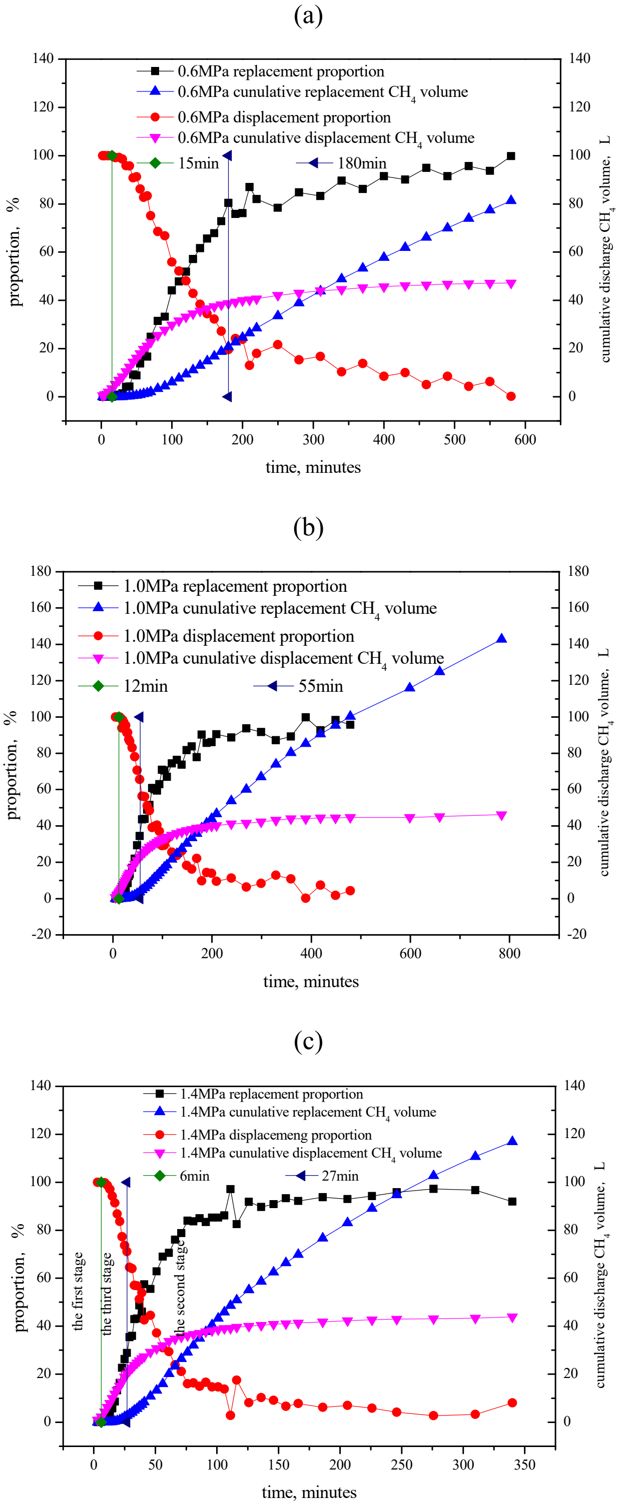

Figure 9. Change of displacement and replacement rate and volume with time: (a) 0.6 MPa; (b) 1.0 MPa; (c) 1.4 MPa

When gas injection pressure is 1.4 MPa, the whole test duration is 340 min. The replacement percentage decreased from 100 to 27.32%, while the displacement percentage increased from 0 to 72.68%. The volume of accumulated replaced gas is 43.95 l, while that of accumulated displaced gas is 116.91 l. The replacement percentage is equal to displacement percentage at 91 min. Therefore, displacement is dominant during the whole test of CH_4 replacement and displacement by N_2.

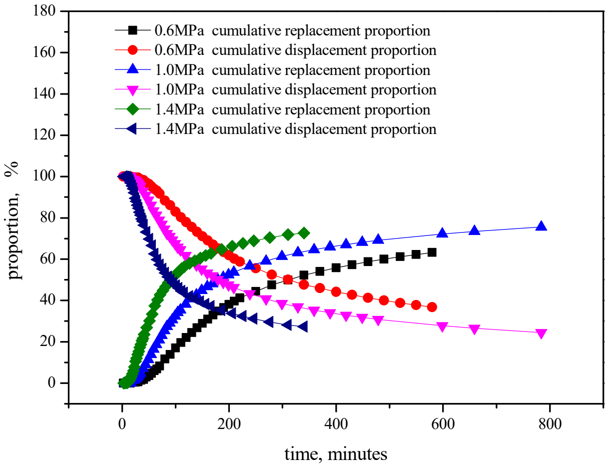

Figure 10. Change of displacement and replacement rate with time

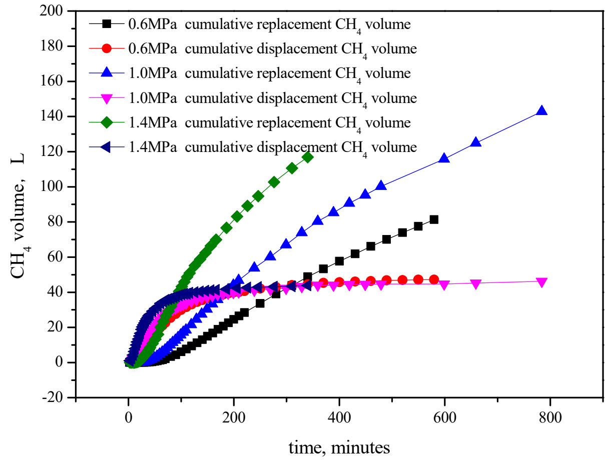

Figure 11. Change of displacement and replacement volume with time

5. CONCLUSIONS

Under the assumption of ideal gases, N_2 can upset the adsorption balance of CH_4 because of a partial pressure gradient based on Dalton's law of partial pressures. The volume of N_2 which remains in the coal and displaces methane can be seen as the quantitative contribution of the displacement effect. If the coal seam methane discharged with the gas flow because of carrying of or driving the gas injection, then the volume of N_2 discharged which will replace the coal methane can be seen as the quantitative contribution of replacement effect.

N_2-ECBM experiment is a time-dependent process. Initially, all the injected N_2 remains in the coal. This part of nitrogen only shows the replacement effect. As the time goes on, some of the injected N_2 gradually begins to discharge. The displacement effect is decreasing, and the replacement effect is increasing. The rate of the replacement function is over 60%, and the displacement function is 40%, so the replacement plays a dominant role and the displacement plays a secondary role.

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МЕХАНІЗМ ПРОЦЕСУ ДЕГАЗАЦІЇ Й ЧАСОВІ ПАРАМЕТРИ ЗАСТОСУВАННЯ N_2-ECBM ТЕХНОЛОГІЇ

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Мета. Вивчити процес вприскування газу у вугільний пласт й механізм його впливу на основі технології, яка дозволяє забезпечити дренаж метану, інтенсифікований за рахунок нагнітання газу.

Методика. Використано експериментальний метод фізичного моделювання: була змонтована установка з моделлю вугленосного пласта для дослідження вприскування газу з метою витіснення метану. В експерименті попередньо стиснені зразки шаруватого вугілля піддавалися вертикальному навантаженню при тисках 200 кН, аналогічних тиску вприснутого газу. Газ для ін'єкцій вимірювався контролером масової витрати з максимальною швидкістю 5 л/хв, і через монітор контролювалися миттєвий і загальний потоки. В експерименті використано антрацит вугільної шахти Хуатай.

Результати. Експериментальними дослідженнями встановлено, що концентрація і об'єм метану призводять до змін тиску, витрати і часу вприскування азоту, що свідчить про те, що процес заміщення метану вугільного пласта шляхом закачування азоту залежить від часу. Доведено, що експеримент з використанням технології N_2-ECBM (інтенсивного вилучення вугільного метану) – це динамічний процес, в якому фактор часу відіграє вирішальну роль. Об’єм азоту, який залишається у вугіллі й витісняє метан, можна розглядати як кількісний вклад ефекту зміщення. Виявлено, що в результаті використання даної технології, рівень заміщення метану зріс більш, ніж на 60%; а рівень його витіснення – на 40%.

Наукова новизна. Вивчено ефект витіснення метану при нагнітанні азоту у вугільний пласт з урахуванням поведінки газу у вугленосній товщі, а також дана кількісна оцінка ефекту заміщення, що чинить ключовий вплив на всіх стадіях процесу, в той час як роль витіснення – другорядна.

Практична значимість. Результати експериментів мають принципове значення для оптимізації параметрів газу та для вибору джерела вприскування газу у вугільні пласти.

Ключові слова: *механізм N_2-ECBM, фактор часу, ефект витіснення, ефект заміщення, кількісний аналіз, вугільна шахта*

МЕХАНИЗМ ПРОЦЕССА ДЕГАЗАЦИИ И ВРЕМЕННЫЕ ПАРАМЕТРЫ ПРИМЕНЕНИЯ N_2-ECBM ТЕХНОЛОГИИ

Л. Чен, Т. Янг, Х. Янг, Л. Ванг

Цель. Изучить процесс впрыскивания газа в угольный пласт и механизм его воздействия на основе технологии, которая позволяет обеспечить дренаж метана, интенсифицированный за счет нагнетания газа.

Методика. Использован экспериментальный метод физического моделирования: была смонтирована установка с моделью угленосного пласта для исследования впрыскивания газа с целью вытеснения метана. В эксперименте предварительно сжатые образцы слоистого угля подвергались вертикальной нагрузке при давлениях 200 кН, аналогичных давлению впрыскиваемого газа. Газ для инъекций измерялся контроллером массового расхода с максимальной скоростью 5 л/мин, и через монитор контролировались мгновенный и общий потоки. В эксперименте использован антрацит угольной шахты Хуатай.

Результаты. Экспериментальными исследованиями установлено, что концентрация и объем метана приводят к изменениям давления, расхода и времени впрыска азота, что свидетельствует о том, что процесс замещения метана угольного пласта путем закачки азота зависит от времени. Доказано, что эксперимент с использованием технологии N_2-ECBM (интенсивного извлечения угольного метана) – это динамический процесс, в котором фактор времени играет решающую роль. Объем азота, который остается в угле и вытесняет метан, можно рассматривать как количественный вклад эффекта смещения. Выявлено, что в результате использования данной технологии, уровень замещения метана возрос более, чем на 60%; а уровень его вытеснения – на 40%.

Научная новизна. Изучен эффект вытеснения метана при нагнетании азота в угольный пласт с точки зрения поведения газа в угленосной толще, а также дана количественная оценка эффекту замещения, оказывающему ключевое влияние на всех стадиях процесса, в то время как роль вытеснения – вторична.

Практическая значимость. Результаты экспериментов имеют принципиальное значение для оптимизации параметров газа и для выбора источника впрыскивания газа в угольные пласты.

Ключевые слова: *механизм N_2-ECBM, фактор времени, эффект вытеснения, эффект замещения, количественный анализ, угольная шахта*

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