

Article

Simulation of Water Influx and Gasified Gas Transport during Underground Coal Gasification with Controlled Retracting Injection Point Technology

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Abstract: Underground coal gasification (UCG) may change the energy consumption structure from coal-dominated to gas-dominated in the years to come. Before that, three important problems need to be solved, including failure of gasification due to large amounts of water pouring into the gasifier, environmental pollution caused by gas migration to the surface, and low calorific value caused by poor control of the degree of gasification. In this study, a geological model is first established using the computer modeling group (CMG), a commercial software package for reservoir simulation. Then, the inflow of coal seam water into the gasifier during the controlled retracting injection point (CRIP) gasification process is simulated based on the geological model, and the maximum instantaneous water inflow is simulated too. Meanwhile, the migration of gasified gas is also simulated, and the migration discipline of different gases is shown. Finally, the pressure distributions in two stages are presented, pointing out the dynamic pressure characteristics during the UCG process. The results show that (a) the cavity width, production pressure, and gasifier pressure are negatively correlated with the maximum instantaneous water inflow, while the initial formation pressure, injection pressure, coal seam floor aquifer energy, and temperature are positively correlated; (b) CO₂ is mainly concentrated near the production well and largely does not migrate upward, O₂ migrates upward slowly, while CH₄, CO and H₂ migrate relatively quickly. When the injection–production pressure difference is 2 MPa, it takes 33.5 years, 40 years, and 44.6 years for CH₄, CO, and H₂ to migrate from a depth of 1000 m to 200 m, respectively. When the pressure difference increases to 4 MPa, the gas migration rate increases about two-fold. The aquifer (3 MPa) above a coal outcrop can slow down the upward migration rate of gas by 0.03 m/day; (c) the pressure near the production well changes more significantly than the pressure near the injection well. The overall gasifier pressure rises with gasifier width increases, and the pressure distribution always presents an asymmetric unimodal distribution during the receding process of the gas injection point. The simulation work can provide a theoretical basis for the operation parameters design and monitoring of the well deployment, ensuring the safety and reliability of on-site gasification.

Keywords: underground coal gasification (UCG); controlled retraction injection point (CRIP); water inflow; gas migration; pressure distribution



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1. Introduction

With proposals for peak carbon and carbon neutrality, human beings have increased the pace of moving from using high carbon energy to using low-carbon and no-carbon

energy [1,2]. As a clean technology, underground coal gasification can not only exploit deep coal resources to enrich natural gas supply, but also reduce the environmental pollution caused by coal combustion [3,4]. At present, the commercial application of the technology is still challenging, and three concerns need to be focused on, including gasification safety [5,6], environmental pollution assessment [7,8] and gasification process control [9,10].

In poor hydrogeological conditions, a large amount of water may flood into the gasifier, which restricts the long-term safe and stable operation of underground coal gasification [11]. The migration law of gasified gas is not clear [12]. If gasified gas migrates to the surface along the coal seam, the release will result in atmospheric pollution. Gasifier pressure is an important factor affecting the stability of gasification [13]. Water inflow, gas migration, and gasifier pressure can affect gasification safety, environmental pollution degree, and the degree of gasification process control, respectively, to some extent. At present, a large amount of literature focuses on simulations of the development of combustion cavity [14] and surface subsidence [15], while simulations of water inflow, gas migration, and pressure propagation are lacking. Thus, it is necessary to carry out dynamic simulations of water inflow, gas migration, and pressure propagation to study gasification safety, environmental influence, and gasification control, respectively.

In this study, first, a geological model is established using the computer modeling group (CMG). Second, the inflow of coal seam water into the gasifier during the controlled retracting injection point (CRIP) gasification process is simulated based on the geological model. The instantaneous maximum water inflow is also simulated with different well pattern, gasifier width, operation pressure, injection/production pressure difference, gasifier pressure, initial formation pressure, coal seam floor aquifer, and temperature. Third, the migration of gasified gas is also simulated, and the migration discipline of different gas types is revealed. Finally, the pressure distributions in two stages are presented, pointing out the dynamic pressure characteristics during the UCG process. The simulation of water inflow, gas migration and gasification pressure can provide a theoretical basis for the operation parameters design and the monitoring of well deployment in advance, ensuring the safety and reliability of on-site gasification.

2. Geological Model

The study area is the middle part of the middle Jurassic Xishanyao Formation (J₂x) in the Xi'xiagou block of Santanghu basin. The burial depth spans from 800 m to 1500 m, and the dip angle is about 15°, which reflects the gently dipping coalbed. The overall structure of the coalbed in the area is monoclinical with a low southwest and high northeast and has grooves and nose-like structures. There are low-lying structures in the southwest corner of the study area, and the coalbed is denuded and completely affected by Chahaquan uplift in the northeast. The tectonic movement of the coalbed is obviously affected by the palaeohigh, and the dip angle changes greatly in the northeast, while the coalbed dip angle is small in the southwest. Figure 1a,b are tectonic maps of the Xi'xiagou coalbed roof and coalbed floor, respectively. Based on the interpretation of 3D seismic data, eight faults (F1–F8) are mainly developed in the study area, which are mainly distributed in the north and south wings of the Tiaohu Sag.

Figure 2a,b show the hydrogeological profiles of the Tiaohu Sag along the northeast-southwest direction and the northwest-southeast direction, respectively. It can be seen from Figure 2a that the coalbed is uplifted in the northeast direction and exposed to the surface. Atmospheric precipitation and surface water can penetrate the aquifer and the coalbed outcrop, then flow in the southwest direction along the monocline dip. There is a fault F1 with a large fault distance in the west dip direction, and a fault F2 with a small fault distance in the east dip direction. The coalbed average dip angle in the gasification area is about 15 degrees, which has good water isolation and drainage conditions. From Figure 2b, the tectonic changes of the coalbed and overburden are relatively gentle, and there is no significant fault influence near the gasification area.

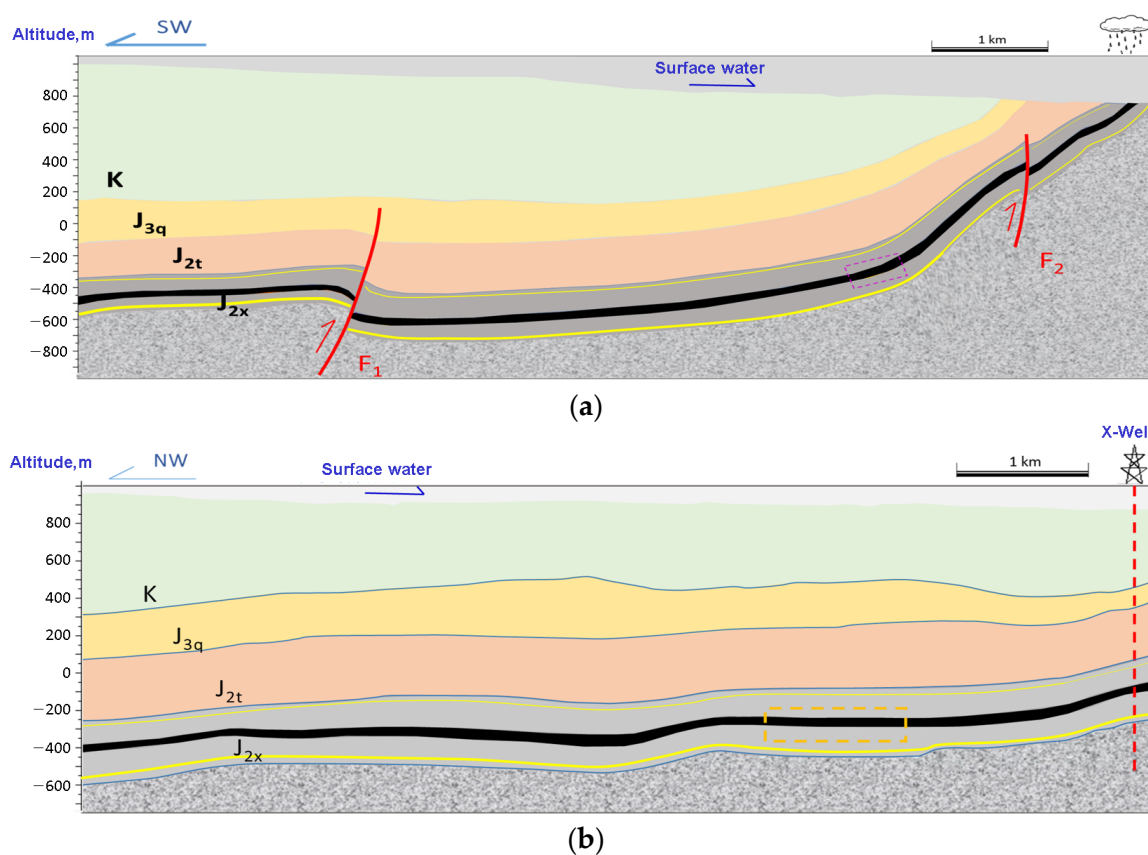
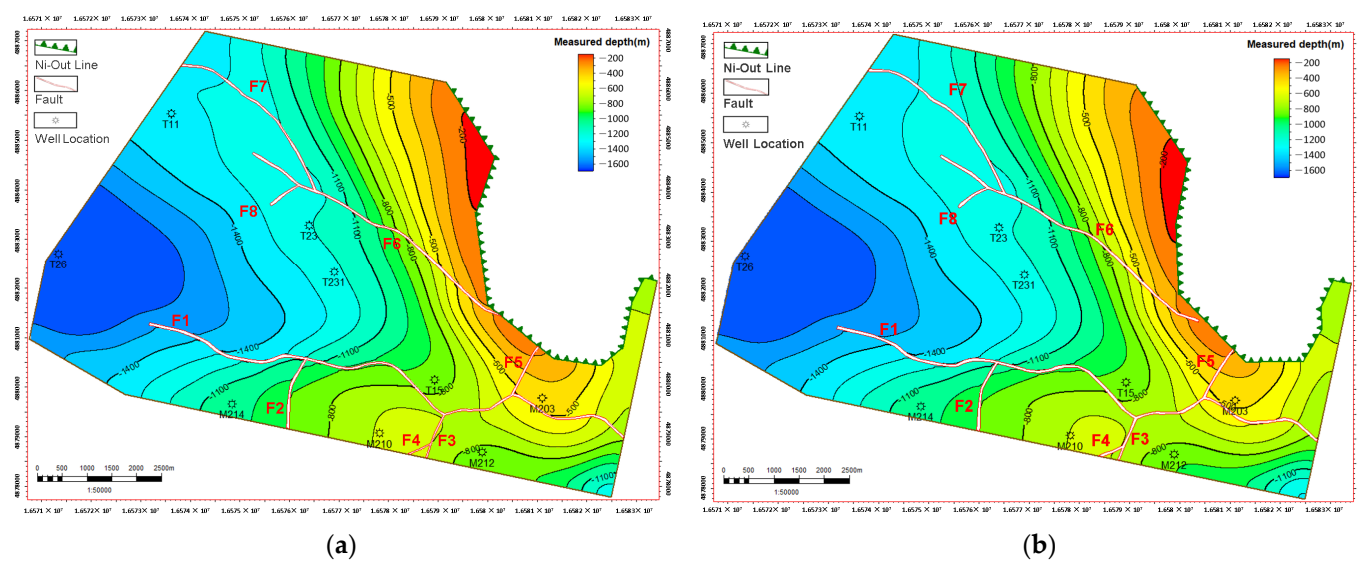
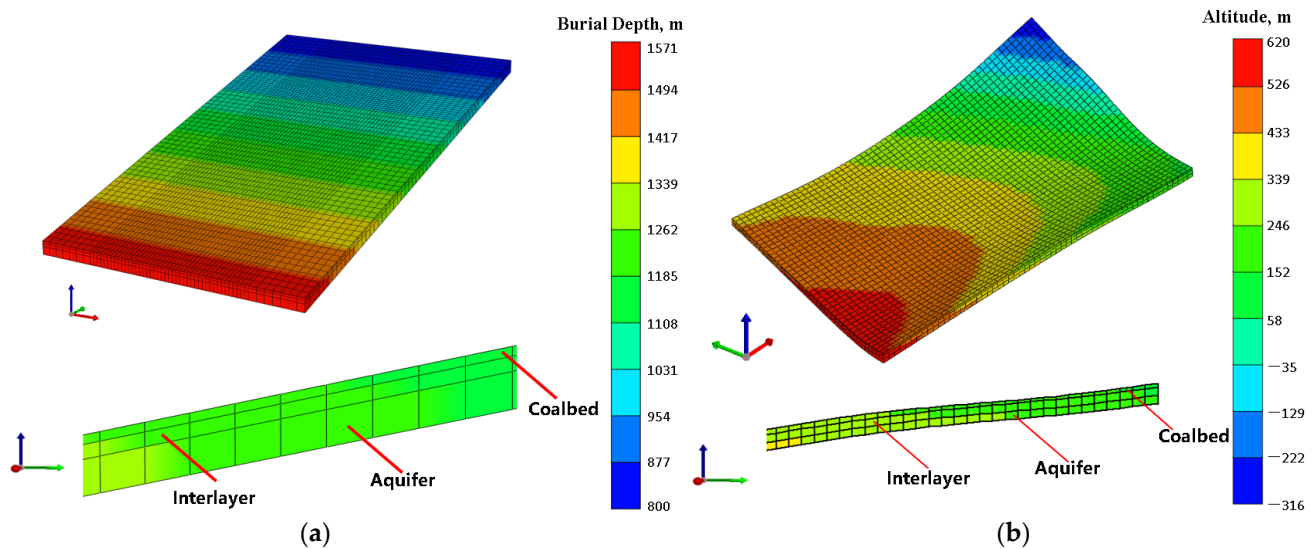


Figure 2. The hydrogeological profile of the Tiaohu Sag. (a) Along the northeast-southwest direction. (b) Along the northwest-southeast direction.

According to hydrogeological study, the coal seam roof has enough safety thickness, with little impact on gasification, so only the influence of the coal seam floor shall be considered. Table 1 shows the basic parameters of the geological model. Figure 3a,b show an ideal conceptual model and an actual geological model of the pilot area, respectively.

Table 1. Basic model parameters.

Item	Value
Coalbed thickness, m	13
Coalbed angle, °	15
Interlayer thickness, m	20
Aquifer thickness, m	50
Porosity, %	9.87
Coalbed middle depth, m	1000
Fracture permeability, mD	15
Grid size, m ³	57 × 64 × 3
Control area, m ²	1800 × 2850
Grid type	Non-orthogonal corner point
Fluid model	GEM
Pore permeability model	DUALPERM
Matrix permeability, mD	2

**Figure 3.** The geological model. (a) The ideal conceptual model. (b) The actual geological model.

The gasification process of the CRIP is simulated according to the established geological model. In this study, the retraction dynamic process is realized by moving the injection well position, as shown in Figure 4. The receding speed of the gas injection point is 50 m/50 days.

The above implementation principle is shown in Figure 5. The first gasifier is 50 m and lasts for 50 days. In the second 50 days, the gas injection point recedes from 1 to 2, and the length of the gasifier increases to 100 m. During the third 50 days, the injection point is reduced from 2 to 3, and the length of the gasifier is increased to 150 m. This process is repeated until the desired gasification length is reached and the entire gasification process is completed.

According to the model, the characteristics of coal seam water, gasified gas, and pressure in the gasification process are studied, respectively.

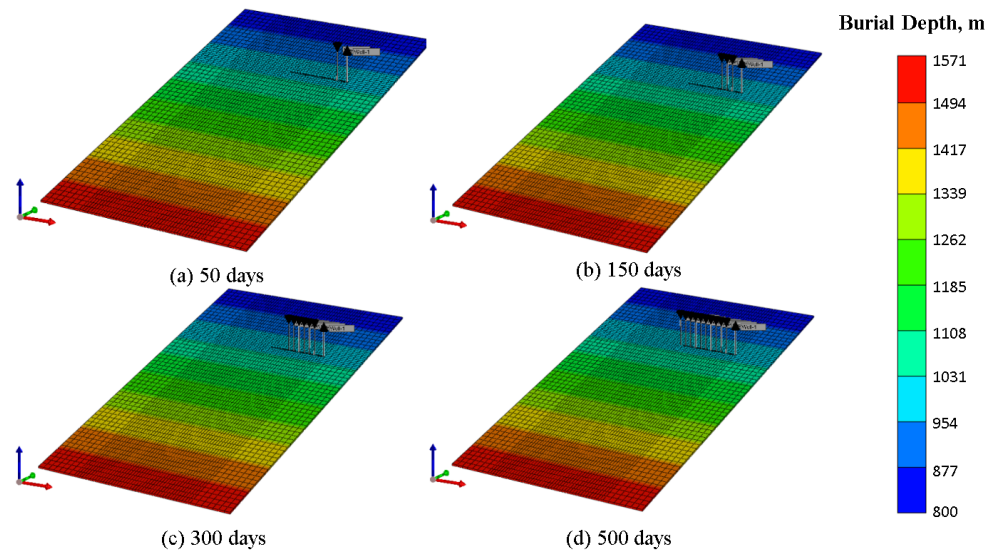


Figure 4. The retraction dynamic process.

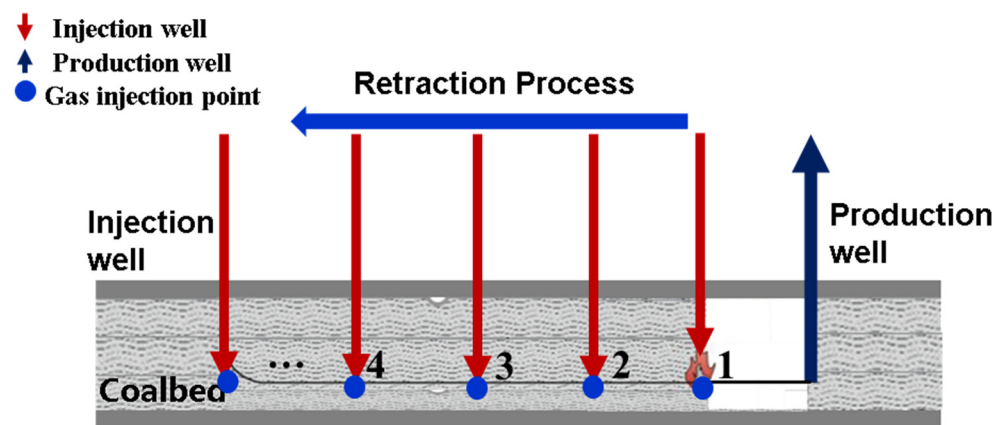


Figure 5. The principle of CRIP.

3. The Inflow Characteristics of Coal Seam Water

Most underground coal gasification projects are affected by the gasification technology used; the implementation of unsuitable technology may result in operational shutdown. For example, at the initial moment of gasification, coal cannot be ignited or burned normally due to the large influx of water from outside the gasifier, which leads to gasification failure and other adverse effects [16,17]. The mechanism of the negative effect of groundwater influx on the gasification process is as follows:

- The high temperature flow is cooled, and the CO/CO₂ conversion is dominant, leading to a relative reduction in combustible components, thus reducing the calorific value.
- The groundwater influx creates a water layer in the tunnel, blocking the narrow air passage.

Notably, the amount of groundwater entering gasifiers during coal gasification, should be less than the safe upper limit of water inflow to ensure gasification safety. If the water inflow is too much, a reasonable dewatering method should be selected according to the location conditions [18,19].

According to hydrogeological analysis in this coal deposit, the safe upper limit of water inflow is 1 m³/t [20,21].

The coal seam initial water reserve can be determined according to the flowing material balance equation [22]. The dynamic change in pore structure and permeability of a coal seam can also be determined by dewatering data [23–25]. Daily water inflow per

ton (DWIPT) is calculated to quantitatively evaluate the safety of water inflow, and its transformation relationship with daily water inflow (DWI) as follows:

$$DWIPT = \frac{DWI + w \cdot h \cdot l \cdot \varphi_{\text{coal}} \cdot S_{\text{wi}}}{w \cdot h \cdot l \cdot \psi_{\text{burned}} \cdot \rho_{\text{coal}}} \quad (1)$$

where $DWIPT$ represents the water inflow per ton of coal, m^3/t ; DWI is the daily water inflow into the gasifier, m^3/d ; w is the gasifier width, m ; h is the coalbed thickness, m ; l is the daily increase of gasifier length, m/day ; φ_{coal} is the porosity of coal, fraction; S_{wi} is the initial water saturation, fraction; ψ_{burned} is the percentage of burned volume in unit volume of coal, fraction; and ρ_{coal} is the coal density, t/m^3 .

Coal seam water pouring into the gasifier is generally a three-stage process, including a spurt stage, a decline period, and a stable period. Figure 6 shows the change in water inflow when a certain gasifier is instantly burned to a predetermined size. Section A–B is the first stage, and the coal seam water inflow into the gasifier increases sharply until it reaches the maximum value B. Point B becomes the maximum instantaneous inflow. In the second stage B–C, the coal seam water inflow into the gasifier begins to decrease. After point C, the water inflow into the gasifier changes little and becomes stable. Point D becomes the steady water inflow. The maximum instantaneous water inflow, the value of point B, ought to be focused on, and the data starting from point B should be recorded in subsequent studies.

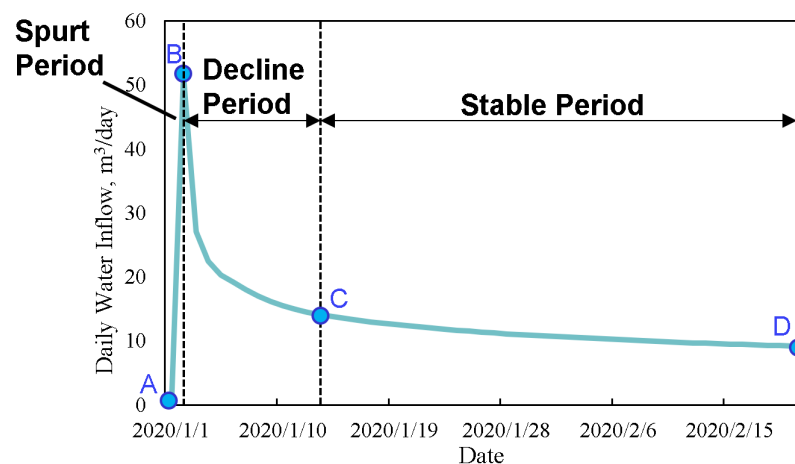


Figure 6. The stage in which water pours into the gasifier.

The water inflow is determined not only by the natural conditions of the coal deposit (such as the coal seam floor aquifer, initial formation pressure, etc.), but also by artificial factors during coal gasification [16], including the well pattern, gasifier width, operating pressure, injection–production pressure difference, gasifier pressure, and temperature. Detailed consideration of these factors on the coal seam water inflow is presented below.

3.1. Well Pattern

The CRIP unit adopts a U-shaped structure, which consists of a production well and a horizontal injection well. The combustion diffusion, combustion time and water inflow are different with position alteration of the injection well and the production well because of the dip angle [26]. In order to explore the influence of different gasifier types on gasification, three different well patterns are designed in this project. Figure 7a,b show the well pattern of horizontal wells along the dip of the coal seam and along the strike of the coal seam, respectively. In Figure 7c, the horizontal well extends along a 45° dip with the coal seam inclination.

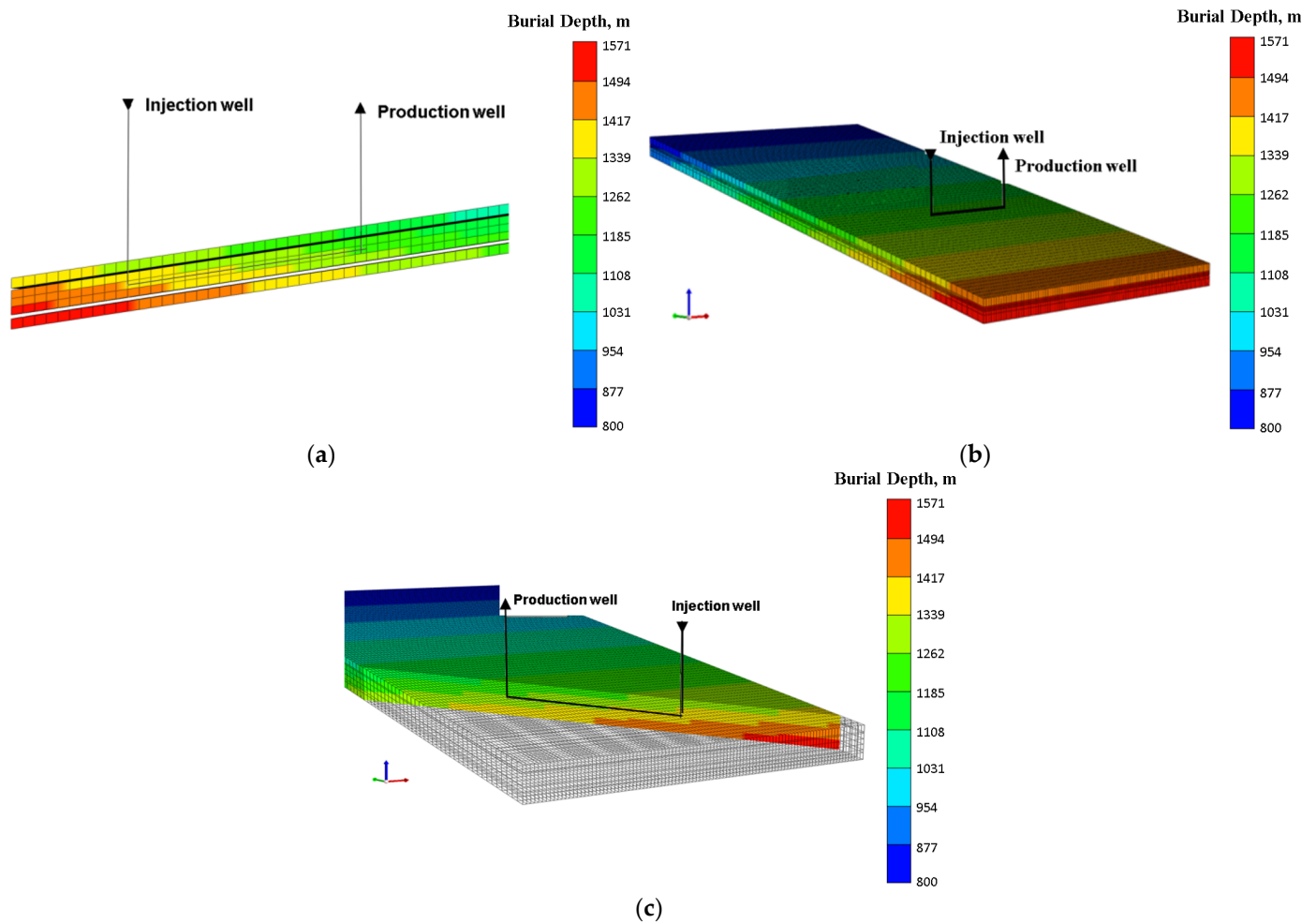


Figure 7. Three different well patterns. (a) Well-pattern I: Along the dip of coal seam. (b) Well-pattern II: Along the strike of the coal seam. (c) Well-pattern III: Along a 45° dip with the coal seam inclination.

In Figure 7a,c, the injection well is located below the production well, ensuring gasification safety. Due to gravity, coal seam water will migrate to the low-lying area in the gasification process; thus, the gasification cavity, with a high capacity to deal with coal seam water influx, should be arranged at the lower part of the coal seam. For the first gasification cavity, the overall temperature is low, and the ability to deal with coal seam water influx is low. After a period of gasification, the temperature in the gasifier increases, strengthening the ability to deal with more coal seam water by evaporation. Therefore, the moving direction of the gas injection point should be along the downward dip direction of the coal seam. The daily water inflow per ton (DWIPT) of the three different well patterns above are simulated, and the results are shown in Figure 8.

The gasification well pattern is evaluated from three perspectives: gasification safety, the construction cost of the gasifier and the difficulty of gasification process control.

- Gasification safety: At the initial moment, the water inflow of well-pattern II is slightly higher than that of the others, indicating that the water influx speed of well-pattern II is slightly higher than that of the other two patterns at the initial moment. In the later stage, the water inflow of well-pattern II is less than that of the other two well patterns, indicating that the safety of well-pattern II is the best under the quasi-steady state of gasification.
- Construction cost: The drilling of well-patterns I and III requires precise consideration of the impact of the coal seam dip angle, while well-pattern II does not. Therefore, well-pattern II has the simplest drilling method and the most economical construction cost.

- Gasifier control: The shape of the gasification cavity in well-patterns I and III is difficult to control.

To sum up, in terms of the above three considerations, well-pattern II is the optimal deployment. Comparative analysis of the gasification yield is a factor that can be considered in future optimization.

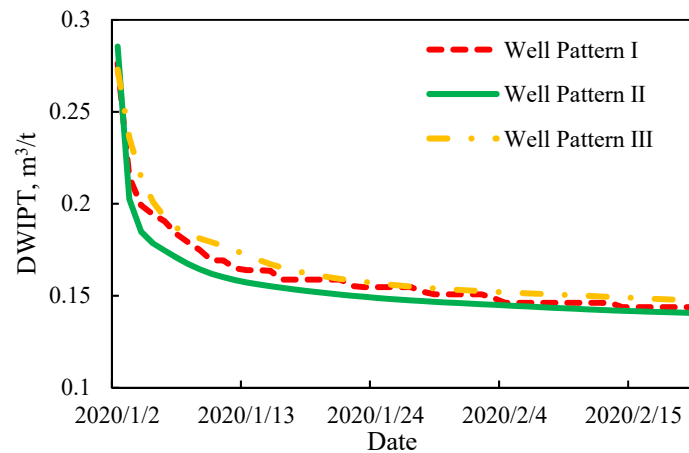


Figure 8. DWIPT changes by date for different well patterns.

3.2. Cavity Width

The quality of generated gas can be guaranteed with a reasonable cavity width. When the gasification cavity is too large to maintain chemical reaction conditions, the quality of the gasification gas will reduce. At this point, the gas injection point needs to be withdrawn to carry out the gasification process in the next coal seam. In the combustion process of each section, the coal needs to be burned gradually from small to large, until the predetermined size of the gasifier is reached. It is worth considering how the water inflow changes in this process and whether it will harm the safety of gasification.

Setting the cavity width as 1, 1.5, 2, 2.5, 3, 3.5 and 4 times the coalbed thickness, respectively, the correlation between the cavity width and the water inflow is studied. Figure 9 shows the grid diagram for different gasification cavity widths.

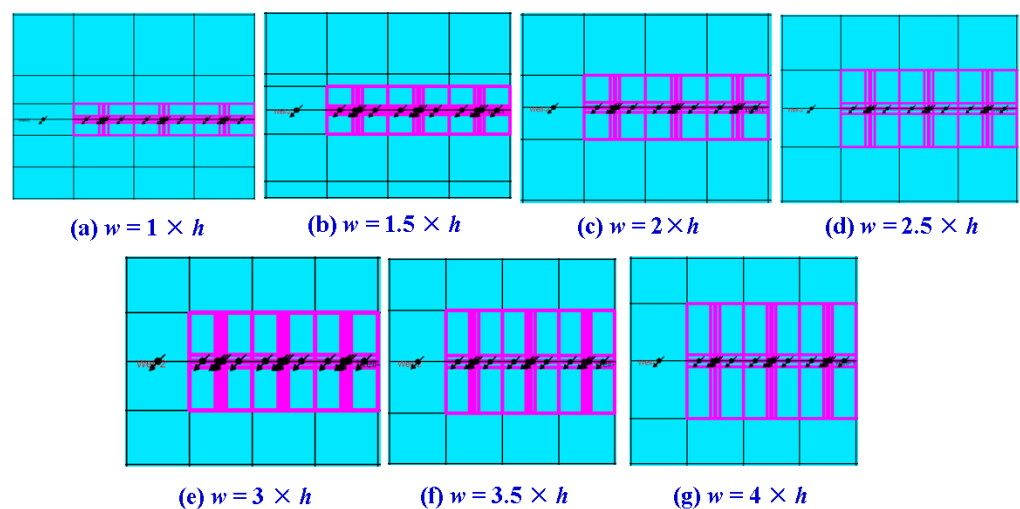


Figure 9. The grid diagram for different cavity widths.

Water inflow is simulated for the above seven different cavity widths, and the results are shown in Figure 10. Represented by the maximum inflow, the trend of inflow with the increase of cavity width is shown in Figure 11.

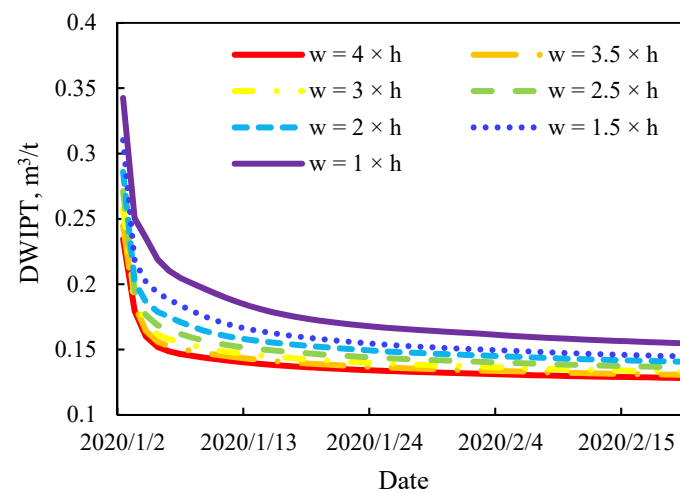


Figure 10. DWIPT changes by date for different cavity width.

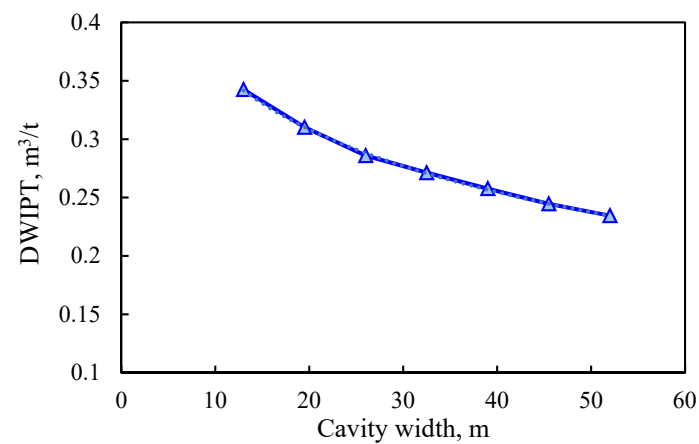


Figure 11. The change in water inflow as the cavity gradually enlarges.

According to Figure 10, at any time, the smaller the cavity width, the larger the water inflow. This suggests that the groundwater influx becomes more harmful the smaller the cavity, particularly at the initial moment of gasification. Figure 11 shows that there is a logarithmic relationship between water inflow and cavity width:

$$DWIPT = -0.077 \ln w + 0.5402 \quad (2)$$

To ensure that the water inflow in the gasification process will not pose a safety threat, the water inflow when the cavity is extremely small ought to be calculated. It is assumed that the size of the limit gasifier is $1 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$. At this time, encryption is required on the grid i, j and k directions, as shown in Figure 12.

The water inflow of the limit gasifier is simulated as shown in Figure 13. It can be observed that when the gasifier size is extremely small, the water inflow is also less than $1 \text{ m}^3/\text{t}$ (the upper limit of safe inflow). Thus, the limit water inflow in this area will not pose a challenge to the gasification safety. According to the test data, the trend of water inflow with the change in gasifier volume is shown in Figure 14.

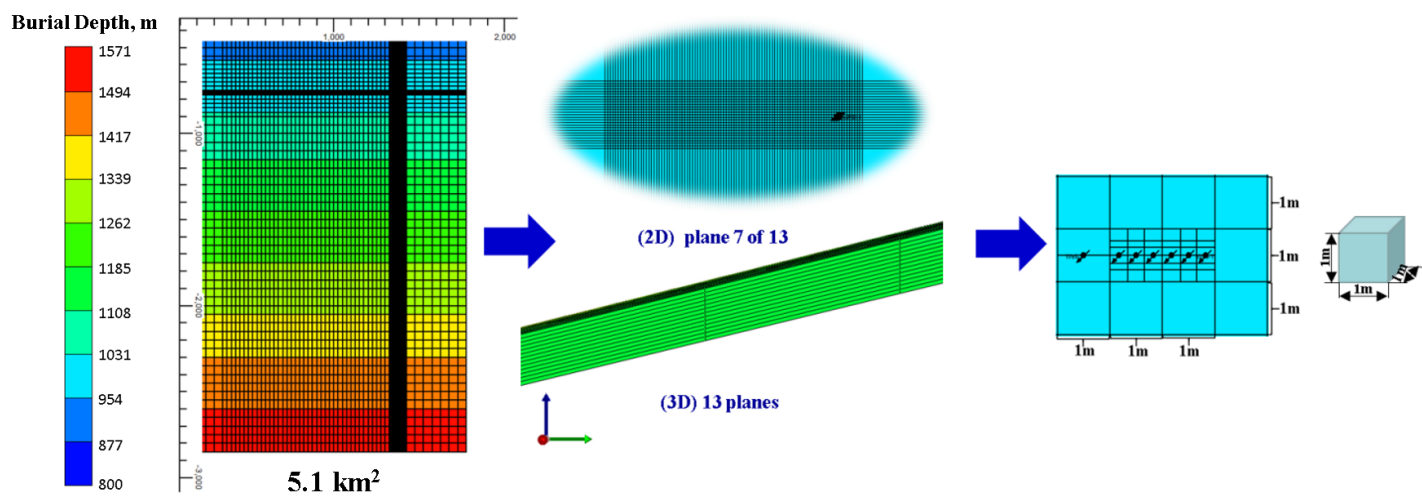


Figure 12. Construction of limit gasifier model.

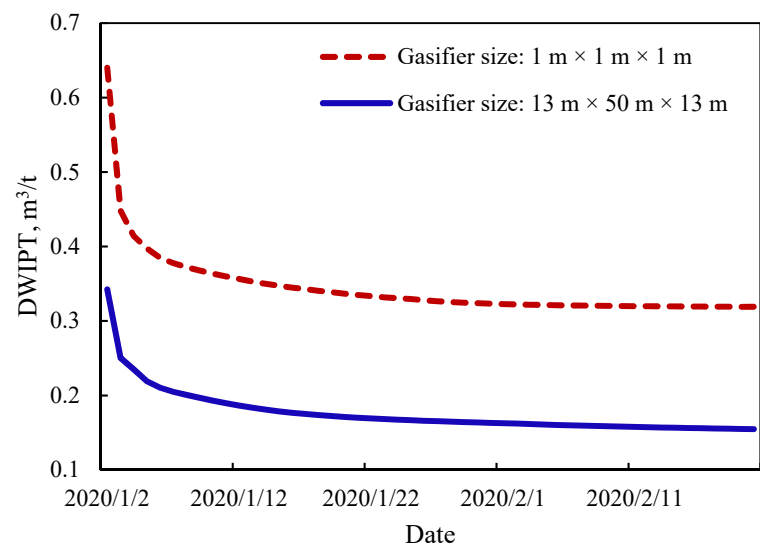


Figure 13. DWIPT changes by date for different gasifier size.

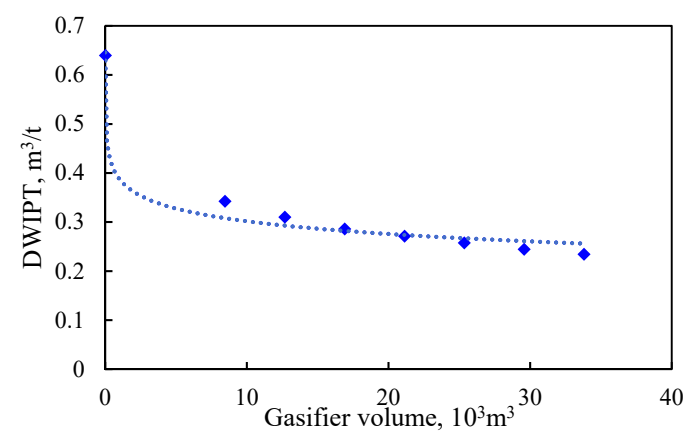


Figure 14. Correlation between water inflow and gasifier volume (the middle Jurassic Xishanyao Formation).

As shown in Figure 14, the relationship is correlative and falls in the range of variability of the gasifier volume from 1 m^3 to $33.8 (1000 \text{ m}^3)$, which can be expressed by a logarithmic equation:

$$DWIPT = -0.037 \ln V + 0.3877 \quad (3)$$

where V denotes the gasifier volume, 10^3 m^3 . The formula can be used to roughly calculate the water inflow of any cavity size. The correlations clearly show that, as the volume of gasifier increases, the water inflow per ton of coal decreases.

3.3. Operation Pressure

Operation pressure will affect the gasified gas quality, gasification efficiency and thermal efficiency [3]. Both the model and field tests show that desirable gas quality, gasification efficiency and thermal efficiency can be obtained under periodic pressure. In this condition, convective heat transfer between the fluid and coal seam is dominant, which has the following two advantages:

- Preheating of the coal seam within a certain distance in front of the gasification reaction zone, which is beneficial to the combustion and gasification of coal seam.
- Increasing the pyrolysis products and avoiding the combustion of pyrolysis gas.

Therefore, it is necessary to study the water inflow under different injection–production pressures and to explore the effect of injection–production pressures on water inflow to ensure the safety of the gasification process. The injection pressure is set as 11 MPa and the production pressure is changed to explore the effect of production pressure on the water inflow (Figure 15).

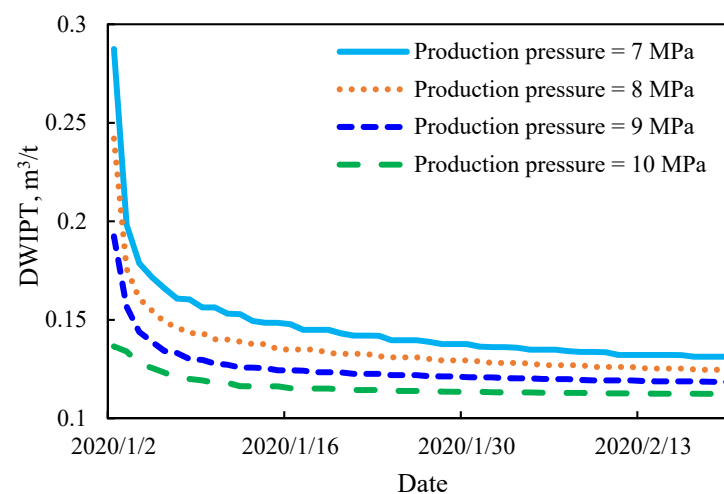


Figure 15. DWIPT changes by date for different production pressures (Injection pressure = 11 MPa).

As shown in Figure 15, the lower the production pressure is, the higher the water inflow is. When the production pressure is fixed at 9 MPa, the relationship between the injection pressure and water inflow is displayed in Figure 16.

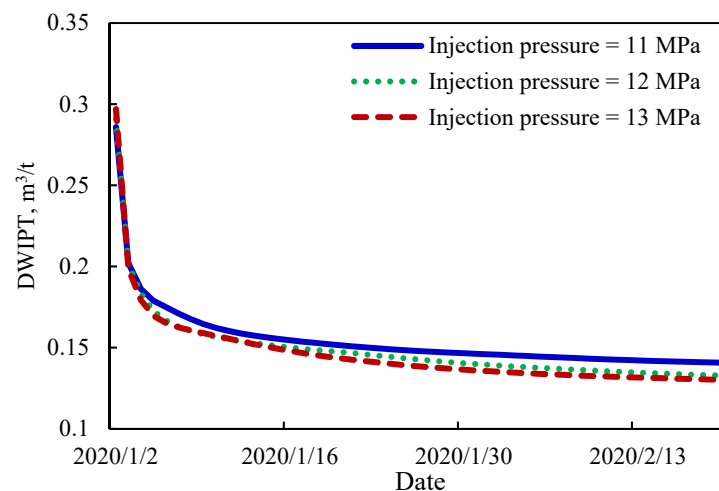


Figure 16. DWIPT changes by date for different injection pressures (production pressure = 9 MPa).

As shown in Figure 16, the change in water inflow is not obvious when the production pressure is fixed and the injection pressure is changed. Through the above analysis of production pressure and injection pressure, it can be seen that the production pressure has a more significant effect on water inflow than injection pressure. In the field, there are two basic principles for the selection of injection–production pressure:

- The gasifier pressure should be less than the reservoir pressure as far as possible, so that the gas generated does not migrate to the reservoir (reservoir pressure is 10.601 MPa)
- The injection–production pressure difference should be less than 2 MPa, so that the injected gas can fully participate in the chemical reaction.

According to the above two principles, six schemes of injection–production pressure are formulated, as shown in Table 2. Their water inflow is simulated in Figure 17.

Table 2. Six schemes of injection–production pressure.

Number	Production Pressure, MPa	Injection Pressure, MPa
1	10	11
2	10	11.5
3	10	12
4	9.5	11
5	9.5	11.5
6	9	11

According to the above results, when the pressure in this area changes periodically, the water inflow will not pose a threat to safety. When the production pressure is the same, the stable water inflow in the later stage is basically the same. This demonstrates that the production pressure has a more significant effect on water inflow than the injection pressure.

3.4. Injection–Production Pressure Difference

The change in the injection–production pressure difference will affect the water inflow and gas calorific value, which can be explained by the following two points:

- In the field, increasing the injection–production pressure difference can improve the reaction temperature, which is conducive to the conversion of part of the influx water into steam.
- The calorific value of the gas can be increased by increasing the injection–production pressure difference in a certain range. When exceeding the range, the calorific value of the gas decreases and the content of CO₂ increases, indicating that part of the

gasification products are burned. Therefore, an appropriate injection–production pressure difference should be selected to avoid gas leakage and CO oxidation.

Different injection–production pressure difference leads to different water inflow, so it is necessary to explore the relationship of water inflow under different injection–production pressure difference to ensure the safety of water inflow in the gasification process. According to the field experience, the injection–production pressure difference should be less than 2 MPa as far as possible, so that the injected gas can fully participate in the chemical reaction. Setting the injection–production pressure difference at 2 MPa, the water inflow was simulated under different injection–production pressures, as shown in Figure 18.

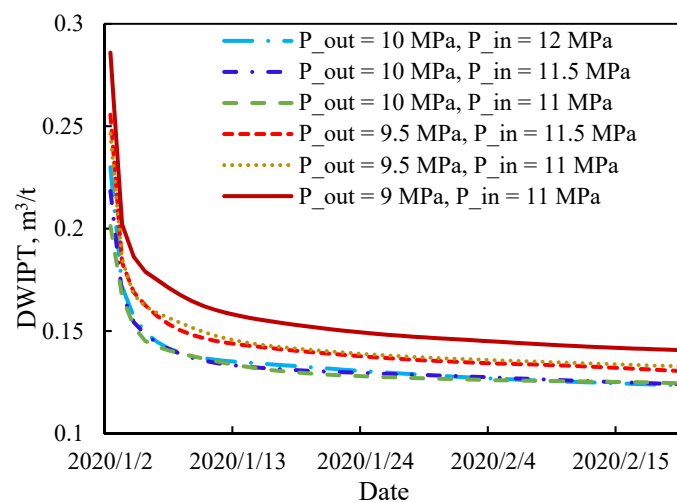


Figure 17. DWIPT changes by date for six pressure schemes.

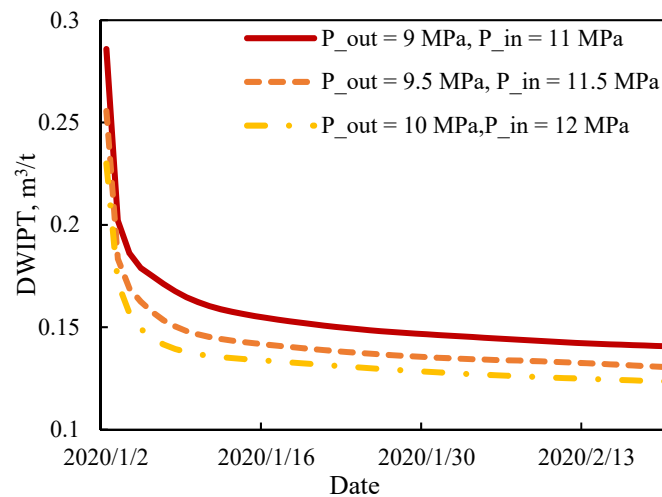


Figure 18. Water inflow when injection–production pressure difference is 2 MPa.

According to the figure, under the same injection–production pressure difference, the smaller the production pressure, the larger the water inflow. The injection–production pressure difference is increased to 4 MPa and 5 MPa, respectively, and the water inflow simulation is shown in Figure 19.

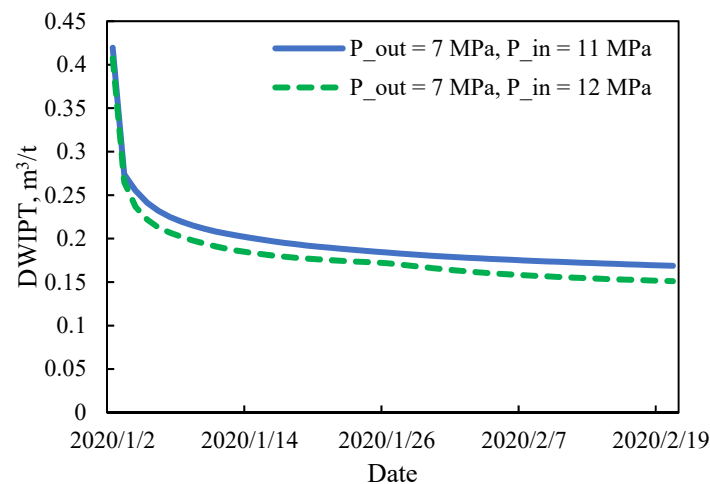


Figure 19. Water inflow when injection–production pressure difference is 4 MPa and 5 MPa.

It can be seen from Figure 19 that when the pressure difference increases by 1 MPa by increasing the injection pressure and keeping the production pressure constant, the maximum instantaneous water inflow and steady water inflow decrease. This implies that the increasing injection–production pressure difference does not always correspond to a greater water inflow, as a result of the reduced pressure difference between the coal seam and the gasifier; in other words, the water inflow driving force decreases.

3.5. Gasifier Pressure

There are some relationships among the gasifier pressure, injection pressure, production pressure and the initial formation pressure. The injection pressure is higher than the initial formation pressure, the production pressure is lower than the initial formation pressure, and the gasifier pressure is between the injection pressure and production pressure. In order to represent the gasifier pressure simply, the average value method is adopted in this study, as follows:

$$P_{\text{gasifier}} = \frac{P_{\text{in}} + P_{\text{out}}}{2} \quad (4)$$

where P_{gasifier} denotes the gasifier pressure, P_{in} is the injection pressure, and P_{out} is the production pressure. The injection pressure should be slightly higher than the reservoir pressure of 10.601 MPa. In this study, the injection pressure is set as 11 MPa, and different gasifier pressures can be obtained by changing the production pressure. Table 3 shows eight schemes of the gasifier pressure. Their water inflows are shown in Figure 20.

Table 3. Eight schemes of the gasifier pressure.

Number	Injection Pressure, MPa	Production Pressure, MPa	Gasifier Pressure, MPa
1	11	10.4	10.7
2	11	10.2	10.6
3	11	10.0	10.5
4	11	9.8	10.4
5	11	9.6	10.3
6	11	9.4	10.2
7	11	9.2	10.1
8	11	9.0	10.0

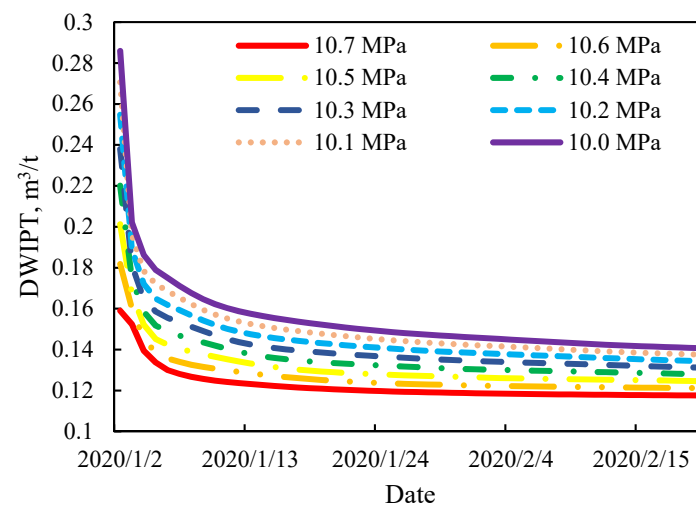


Figure 20. DWIPT changes by date for different gasifier pressures.

Taking the maximum instantaneous water inflow as an example, the variation trend in water inflow under different gasifier pressures is depicted (see Figure 21). The correlation between the gasifier pressure and the water flow is polynomial within the range of gasifier pressures from 8.50 MPa to 10.50 MPa:

$$DWIPT = -0.0201P_{gasifier}^2 + 0.2438P_{gasifier} - 0.1477 \quad (5)$$

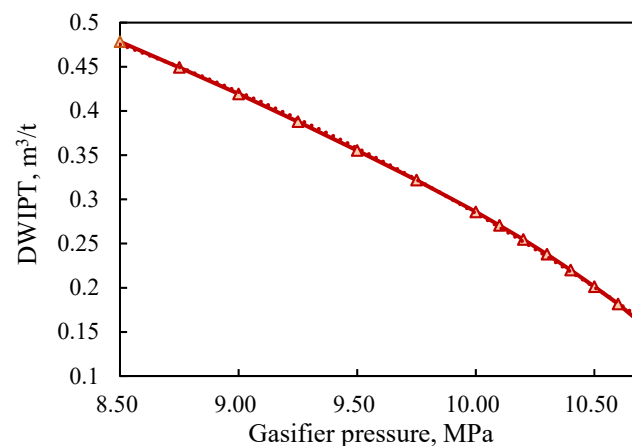


Figure 21. The relationship between gasifier pressure and water flow.

As shown in Figure 21, the smaller the gasifier pressure, the larger the water inflow. At the same time, with decrease in the gasifier pressure, the water inflow shows a rising trend, and the rising amplitude slowly decreases.

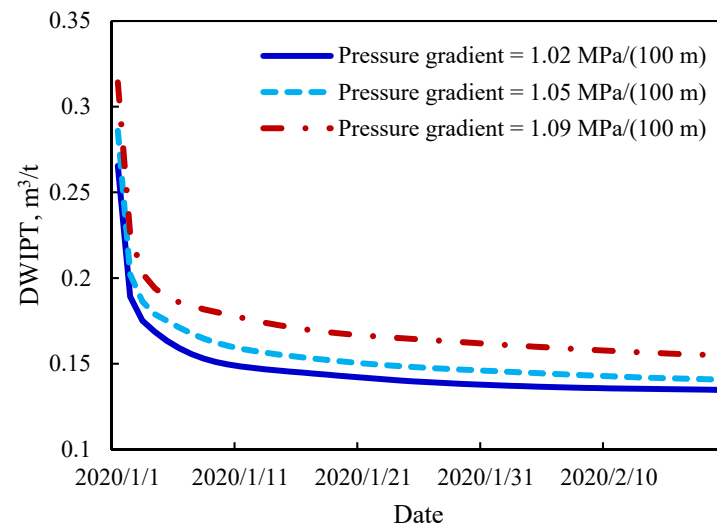
3.6. Initial Formation Pressure

Since the initial pressure of the coal seam will affect the water inflow, the deployment of gasification wells and monitoring wells in the test area will affect the water inflow. Research on the correlation between the initial formation pressure and the water inflow can provide guidance for well placement.

According to the field data, the ground pressure gradient ranges from 1.02 MPa/(100 m) to 1.09 MPa/(100 m). Three different ground pressure gradients are set to obtain three different coal seam pressures (see Table 4). Their water inflow was simulated, as shown in Figure 22.

Table 4. Three different initial coal seam pressures.

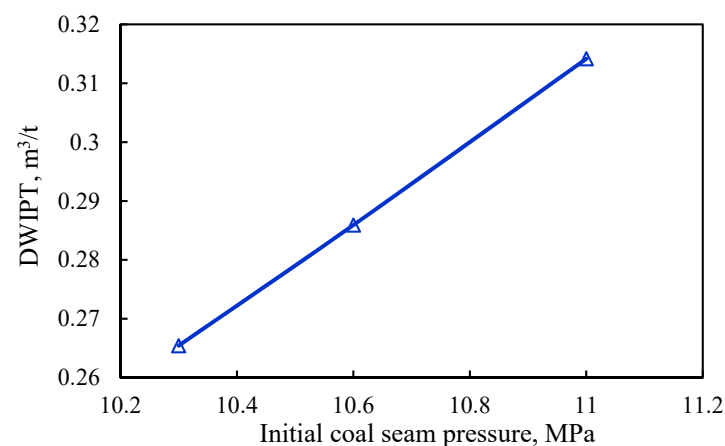
Number	Pressure Gradient, MPa/(100 m)	Initial Coal Seam Pressure, MPa
1	1.02	10.30
2	1.05	10.60
3	1.09	11.00

**Figure 22.** The water inflow under three initial coal seam pressures.

The data for the maximum instantaneous water inflow was taken and the trend in water inflow with increasing coal seam pressure drawn, as shown in Figure 23. The resulting diagram shows that with increase in the initial coal seam pressure, the water inflow also increases gradually, conforming to a linear relationship:

$$DWIPT = 0.0687P_i - 0.4523 \quad (6)$$

where P_i denotes the initial pressure of the coal seam, MPa.

**Figure 23.** The trend of water inflow as initial coal seam pressure increases.

3.7. Coal Seam Floor Aquifer

When the floor breaks, aquifer water may pose a great threat to the safety of the gasification process. In the Tremedal project in Spain and the Hoe Creek Project in the United States, due to damage to the coal seam roof during gasification, the aquifers above the coal seam roof flooded into the gasification channel, resulting in combustion failure [27,28].

Thus, for gasification site selection, it is of great importance to study the water inflow in the case of coal-seam roof and coal-seam floor rupture.

According to the analysis of the hydrogeological characteristics of the study area, there is no aquifer within 42 m from the coal-seam roof, so the risk of roof water inflow can be ignored, and only the water inflow caused by coal-seam floor rupture is studied. The water inflow, at different temperatures, different original aquifer pressures and different aquifer thicknesses, with coal-seam floor rupture is studied successively below.

The coal-seam floor was set as 53.5 °C (reservoir temperature) and 70 °C, respectively, and the water inflows are shown in Figure 24.

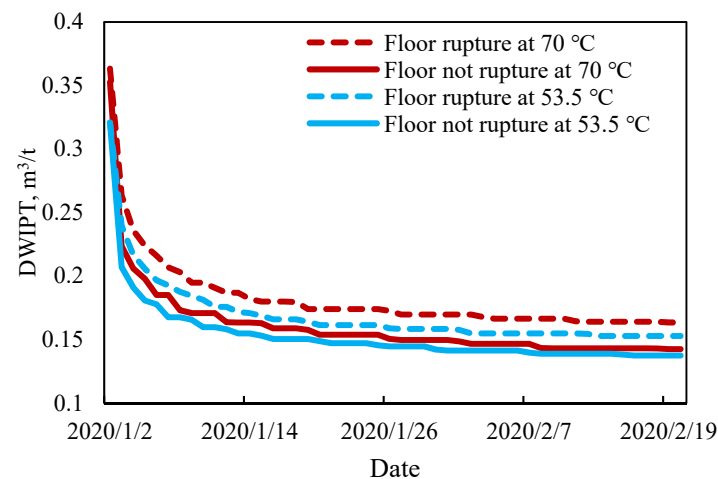


Figure 24. DWIPT changes by date for different aquifer temperature.

As can be seen, the temperature of the coal-seam floor has little influence on water inflow, therefore the change in floor temperature can be ignored. When the floor temperature is higher than the saturated steam temperature of water in the coal seam, the coal-seam water exists in the form of steam, which will not cause further harm to gasification.

Figure 25 shows the water inflow when the original aquifer pressure is set to 11 MPa, 12 MPa, and 13 MPa, respectively. The results show that the bottom-water energy has little effect on the maximum instantaneous water inflow but has a great effect on the steady water inflow. With the progress of gasification, the difference in the influence of the bottom water energy on water inflow gradually increases. The water inflow of the strong bottom water energy is 0.037 m³/t~0.069 m³/t, larger than that of the floor without rupture.

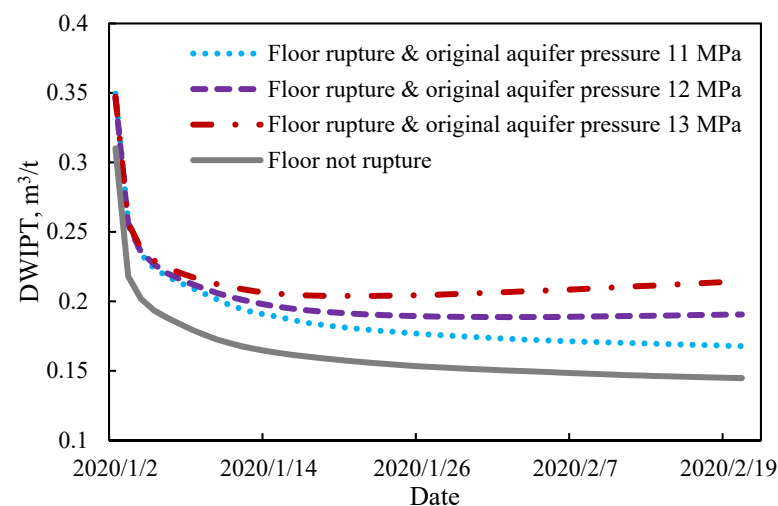


Figure 25. DWIPT changes by date for different bottom water energy.

Figure 26 shows the water inflow when the aquifer thickness is set as 10 m, 30 m and 50 m, respectively. The results show that the maximum instantaneous water inflow increases with increase in aquifer thickness, and when it increases to a certain thickness, the maximum instantaneous water inflow does not increase with increase in aquifer thickness. When the aquifer thickness is 50 m, the maximum instantaneous water inflow increases by $0.34 \text{ m}^3/\text{t}$ compared with the case that the coal seam floor rupture has not occurred.

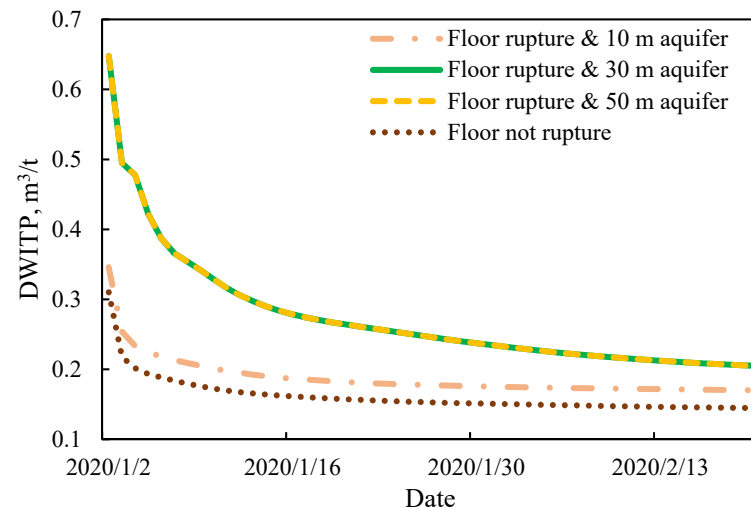


Figure 26. DWITP changes by date for different aquifer thicknesses.

3.8. Temperature

For the gasification process of Long Passage, Large Section, Two Stages proposed by China, the temperature field is extremely important for the production of high calorific value water vapor [29]. Two-stage gasification is an underground gasification process in which air and water vapor are supplied through a circulating system. Each cycle consists of two stages. The first stage is to produce aired coal gas by injecting air into the coal and burning it to retain heat. The second stage is to produce groundwater coal gas by injecting water vapor [30]. The two stages are related, and only enough heat is stored in the first stage; the water vapor reaction can be achieved in the second stage. In addition, the degree of thermal decomposition of the coal seam and the yield of pyrolytic gas completely depends on the temperature distribution in the coal seam. The temperature of the coal seam can reach more than 1000°C during gasification [31]. Thus, it is worth exploring whether the water inflow will threaten the gasification safety at different temperatures.

The temperature was set to 53.5°C (reservoir temperature), 150°C , 310°C (saturated steam temperature), 500°C , 610°C , 800°C , and 1000°C . Figure 27 shows the water inflow at different temperatures.

It can be seen that the water inflow increases with temperature increases and the water flow is more sensitive to the temperature when the temperature is lower than the saturation steam temperature. When the temperature is 310°C , the water is saturated steam, and the DWITP is less than the safe upper limit of water inflow ($1 \text{ m}^3/\text{t}$). When the temperature is higher, the water is gaseous and will not cause harm to the safety of gasification.

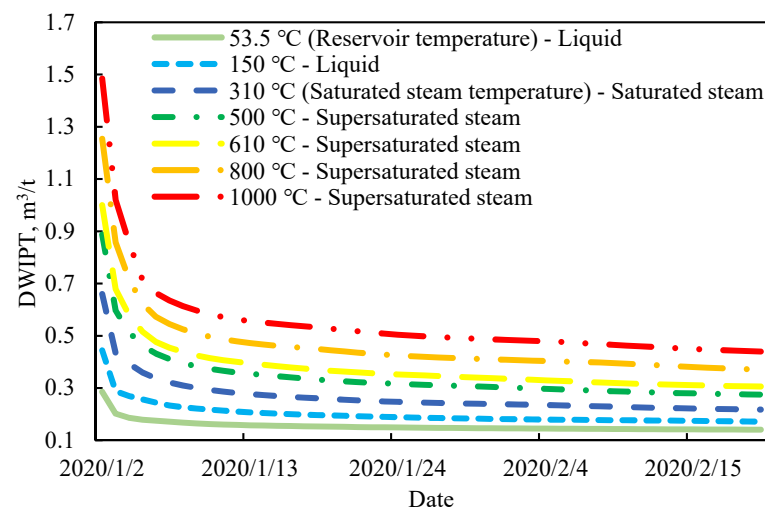


Figure 27. DWIPT changes by date for different temperature.

4. The Migration Characteristics of Gasified Gas

The diffusion of coal gas may pollute groundwater [32]. The components of gasified gas are CH_4 , CO , CO_2 , H_2 , and O_2 , etc. Acid gas, such as CO_2 , penetrates the groundwater and changes the PH value of the groundwater. The gas migration velocity is mainly related to the relative molecular mass of gas, the concentration difference between inside and outside the gasifier, the gasifier pressure and the gasifier temperature [33]. Under the same gasifier pressure and temperature, the gas migration velocity is mainly related to the relative molecular mass of gas and the concentration difference between inside and outside the gasifier.

According to the field test, the components of the gasified gas in the simulation include five gas types: CH_4 , CO , CO_2 , H_2 , and O_2 , with proportions of about 26%, 18%, 30%, 17% and 9%, respectively. After gasification for 500 days, the mole fraction of each gas, relative to the total gas in the coal seam matrix along the coal seam dip direction, is shown in Figure 28. The decimals on the color scale indicate the mole fraction of each gas to the gas mixture.

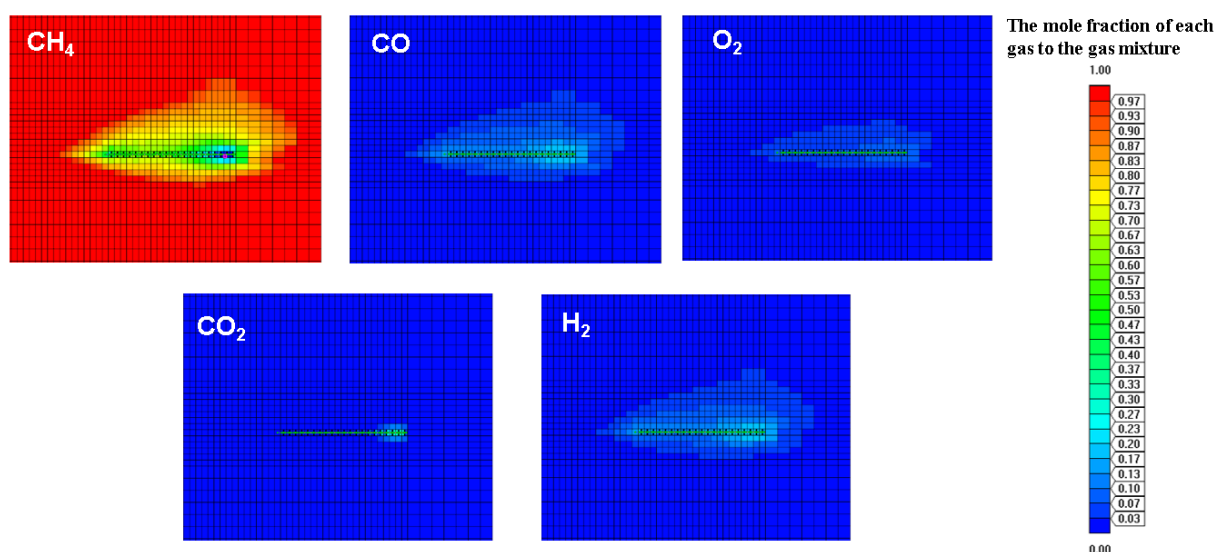


Figure 28. Distribution map at 500 days of gasification.

Different colors represent different values of the mole fraction of each gas to the gas mixture. The color changes from blue to green, to yellow, and finally to red, indicating

that the mole fraction of a certain gas to the gas mixture at some point in the coal seam increases. Before gasification, CH_4 in the coalbed matrix accounts for about 0.95 of the gas mixture, so the background color of CH_4 distribution map is red. The proportion of CO , CO_2 , H_2 , and O_2 to the gas mixture is about zero, so their background color is blue. After gasification, CO , CO_2 , H_2 , and O_2 generated by gasification diffuse in the coal seam, making the proportion of these gases in the gas mixture rise to a certain point in the coal seam matrix, while the proportion of CH_4 gas decreases. CO_2 is mainly concentrated near the production well and does not migrate upward. O_2 migrates upward, but slowly and over short distances. CH_4 , CO , and H_2 migrate upward, and their migration distances are correlated with time. Therefore, attention should be paid to CH_4 , CO , and H_2 in the study of gasified gas transport.

The relative molecular masses of the five gases are in descending order: $\text{CO}_2 > \text{O}_2 > \text{CO} > \text{CH}_4 > \text{H}_2$, and the concentration differences of the five gases in and out of the gasifier are in descending order: $\text{CO}_2 > \text{CH}_4 > \text{CO} > \text{H}_2 > \text{O}_2$. According to the calculation, the upward migration distances of the five gases in the same time are as follows: $\text{CH}_4 > \text{CO} > \text{H}_2 > \text{O}_2 > \text{CO}_2$. The higher the relative molecular mass, the more difficult the upward migration of the gas. The larger the concentration difference inside and outside the gasifier, the faster the diffusion rate. From the above simulation results, it can be concluded that the concentration difference between inside and outside the gasifier is the dominant factor, but the relative molecular mass cannot be ignored at the same time.

When the gasified gas migrates to the site at 200 m vertical depth away from the ground, it is likely to spread to the surface and cause environmental pollution on the surface. Thus, it is necessary to estimate the migration distance of gasification gases and find out their migration rules. The thickness of the coalbed roof in this area is large, and the agent to prevent gas escape is set on the top of the coal seam, so most of the gasified gas will not escape into the aquifer (or sandstone) above the roof of the coal seam. Therefore, this paper mainly studies the gas migration in the coal seam. Figure 29 shows the gas migration distance model.

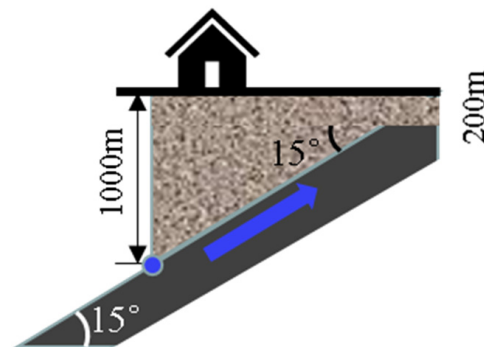


Figure 29. Diagram of the gas migration distance model.

4.1. The Influence of Injection–Production Pressure Difference

The injection–production pressure difference was set as 2 MPa (injection pressure = 11 MPa, production pressure = 9 MPa) and 4 MPa (injection pressure = 12 MPa, production pressure = 8 MPa), respectively, to observe the influence of the injection–production pressure difference on the gas migration law. Figure 30 shows how the migration displacements of CH_4 , CO , and H_2 change with gasification time under two pressure differences.

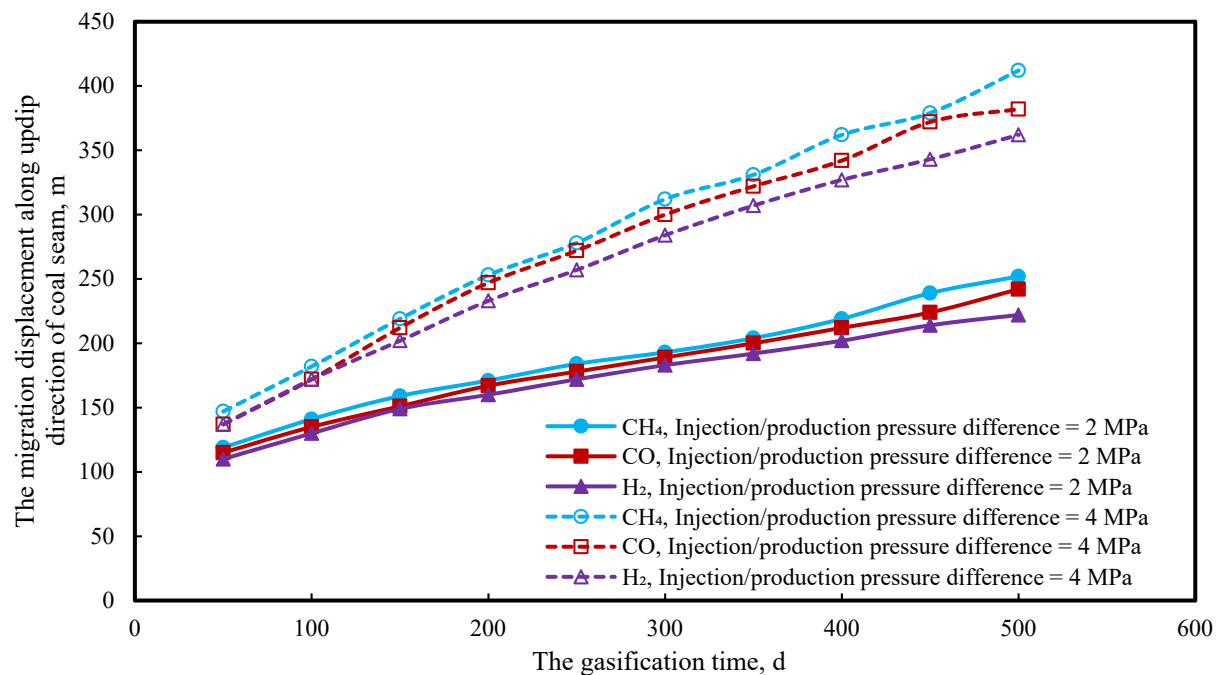


Figure 30. The migration displacement of CH₄, CO and H₂ changes by gasification time for different injection–production pressure difference.

From 50 days to 500 days of gasification, the average gas migration rate is the slope of the respective displacement–time curve. The respective migration speeds were obtained through linear fitting, as shown in Table 5.

Table 5. Gas migration rate (without aquifer, ideal model).

Gas Type	Gas Migration Rate, m/day		Increased Multiple
	Pressure Difference = 2 MPa	Pressure Difference = 4 MPa	
CH ₄	0.2975	0.5754	0.93
CO	0.2676	0.5464	1.04
H ₂	0.2291	0.4965	1.16

With increase in the injection–production pressure difference, in the same gasification time, more gas will migrate upward along the coal seam. That is, when the injection–production pressure difference is larger, the gas migration rate along the updip direction of the coal seam will be faster. When the injection–production pressure difference increases from 2 MPa to 4 MPa, the gas migration velocity doubles.

4.2. The Influence of Aquifer above Coal Outcrop

According to the hydrogeological data, the maximum aquifer energy over the coal outcrop in this area is 3 MPa. The influence of aquifer above coal outcrop on gas migration was simulated when the injection–production pressure difference was 2 MPa (injection pressure = 11 MPa, production pressure = 9 MPa), as presented in Figure 31.

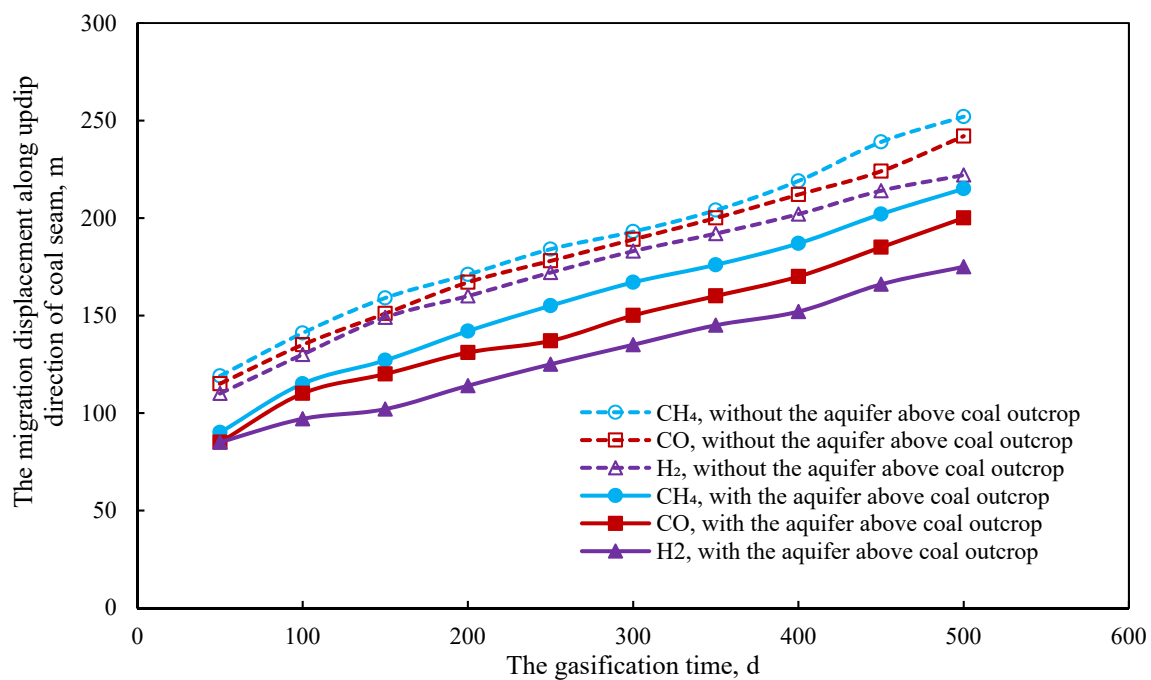


Figure 31. The migration displacement of CH₄, CO, and H₂ changes by gasification time when the aquifer above coal outcrop is considered.

The average gas migration rate was also obtained by means of linear fitting, and the gas migration rate was compared between the cases with and without aquifer (Table 6).

Table 6. Gas migration rate (Injection–production pressure difference = 2 MP, ideal model).

Gas Type	Without the Aquifer above Coal Outcrop	With the Aquifer above Coal Outcrop	Reduced Speed
CH ₄	0.2975 m/day	0.26044 m/day	0.037 m/day
CO	0.2676 m/day	0.2315 m/day	0.036 m/day
H ₂	0.2291 m/day	0.1995 m/day	0.030 m/day

Considering the aquifer above the coal outcrop, the relative gas migration rates of the five gas types along the up-dip direction of coal seam remain unchanged, which is still CH₄ > CO > H₂ > O₂ > CO₂, but the migration rate of each gas slows down. The reason for this phenomenon is that, when there is an aquifer above the coal outcrop, there will be a hydraulic sealing effect, which will make it difficult for the gas to diffuse upward. When the aquifer energy is 3 MPa, the gas migration rate along the up-dip direction of the coal seam decreases by about 0.03 m/day.

4.3. The Difference between the Ideal Model and the Actual Model

The migration displacement of CH₄, CO, and H₂ in the ideal model and the actual geological model were simulated for the case that the injectional–production pressure difference was 2 MPa and the aquifer above the coal outcrop was considered (Figure 32).

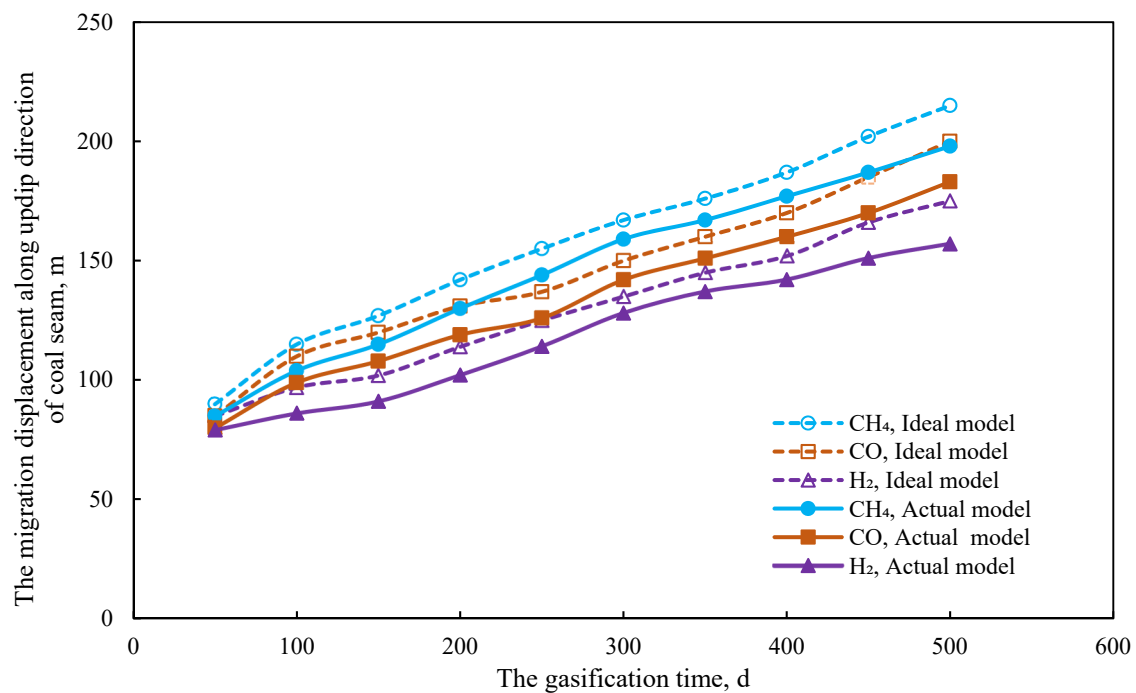


Figure 32. The migration displacement of CH₄, CO and H₂ changes by gasification time for ideal model and actual model.

Comparing the gas migration rate in the actual geological model with that in the ideal model, it can be seen that the gas migration rate in the actual geological model is slightly lower than that in the ideal model, which is less than 0.01 m/day (Table 7).

Table 7. Gas migration rate (Injection–production pressure difference = 2 MP, with aquifer).

Gas Type	Gas Migration Rate, m/day		Reduced Speed
	Ideal Model	Actual Geological Model	
CH ₄	0.26044	0.2465	0.0139 m/day
CO	0.2315	0.2177	0.0138 m/day
H ₂	0.1995	0.1856	0.0139 m/day

In the actual geological model, for CH₄, CO, and H₂, the correlation between the migration displacement from 50 days to 500 days of gasification and the gasification time is shown as Equations (7)–(9), respectively.

$$y = 0.2465 t + 78.8 \quad (7)$$

$$y = 0.2177 t + 73.933 \quad (8)$$

$$y = 0.1856 t + 67.667 \quad (9)$$

When CH₄, CO, and H₂ move from 1000 m in depth to 200 m in depth, the migration distance in the dip direction is 3091 m, and the movement lasts for 33.5 years, 40 years, and 44.6 years, respectively. The simulation of gas migration characteristics in advance can provide a theoretical basis for the deployment of monitoring wells. Monitoring wells can be used to sample coal seam water and monitor gas composition.

5. Pressure Characteristic

During UCG in the gasification channel, two stages of the cavity growth are differentiated [34]. In the first stage, the cavity grows along the gasifier width. In the second stage, the cavity mainly grows along the gasifier length, as shown in Figure 33. The pressure characteristics of these two stages are analyzed below.

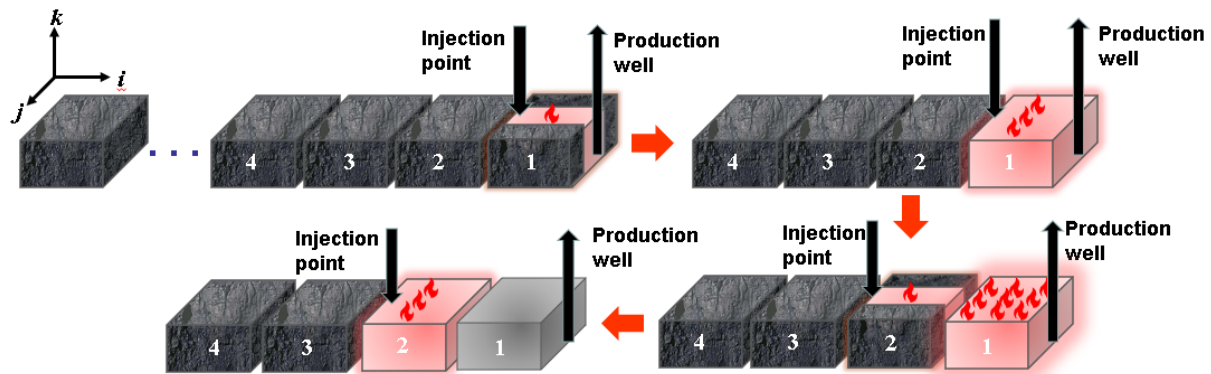


Figure 33. The growth stage of the cavity.

(1) The first stage: Along the gasifier width

The gasifier widths were set to be 2, 2.5, 3, 3.5, and 4 times the thickness, respectively. The pressure distribution of different gasifier widths is shown in Figure 34. Different colors represent different formation pressures. The number on the right side of the color palette represents the pressure range for each color in MPa.

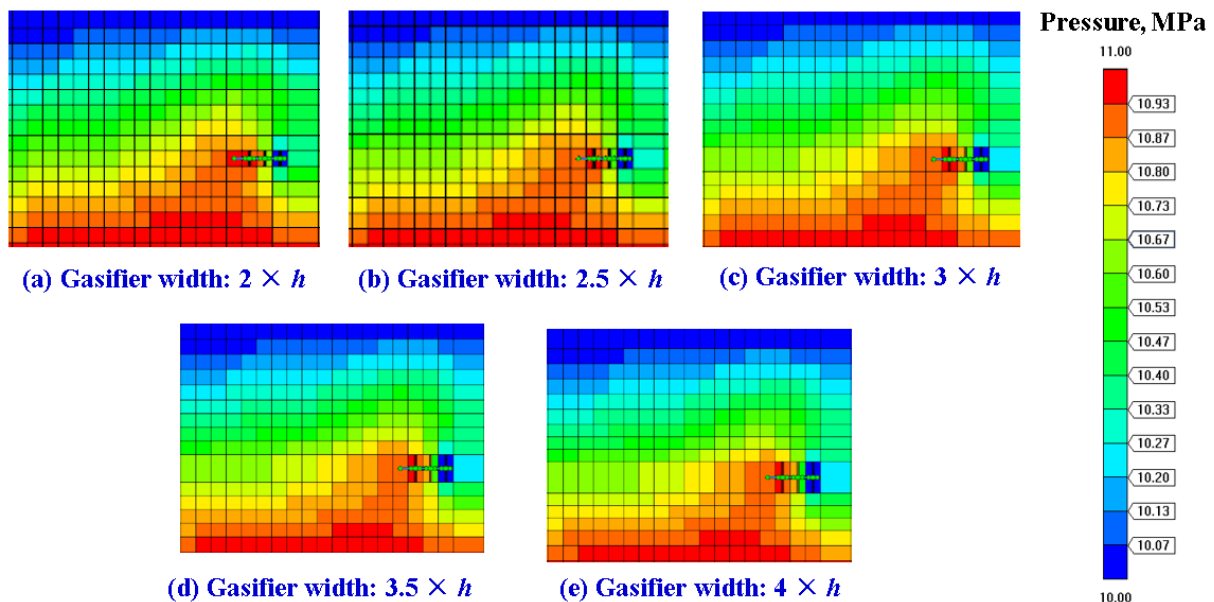


Figure 34. The pressure distribution of different gasifier widths.

From Figure 34, it can be seen that the pressure distribution patterns of gasification cavities with different widths are similar. With progress of gasification, the cavity width gradually increases, the pressure expands along the coal seam tendency direction, and the gasifier pressure also changes gradually. Figure 35 shows the gasifier pressure along with the change in gasifier width.

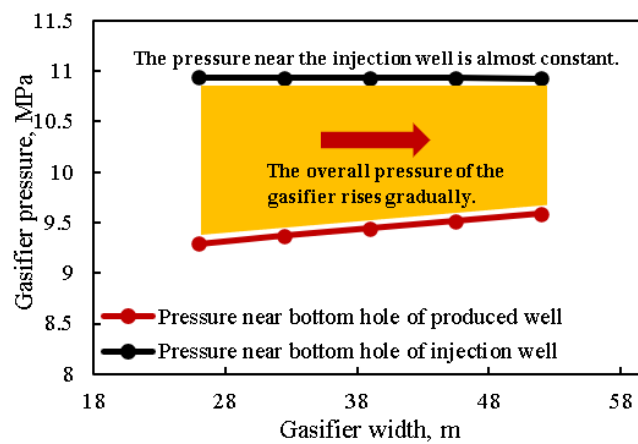


Figure 35. The gasifier pressure changes along the gasifier width.

It can be seen that with the gasifier width increasing, the pressure near the injection well is basically unchanged, while the pressure near the production well gradually increases. It is also implied that the pressure near the production well changes more significantly than the pressure near the injection well. The overall gasifier pressure rises with gasifier width increases; the correlation between them is expressed as the following equation:

$$P_{\text{gasifier}} = 0.0115w + 8.993 \quad (10)$$

where P_{gasifier} denotes the gasifier pressure, MPa, and w is the gasifier width, m.

(2) The second stage: Along the gasifier length

Figure 36 shows the change in gasifier pressure during the retreat of the gas injection point. The meaning of the color palette is the same as in Figure 34. The pressure always presents an asymmetric unimodal distribution during CRIP. The faster the gas injection point recedes, the faster the pressure expands in the direction of the coal seam strike.

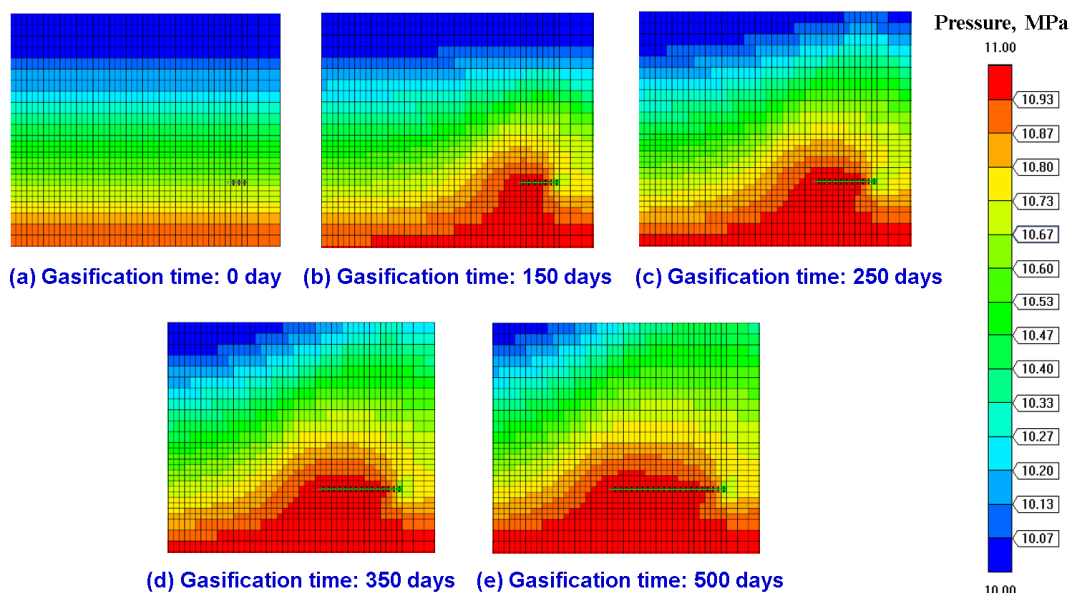


Figure 36. The gasifier pressure changes along the gasifier length.

In the field, the pressure extends first along the width of the gasifier, and then along the length direction of the gasifier. The process is repeated until gasification is completed. A reasonable determination of gasification pressure is of great significance to the control of water influx and gas migration in the gasification process [35].

Figures 37 and 38 show the matching correlations among gasifier pressure, initial coal seam pressure, and outer boundary pressure in this area, which, respectively, represent the maximum instantaneous water inflow and steady water inflow.

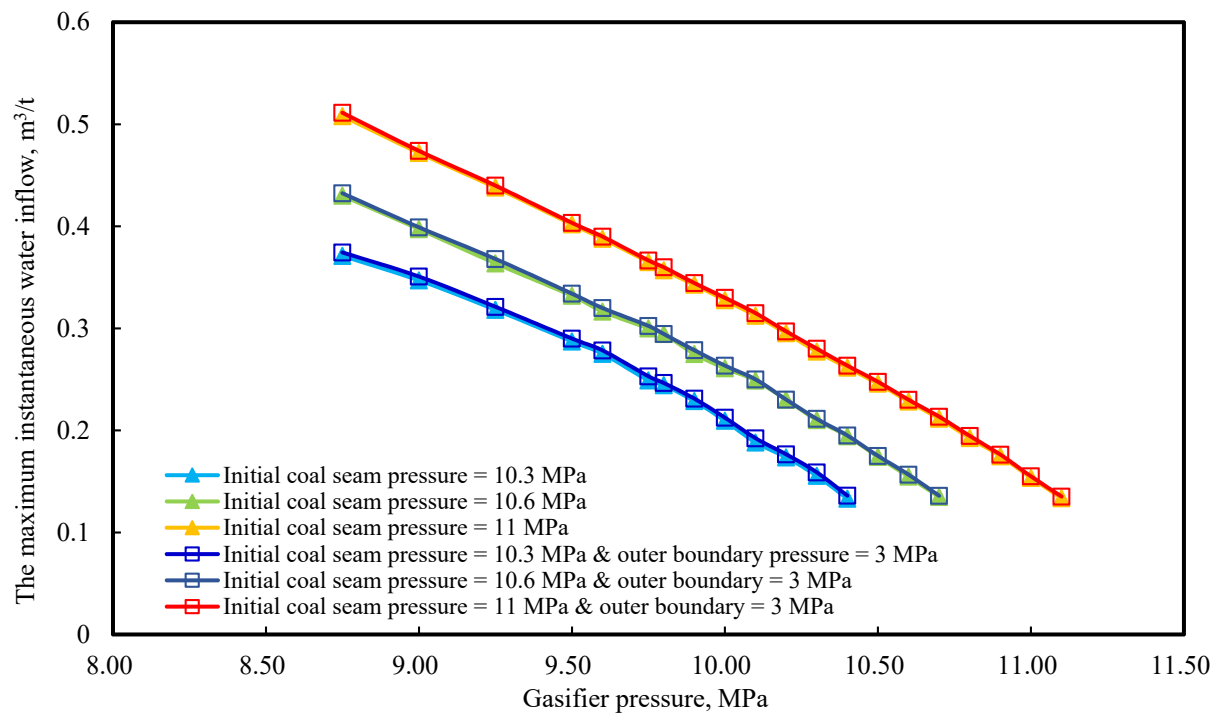


Figure 37. The correlation among gasifier pressure, initial coal seam pressure, and outer boundary pressure for the maximum instantaneous water inflow (the middle Jurassic Xishanyao Formation).

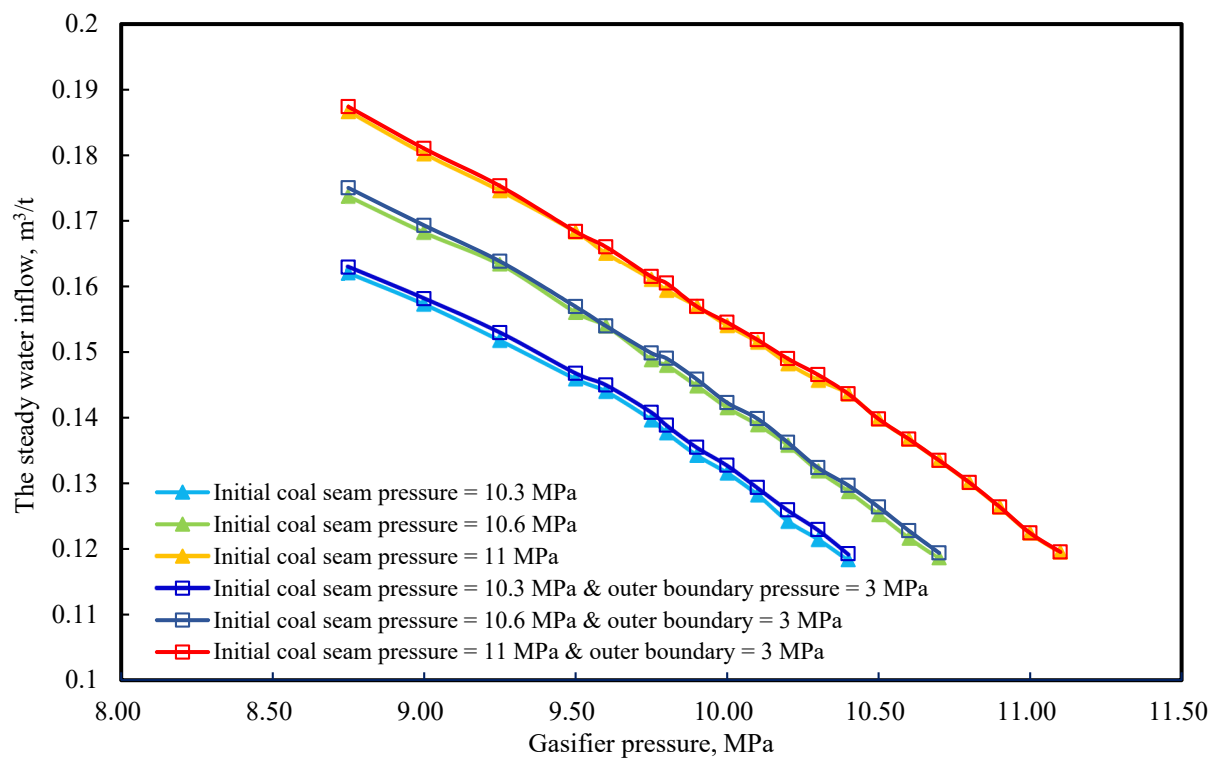


Figure 38. The correlation among gasifier pressure, initial coal seam pressure, and outer boundary pressure for the steady water inflow (the middle Jurassic Xishanyao Formation).

During underground gasification of the middle Jurassic Xishanyao Formation, the values of the maximum instantaneous water inflow and the steady water inflow can be roughly obtained by searching Figures 37 and 38 using the values of gasifier pressure, initial coal seam pressure, and outer boundary pressure.

6. Conclusions

Several conclusions can be drawn after simulating the transport of coal seam water and gasified gas during the underground coal gasification process.

(1) The cavity width, production pressure, and gasifier pressure are negatively correlated with the maximum instantaneous water inflow, while the initial formation pressure, injection pressure, coal seam floor aquifer energy, and temperature are positively correlated. Production pressure has a more significant effect on water inflow than the injection pressure. When the production pressure is the same, the steady water inflow in the later stage is basically the same. The bottom water energy has little effect on the maximum instantaneous water inflow but has a great effect on the steady water inflow. When the thickness of the coal seam floor aquifer is 50 m, the water inflow increases by 0.34 m³/t. The simulation of the actual geological model shows that the water inflow will not pose a threat to gasification safety in the middle part of the middle Jurassic Xishanyao Formation (J₂x).

(2) The gas migration velocity is mainly related to the relative molecular mass of gas, the concentration difference between inside and outside the gasifier, the gasifier pressure and the gasifier temperature. The higher the relative molecular mass, the more difficult the upward migration of the gas. The larger the concentration difference inside and outside the gasifier, the faster the diffusion rate. The results show that the concentration difference between inside and outside the gasifier is the dominant factor, but the relative molecular mass cannot be ignored.

When the proportion of CH₄, CO, CO₂, H₂, and O₂ is 26%, 18%, 30%, 17%, and 9% respectively, the upward migration rate of the five gas types follows a descending order: CH₄ > CO > H₂ > O₂ > CO₂. CO₂ is mainly concentrated near the production well and largely does not migrate upward, O₂ migrates upward slowly, while CH₄, CO, and H₂ migrate relatively quickly. According to the core test and permeability dynamic inversion method, the permeability along the coalbed tendency direction is 1.5 mD in this area. When the injection–production pressure difference is 2 MPa, it takes 33.5 years, 40 years, and 44.6 years for CH₄, CO, and H₂ to move from 1000 m in depth to 200 m in depth, respectively. When the pressure difference is increased to 4 MPa, the gas migration rate increases by about twice. The aquifer (3 MPa) above the coal outcrop can slow down the upward migration rate of gas by 0.03 m/day. The gas migration rate in the actual geological model is 0.01 m/day lower than that in the ideal model.

(3) The pressure near the production well changes more significantly than the pressure near the injection well. The pressure near the injection well is basically unchanged, while the pressure near the production well increases with increase in the gasifier width. In the process of gasification, the pressure expands first along the width of the gasifier, and then along the length direction of the gasifier. The process is repeated until gasification is completed. The overall gasifier pressure rises with gasifier width increases, and the pressure always presents an asymmetric unimodal distribution during CRIP.

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