Numerical Simulation of the Temperature Distribution and Evolution Law of Underground Lignite Gasification

He Zhou, Caifang Wu,* Hao Chen, Mingyang Du, Zhenzhi Wang, and Xiuming Jiang

ABSTRACT: To study the temperature distribution characteristics and evolution law of underground lignite gasifiers, a three-dimensional heat conduction model of underground lignite gasification was constructed. Moreover, the effects of different coal thicknesses, advance speeds of the flame working face, and surrounding rock types on the gasifier were analyzed. The results show that with the increase in the coal thickness, the transfer range and distance of temperature in the roof, floor, and coal seam gradually increase, as does the coal quantity in the three zones. The heat loss rate of the gasifier decreased gradually with the coal seam thickness. When the advance speed of the flame working face is 0.5 m/d, the ideal gasification coal thickness range of lignite is 2.5–17.5 m. With the increase in the gasification rate, the maximum transfer distance of temperature to the roof and floor, the average temperature of the gasifier, and the coal quantity of the three zones gradually increase. Conversely, the coal thickness corresponding to the intersection of the coal quantity of the oxidation and reduction zones and the heat loss rate of the gasifier gradually decrease. When the coal seam below 2.5 m is gasified, the gasification rate can be increased appropriately. When the coal seam is above 13 m, increasing the gasification rate will make the coal quantity in the oxidation zone close to or even higher than that in the reduction zone. Regarding the surrounding rock types comprising a combination of siltstone, mudstone, sandy mudstone, and fine sandstone, the most favorable roof and floor type for underground coal gasification is the combination of fine sandstone and sandy mudstone (without considering the sealing and mechanical properties). These results provide important theoretical support for the industrialization of underground coal gasification.

1. INTRODUCTION

China, as a country with “rich coal and little gas,” is rich in deep coal resources, and the technical challenges of using machinery to exploit these resources have increased. Compared with traditional coal mining technology, underground coal gasification (UCG) is a controllable combustion technology that can be used in deep coal and residual coal mining. Its advantages include safe production, high efficiency, low pollution, and high benefit. With the background of rapid economic and low carbon development, UCG combines the advantages of clean coal resource application and supplement NG supply with syngas and has become an important research direction in the energy field. Therefore, UCG has vital practical significance for alleviating the energy crisis and adjusting the national energy structure.

UCG is a new technology of raw coal conversion, which integrates well construction, coal mining, and gasification. In the gasifier, oxygen is injected by drilling and flowed along the gasification channel, forming three areas in turn: oxidation zone, reduction zone, and dry distillation drying zone. There are obvious differences in temperature, chemical reactions, and reaction products among the three regions. Generally speaking, the oxidation zone comprises mainly the combustion reaction of
semcoke and its temperature is between 900 and 1200 °C, and the main reactions in the reduction zone (600–900 °C) are the steam gasification reaction, carbon dioxide reduction reaction, water gas shift reaction, and high-temperature pyrolysis of coal. The reactions that occur in the dry distillation drying zone include the evaporation of water, the resolution of methane, and the low-temperature pyrolysis of coal. The temperature is generally between 200 and 600 °C.15 It can be seen that UCG is a complex physical and chemical process,10–14 which mainly includes the flow, heat transfer, mass transfer, and pyrolysis of gasification agents and gasification products.10–14 Among them, heat transfer runs through the whole changing process of UCG, which is one of the basic problems that need to be paid more attention to. In the oxidation zone, the semicoke layer burns under the action of the oxidizer, releasing a large amount of heat, which is transferred to the front of the coal seam, forming a reduction zone and a distillation drying zone. In addition, the heat released by combustion is transferred to the roof and floor, which increases the temperature of the roof and floor and also causes a certain amount of heat loss.\(^15\)

**Figure 1.** General model of underground coal gasification.

Since the 20th century, dozens of pilot mining areas for UCG have been built in China, the former Soviet Union, Britain, France, Belgium, the United States, and Eastern European countries. Almost all kinds of coal (lignite, long-flame coal, gas coal, fat coal, gas-fat coal, coking coal, lean coal, and anthracite) were recorded experimentally, and the corresponding coal thicknesses range from 0.4 to 18 m.\(^16\),17 Because of the great differences in resource and surrounding rock conditions of each experimental mining area, it is difficult to compare the gasification parameters horizontally among the gasification mining areas, which hinders the industrialization process of UCG to a certain extent. The method to solve this difficulty involves simulation, which considers the control variable method as the core to explore the influence of individual resources and surrounding rock conditions on the gasifier. At present, physical and numerical simulations are the two commonly used research methods in the field of UCG.\(^18\),19 The physical simulation involves gasifying the experimental coal by reducing the size of the gasifier in the same proportion and using the appropriate gasification process to obtain the composition and calorific value range of the produced gas under different gasification agents.\(^20\),21 Owing to limitations of the model size, it is difficult to obtain the gasification parameters of thick and superthick coal seams, but a numerical simulation method can be realized.\(^12\) Kinetic and thermodynamic equilibrium models are commonly used numerical simulation models of UCG.\(^13\),\(^22\) Most of the attention is on the composition of the produced gas (H\(_2\), CO, CH\(_4\), etc.) and the temperature distribution in the gasifier under the condition of single coal thickness.\(^22\),23 In addition, the temperature field under the condition of single coal seam thickness is studied by means of mathematical analysis or numerical simulation, and the corresponding analytical solution is obtained.\(^20\)–\(^26\) Xin uses the physical envelope curve method to study the temperature field under fixed boundary conditions and determines the influence range of the temperature field.\(^31\),\(^32\) However, there is a lack of lateral quantitative comparative studies of gasification parameters under various coal thickness conditions.

Lignite is the preferred experimental coal because of its high volatile content and gasification activity.\(^33\) and is the main coal studied in our work. When the coal seam is thin, the heat generated by the coal seam is low, and the surrounding rock absorbs a large amount of this heat. This results in a reduction in the temperature of the gasification face, gasification thermal efficiency, and calorific value of the output gas. With increasing coal thickness, the temperature of the gasifier and the calorific value of the produced gas gradually increase.\(^7\) Although the surrounding rock absorbs a large amount of heat when the coal seam is less than 2 m, such instances still occur, like in

**Figure 2.** Heat source of the gasifier.
Shanjiaoshu Coal Mine in Guizhou Province. Compared with the gasification rate of thick coal seams (Wulanchabu, 8.3 m, 0.568 m/d), that of Shanjiaoshu Coal Mine (1.5 m, 1.287 m/d) is obviously faster.34 This indicates that there are differences in the gasification rates of coal seams with different thicknesses (especially in coal seams less than 2 m). Therefore, there is no systematic conclusion on the effect of coal thickness on UCG, and there is little research on the relationship between the gasification rate and coal thickness, which necessitates further research.

As we all know, the permeability and mechanical strength of the surrounding rock affect the tightness and stability of a gasifier, respectively. These studies show that a certain thickness of mudstone, siltstone, and sandy mudstone can be regarded as a stable waterproof layer, which acts as a good sealant in coal gasification.35,36 Fine sandstone can also be used as a surrounding rock for gasification because of its high mechanical strength and low permeability.37 Under the same coal type and coal thickness conditions, different types of surrounding rock have different specific heat capacities and thermal conductivities, resulting in varying heat losses of the gasifier.38,39 Furthermore, when the requirements of mechanics and permeability are met, the types of surrounding rock have a lower heat loss rate, which is helpful for the gasification mining of thin coal seams; other related problems require further study.

In this study, a three-dimensional heat conduction model of underground lignite gasification was constructed based on an in-depth analysis of the UCG process. Based on this model, the three-dimensional distribution characteristics of the temperature field of the gasifier with different coal thicknesses, gasification rates, and surrounding rock types were studied using the method of controlling variables. Subsequently, the comprehensive comparative characteristics of UCG were obtained. The gasification parameters of different surrounding rock types were quantitatively evaluated by the technique for order preference by similarity to an ideal solution (TOPSIS) method and classified according to the comprehensive evaluation index to guide the geological selection evaluation of UCG. These research results provide important theoretical support for the industrialization of UCG.

2. GEOLOGICAL MODEL AND MATHEMATICAL METHODS

2.1. Geological Model of the Gasifier. The gasifier mainly consists of two parts: a coal seam and the surrounding rock. The temperature distribution in the gasifier, the nonuniformity and instability of the gasification reaction, and the heterogeneity and anisotropy of the surrounding rock determine that the geological model of the gasifier must be three-dimensional rather than simply two-dimensional. The complexity of the resource and surrounding rock conditions in the study area determine the limitations of geological modeling around a certain study area. Therefore, based on the conditions of coal thickness, advance speed of the flame working face, and surrounding rock, a three-dimensional geological model was constructed to study the temperature distribution and evolution law, as shown in Figure 1.

In the gasification process, the temperature spread distance of the gasifier is limited and is generally not more than 35 m. From the domestic gasifier field test, the length of the gasifier is approximately 200 m. Therefore, the thicknesses, widths, and lengths of the upper and lower surrounding rocks were set to 40, 80, and 200 m, respectively, in this study. Considering the
generality of the model, the coal seam thickness is not specifically set and can be flexibly set and adjusted through the definition of the global parameters in software to meet the research requirements.

In the gasifier, roughly two directions of heat conduction are observed, one to the front of the coal seam and the other to the gasification channel with the high-temperature combustion gas. The former heat transfer direction increases the coal seam temperature and causes pyrolysis, and the pyrolysis gas migrates

Table 2. Summary of Coal Seam Parameters

| coal category | $\rho$ (kg/m$^3$) | $Z$ (%) | $Q_1$ (MJ/kg) | $V_{lad}$ (%) | $Q_2$ (MJ/kg) | $V$ (m/d) | $h$ (m) | $L$ (m) |
|---------------|------------------|---------|---------------|--------------|---------------|----------|--------|--------|
| lignite       | 1150             | 50.65   | 22.43         | 47.15        | 69.97         | 0.5, 1.0, 1.5 | 0.5, 0.8, 1.3, 2.0, 5.0, 10, 15, 20 | 10     |

*Note: Part data refer to ref 27.*

Figure 3. Temperature distribution of the horizontal section of the gasifier with different coal thicknesses and gasification speeds.
to the gasification channel, which in turn increases the temperature in the gasification channel. The combined action of these two processes causes the pyrolytic gas in the gasification channel to burn and release a large amount of heat. As the reaction progressed, the oxygen concentration in the gasification channel gradually decreased, as shown in Figure 2. Liu et al. found that the oxygen concentration decreased to zero when the gasification channel was approximately 30 m. Therefore, based on the need for control variables, the corresponding gasification channel length was set to 30 m when the oxygen concentration was zero.

2.2. Model Parameters. After determining the scale of the geological model, the heat transfer parameters of the gasified coal seam and surrounding rock are set. In the heat transfer module, the main parameters involved are the density, thermal conductivity, and specific heat capacity, and the density is assumed to remain unchanged with the increase in temperature, while other parameters change with temperature, as presented in Table 1. Other parameters were shown in Table 2. Because of the great influence of water on the model, this paper assumes that there is no water in the surrounding rock and coal seam.

The heat source setting is the basic and core problem in the UCG process. During UCG, a large amount of heat is released from the coal seam combustion, and this heat is transferred to the front, which increases the temperature of the coal seam ahead that it begins to pyrolyze. The pyrolysis gas migrates to one side of the gasification channel, mixes with the oxygen in the gasification channel, and continues to burn at high temperatures; thus, the temperature of the gasifier continues to rise. Therefore, there are two heat sources in the gasifier—the first ($P_1$) is the heat generated by coke combustion at the front end of the oxidation zone, while the other ($P_2$) is that generated by the combustion of the pyrolysis gas in the gasification channel (oxidation zone), as shown in Figure 2. Overall, $P_1$ is related to the width of the gasification face, coal seam thickness, advance speed of the flame working face, density of coal, output rate of semicoke, and calorific value of semicoke; $P_2$ is related to the volatile content and calorific value. To simplify the calculation formula, we assume that the coal seam did not contain gangue. The formulas of the two heat sources are as follows

$$P_1 = \mu ZQ_{pf} v h L$$

$$P_2 = \mu V_{daf} Q_{pf} v h L$$

where $P_1$ and $P_2$ are the heat source power at the front end of the oxidation zone and in the gasification channel, respectively (W); $Z$ is the coke output rate (%); $Q_p$ and $Q_{pf}$ are the calorific values of coke and pyrolysis gas, respectively (MJ/kg); $V_{daf}$ is the volatile content (%); $\rho$ is the coal density (kg/m$^3$); $v$ is the advance speed of the flame working face (m/d); $h$ is the coal seam thickness (m); $L$ is the width of the gasification face (m); and $\mu$ is the pyrolysis coefficient of the oxidation zone, which generally ranges from 1–3.

Additionally, the ratio of the heat absorbed by the surrounding rock to the combustion heat of coke and pyrolysis gas is used as the formula for calculating the heat loss rate, as given below.

$$\eta = 100(\frac{Q_1 + Q_2}{P_1 + P_2})t = \frac{100(C_1 M_1 \Delta t_1 + C_2 M_2 \Delta t_2)}{(P_1 + P_2)t}$$

where $\eta$ is the heat loss rate (%); $Q_1$ and $Q_2$ represent the heat absorbed by the roof and floor, respectively (J); $P_1$ and $P_2$ are the heat source power at the front end of the oxidation zone and in the gasification channel, respectively (W); $C_1$ and $C_2$ are the specific heat capacities of the roof and floor, respectively (J/(kg·k)); $M_1$ and $M_2$ are the quantities of the roof and floor, respectively (kg); and $\Delta t_1$ and $\Delta t_2$ are the temperature differences between the roof and floor, respectively (K).

In the gasifier, the abovementioned two heat sources produced two temperatures in the combustion process. To simplify the model, the average temperature at the front end of the oxidation zone was set to 1200 °C. As the oxygen content in the gasification channel was low and the combustion was insufficient, the average combustion temperature was set at 800 °C. Assuming that the buried depth of the simulated coal seam is 300 m, the initial temperature of the surrounding rock and nongasified coal seam is set to 20 °C.

2.3. Mathematical Method. The TOPSIS (technique for order preference by similarity to an ideal solution) method, that is, the ranking technique which approaches the ideal solution, is a commonly used and effective method in multiobjective decision analysis. The calculation process can be divided into six steps: constructing the initial matrix, constructing the normalization matrix, constructing the weighted gauge matrix, determining the positive ideal solution and negative ideal solution, determining the distance from each scheme to the ideal solution, and calculating the relative proximity between each scheme and the ideal solution. These six steps are described below.

1. Constructing (same trend/same direction) the initial matrix:

Let the multiattribute decision-making scheme set be $D = \{d_1, d_2, ..., d_m\}$, and the attribute variables to measure the advantages and disadvantages of the scheme are $x_1, ..., x_n$. Meanwhile, the vector composed of $n$ index values of each scheme $d_i (i = 1, ..., m)$ in the scheme set $D$ is

![Figure 4. Axial temperature distribution of the lignite gasifier under different coal thicknesses (0.5 m/d). Notes: I represents the temperature distribution in the range of 0–10 m along the direction of the gasification channel; II represents the temperature distribution in the range of 10–60 m along the direction of the gasification channel; and III represents the temperature distribution in the range of more than 60 m along the direction of the gasification channel.](https://doi.org/10.1021/acsomega.1c06559)
Table 3. Relevant Parameters of the Gasifier at Different Gasification Speeds and Coal Thicknesses

| CSGR | CST (m) | CSOZ (m³) | CRZ (m³) | DQDDZ (m³) | DQWZ (m³) |
|------|---------|-----------|----------|-------------|-----------|
|      | >900 °C | 600–900 °C | 300–600 °C | 200–300 °C | ATR(K)   |
| 0.5 m/d | 0.8     | 12.078    | 48.011   | 101.82      | 293.27    |
|       | 1.3     | 38.336    | 77.87    | 160.32      | 1081.57   |
|       | 2       | 49.394    | 124.49   | 256.38      | 1623.34   |
|       | 2.5     | 71.408    | 151.33   | 311.58      | 2324.08   |
|       | 5       | 176.27    | 233.78   | 571.26      | 4962.89   |
|       | 10      | 327.39    | 342.62   | 978.08      | 10973.01  |
|       | 15      | 481.97    | 518.48   | 1161.20     | 17046.35  |
|       | 20      | 697.68    | 693.02   | 1288.60     | 23407.70  |
| 1.0 m/d | 0.8     | 14.81     | 30.853   | 103.50      | 707.82    |
|       | 1.3     | 39.625    | 80.26    | 161.34      | 1301.28   |
|       | 2       | 51.76     | 124.73   | 256.52      | 1925.89   |
|       | 2.5     | 85.35     | 151.33   | 320.78      | 2243.34   |
|       | 5       | 186.52    | 288.49   | 645.59      | 5468.20   |
|       | 10      | 327.29    | 345.97   | 979.98      | 10958.76  |
|       | 15      | 509.81    | 528.83   | 1165.00     | 17001.36  |
|       | 20      | 704.17    | 662.23   | 1290.10     | 23393.50  |
| 1.5 m/d | 0.8     | 16.53     | 31.59    | 104.47      | 710.26    |
|       | 1.3     | 41.43     | 82.34    | 162.32      | 1300.71   |
|       | 2       | 54.83     | 127.19   | 265.73      | 1899.35   |
|       | 2.5     | 95.35     | 152.60   | 320.80      | 2356.15   |
|       | 5       | 190.47    | 288.49   | 647.69      | 5472.25   |
|       | 10      | 341.60    | 356.93   | 988.74      | 10923.73  |
|       | 15      | 556.92    | 555.09   | 1197.10     | 17009.89  |
|       | 20      | 714.21    | 665.10   | 1299.10     | 23352.59  |

Note: CSGR = coal seam gasification rate; CST = coal seam thickness; CSOZ = coal quantity of the oxidation zone; CRZ = coal quantity of the reduction zone; DQDDZ = coal quantity of the dry distillation zone; DQWZ = coal quantity of the warming zone; ATR = average temperature of the roof; ATF = average temperature of the floor; ATG = average temperature of the gasifier; and HLR = heat loss rate.

\[
A = \begin{bmatrix}
    a_{11} & \ldots & a_{1m} \\
    \vdots & \ddots & \vdots \\
    a_{m1} & \ldots & a_{mm}
\end{bmatrix}
\]  

(4)

(2) Standardization/standardization:
Let the initial matrix \(a_{ij}\) and then the normalized decision matrix \(b_{ij}\) as follows:

benefit index: \(b_{ij} = \frac{a_{ij} - a_{ij}^{\text{min}}}{a_{ij}^{\text{max}} - a_{ij}^{\text{min}}}\)

(5)

cost indicator: \(b_{ij} = \frac{a_{ij}^{\text{max}} - a_{ij}}{a_{ij}^{\text{max}} - a_{ij}^{\text{min}}}\)

(6)

where \(a_{ij}^{\text{max}}\) and \(a_{ij}^{\text{min}}\) are the maximum and minimum values in column \(j\), respectively.

(3) Constructing the weighted gauge matrix:
According to the coefficient of variation method, the weight of each index can be determined according to the following steps.

The mean and variance of index \(i\) are calculated as follows

\[
\bar{x}_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}
\]

(7)

\[
S_i^2 = \frac{1}{n-1} \sum_{j=1}^{n} (a_{ij} - \bar{x}_i)^2
\]

(8)

Then, the normalized \(v_i\) is the weight of each index

\[
v_i = \frac{S_i}{S_i^{\bar{1}}}
\]

(9)

Let the weight vector determined by the coefficient of variation method be \(\omega = [\omega_1, \omega_2, \ldots, \omega_m]^T\); then

\[
c_i = v_i \times b_{ij}
\]

(10)

(4) Determining the positive ideal solution and the negative ideal solution:
The positive ideal solution \(C^+\) consists of the maximum value of each column in the \(C\) matrix

\[
C^+ = (\max c_{i1}, \max c_{i2}, \ldots, \max c_{im})
\]

(12)

The negative ideal solution \(C^-\) consists of the minimum value of each column in the \(C\) matrix

\[
C^- = (\min c_{i1}, \min c_{i2}, \ldots, \min c_{im})
\]

(13)

(5) Calculating the Euclidean distance between each target value and the ideal value:
The distance from the alternative \(d_i\) to the positive ideal solution can be calculated as follows

\[
C^+ = (\max c_{i1}, \max c_{i2}, \ldots, \max c_{im})
\]

(14)

The distance from the alternative \(d_i\) to the negative ideal solution can be calculated as follows

\[
C^- = (\min c_{i1}, \min c_{i2}, \ldots, \min c_{im})
\]
Calculating the comprehensive evaluation index of each scheme ($f_i$):

The calculation formula of $f_i$ is calculated as follows

$$f_i = \frac{D_i^-}{D_i^- + D_i^+}$$  \hspace{1cm} (16)

The higher the value of $f_i$, the farther the $d_i$ scheme is relative to the negative ideal solution and the better the $d_i$ scheme.

3. RESULTS AND ANALYSIS OF NUMERICAL SIMULATIONS

3.1. Evolution Characteristics of the Related Parameters of the Gasifier with Different Coal Thicknesses.

Assuming a gasification speed of 0.5 m/d and a roof and floor of siltstone and mudstone, respectively, the three-dimensional distribution characteristics and evolution law of the temperature field of underground igniting gasification at different coal thicknesses are simulated, and the distribution range of the “three zones” is divided. Wang et al. state that when the advance speed of the flame working face ranges from 0.3 to 1.5 m/d, the time required for the temperature field to be stable is generally 10 days, and the temperature reaches its highest after 10 days of gasification.26 Therefore, the simulated gasification time in this study was 10 days.

3.1.1. Distribution Characteristics of the Related Parameters in the Gasifier. The coal seam thickness is an important factor affecting the temperature distribution in the gasifier. The greater the thickness of the coal seam, the more the semicoke involved in combustion and oxidation in the same time range and the higher the temperature in the gasifier. Additionally, under the influence of the high temperature, more pyrolytic gas is produced and migrates into the gasification channel, and the heat released is greater. These two aspects work together to further increase the temperature of the gasifier.

The greater the thickness of the coal seam, the higher the content of semicoke involved in combustion within the same time range and the higher the temperature in the gasifier. Influenced by the high temperature, more pyrolysis gas is produced and migrates into the gasification channel, and the heat released is greater. These two aspects work together to further increase the temperature of the gasifier. The temperature in the gasifier is mainly produced by the exothermic combustion reaction, and a strong correlation exists between the temperature and the distribution of oxygen in the gasifier.25 Oxygen generally exists in the combustion area and gasification channel; thus, the advancing direction of the gasification face is consistent with the direction of oxygen migration. In the advancing

$$C^- = \min(c_{11}, \min(c_{12}, ..., \min(c_{im}))$$  \hspace{1cm} (15)
Figure 6. Temperature distribution of the vertical section under different coal thicknesses and gasification rates.
direction of the gasifier, the temperature in the gasifier has a stepwise distribution, as shown in Figure 3. It can be seen that in the axial direction, a positive correlation was observed between the heat transfer range and coal thickness. The higher the coal seam thickness, the larger the temperature distribution range.

To study the temperature distribution characteristics of the gasifier, the temperature distribution of the gasification channel was investigated in this study. The temperature distribution can be roughly divided into three stages (I, II, and III), as shown in Figure 4. The first stage mainly involves the radiative heat transfer from the high-temperature zone at the front of the gasified coal seam to the combustion zone, which is weakly affected by the coal thickness. When the axial distance is less than 5 m, the temperature is less affected by the radiation and is close to that of the initial model. With the gradual increase in the axial distance (5–10 m), the temperature increased rapidly. The second stage is the gasification reaction stage, when the axial distance is about 10–12 m and the temperature increases to the highest point.23 With an increase in the axial distance, the temperature decreases gradually. This is mainly due to the decrease in the pyrolysis gas and oxygen concentrations with the increase in the axial distance of the gasification channel and the reduced heat released by combustion. Meanwhile, the thicker the gasification coal seam, the higher the axial temperature along the gasification channel and the slower the temperature decrease. This is mainly because a thicker coal seam releases more combustible gas from pyrolysis and more heat from pyrolysis gas combustion; thus, the temperature in the gasifier decreases less. At 20–30 m, the temperature in the gasifier increased slightly and stabilized, which was mainly caused by the release and combustion of a large amount of pyrolytic gas in the gasifier. Subsequently, with an increase in the axial distance, the temperature of the gasifier gradually decreased. The third stage is the waiting reaction stage of gasification; the corresponding axial distance differs when the temperature of coal seams with different thicknesses tends to its initial value, which is mainly affected by the heat transfer of the coal seam and the complete consumption of oxygen in the gasification channel.

UGC is a self-heating equilibrium process, and the temperature field in the gasifier plays an important role. With a decrease in the temperature of the gasifier, the composition of the produced gas changes significantly, and the calorific value of the mixed gas gradually decreases.15 The abovementioned temperature distribution characteristics are only in the direction of the gasification channel and cannot represent the temperature in the gasifier. Therefore, the average temperature of the gasifier in stage II was calculated, as presented in Table 3. Notably, with the increase in coal thickness, the average temperature of the gasifier initially increased and then decreased, and the coal thickness corresponding to the inflection point was approximately 5 m, as shown in Figure 5a. When the coal seam is thinner (0.8 m), the temperature of the gasifier is lower as the surrounding rock absorbs a significant amount of heat. With a further increase in the coal thickness (more than 5 m), the temperature near the gasification channel tends to increase (Figure 4). However, owing to the sharp increase in the amount of coal in the gasifier, the average temperature in the gasifier decreases as a whole.

According to differences in the main chemical reaction, temperature, and gas composition, UGC can be divided into the oxidation, reduction, and dry distillation zones;44 the coal quantities of the three zones are listed in Table 3. With the increase in the coal thickness, the coal quantity in each zone gradually increases. When the coal thickness is less than 17.5 m, the amount of coal in the reduction zone is larger than that in the oxidation zone, after which the amount of coal in the reduction zone is less than that in the oxidation zone, as shown in Figure 5b. The oxidation zone is known to be the energy supply zone of the entire gasifier, and the reduction zone is the main area determining the calorific value of the produced gas. The length of the reduction zone is generally larger than that of the oxidation zone.26,45 Obviously, this situation is not conducive to UGC. Therefore, the ideal upper limit of the coal seam thickness should be approximately 17.5 m without considering other factors.

Table 4. Maximum Transfer Distance of the Lignite Gasifier with Different Thicknesses

| CST (m) | CSGR (0.5 m/d) | CSGR (1.0 m/d) | CSGR (1.5 m/d) |
|---------|----------------|----------------|----------------|
|         | \( h_1 \) (m) | \( h_2 \) (m)  | \( h_1 \) (m)  | \( h_2 \) (m)  |
| 0.8     | 5.75           | 7.16           | 6.88           | 8.17           | 8.31           | 8.38           |
| 1.3     | 9.60           | 9.54           | 9.99           | 9.74           | 9.99           | 11.56          |
| 2       | 10.26          | 12.88          | 10.68          | 12.88          | 10.68          | 13.37          |
| 2.5     | 10.75          | 13.37          | 11.15          | 13.41          | 11.15          | 15.14          |
| 5       | 11.51          | 15.26          | 12.63          | 15.33          | 13.10          | 18.46          |
| 10      | 14.41          | 19.70          | 15.11          | 19.70          | 15.11          | 20.67          |
| 15      | 15.65          | 20.67          | 15.69          | 20.69          | 16.05          | 20.98          |
| 20      | 16.16          | 21.01          | 16.16          | 21.31          | 16.24          | 22.55          |

“Note: CST = coal seam thickness; CSGR = coal seam gasification rate; \( h_1 \) is the maximum distance of temperature transfer in the roof; and \( h_2 \) is the maximum distance of temperature transfer in the floor.”

Figure 7. Heat loss rate of the gasifier.
thereby increasing the maximum distance of temperature to the floor. Due to the obvious temperature difference between the roof and floor and the front end of the gasifier, there must be heat transfer between the gasifier and the surrounding rock. For thin coal seams (<2 m), due to the limited heat released by coal seam combustion, the transfer distance to the roof and floor is small; with the increase in the coal seam thickness, the amount of coal in the oxidation area gradually increases. Under the action of the oxidant, the heat released by combustion also gradually increases, and with more heat transferred to the roof and floor, the maximum transmission distance also gradually increases; when the coal seam thickness increases to a certain extent, the temperature change at the front end of the furnace is not obvious, the change range of the distance transmitted to the roof and floor is gradually smaller, and the maximum transmission distance of heat to the roof and floor is gradually stable.

Additionally, because of the exclusion of data in the temperature range of 20.00 − 20.50 °C, the distance of the temperature transfer in the roof and floor is slightly less than that reported in previous studies; however, this effect is not significant.

As the temperature in the gasifier is transferred to the surrounding rock, the temperature of the surrounding rock increases; therefore, there must be a certain amount of heat loss. According to eq 3, the heat loss rate of the gasifier can be
The greater the oxygen supply, the faster the advance speed of the flame working face. Therefore, with a constant coal seam thickness, appropriately increasing the gasification speed can increase the amount of coal combustion per unit time, which increases the area of the high-temperature zone in the axial and radial directions of the coal seam, as shown in Figures 3 and 6. Under the same coal thickness, with an increase in the gasification speed, the amount of coal gasification per unit time is greater and the temperature of the gasification gradually increases, as shown in Figure 8a. This further increases the maximum transfer distance of temperature in the roof and floor, as shown in Figure 8b,c. As seen in Figure 8a, with a constant coal thickness, the average temperature of the gasifier increases gradually with an increase in the gasification speed. For a particular coal seam thickness, the amount of coal in the “three zones” increases slightly with an increase in the gasification speed, as shown in Figure 8d–f. To express the relationship between the gasification speed and gasifier temperature increment more intuitively, the variation curve of the gasifier temperature increment (ATIG) with coal thickness is shown in this study (Figure 5a). With an increase in coal thickness (especially of coal seams less than 5 m), the temperature increment (ATIG) of the gasifier decreases gradually, and subsequently, the temperature increment of the gasifier tends to be stable. This shows that increasing the gasification rate can significantly increase the temperature of the gasifier for coal seams less than 5 m, thereby increasing the coal quantity in the “three zones” and warming zone, as presented in Table 3.

Meanwhile, as mentioned above, when the gasification speed is 0.5 m/d, the coal thickness corresponding to the intersection of the coal quantity in the oxidation and reduction zones is about 17.5 m. When the mining speeds are 1.0 and 1.5 m/d, the coal thicknesses corresponding to the intersection of the coal quantity in the oxidation and reduction zones are about 16.5 and 13 m, respectively, as shown in Figure 5c,d. This shows that with an increase in the gasification speed, the coal thickness corresponding to the intersection of the coal quantity in the oxidation and reduction zones decreases gradually.
In UCG, because part of the heat is absorbed by the surrounding rock, there must be a certain amount of heat loss in the gasifier. When the coal thickness is constant, the heat loss rate of the gasifier decreases gradually with an increase in the advance speed of the flame working face, as shown in Figure 7. This is mainly because the heat loss rate is controlled by the lithology, thickness, and thermal conductivity of the roof and floor; when these three factors are constant, the amount of heat loss per unit time remains unchanged. With an increase in the gasification rate, more heat is released per unit time, which indicates a decrease in the heat loss rate of the gasifier. When the gasification rate is 1.5 m/d, there is a significant decrease in the heat loss rate of the gasifier in coal seams less than 2.5 m. This indicates that the gasification rate can be increased and the heat loss rate can then be reduced when the thin coal seam is gasified.

Therefore, an increase in the gasification rate is effective in reducing the heat loss rate of the gasifier. When gasifying coal seams less than 2.5 m, the gasification efficiency and heat production rate can be increased appropriately; thus, the heat loss rate can be reduced. When gasifying coal seams more than 13 m, a mining rate of about 0.5 m/d is optimal, and any further increase in the mining rate is not suitable.

3.3. Comprehensive Evaluation of the Related Parameters of Gasifiers with Different Surrounding Rock Types. 3.3.1. Related Parameters of the Gasifier with Different Surrounding Rock Types. The high temperature significantly changes the thermophysical and mechanical

---

**Figure 9.** Distribution of “three zones” and heat loss rate with different surrounding rock types. (a) Relationship between surrounding rock types and CQDZ; (b) relationship between surrounding rock types and CQRZ; (c) relationship between surrounding rock types and the coal quantity of the dry distillation zone; (d) relationship between surrounding rock types and the heat loss rate of the gasifier (HLR).
properties of the surrounding rock. These changes directly or indirectly affect the UCG process, and these effects differ considerably due to different rock types.38,49 As mentioned above, siltstone, mudstone, argillaceous sandstone, and fine sandstone can be used as the roof and floor of the gasifier because of their low permeability and high mechanical strength. Therefore, the focus of this section is on the difference in the relevant parameters of the gasifier caused by the different thermophysical properties and not on the evolution mechanism of the thermophysical and mechanical properties of these four types of rocks with temperature.

It is known that the density, heat conduction coefficient, and specific heat capacity of different rock types are different. In this study, siltstone (A), mudstone (B), fine sandstone (C), and sandy mudstone (D) are arranged and combined to form 16 types of surrounding rock (such as AC when the roof and floor are siltstone and fine sandstone, respectively). The coal type, thickness of coal, and gasification speed are lignite, 5 m, and 0.5 m/d, respectively. Under these conditions, the effects of these 16 roof and floor types on the heat consumption rate and distribution of the “three zones” are studied separately, as shown in Table 5.

Different surrounding rock types have different heat conduction coefficients, and differences must exist in the heat transfer from the gasifier to the roof and floor in unit time. At a certain total heat, there are some differences in the temperature distribution in the gasifier under different types of top and bottom plates that inevitably lead to differences in the coal quantity of the “three zones” (oxidation zone: 122.94–154.23 m³, average: 131.61 m³; reduction zone: 237.66–250.13 m³, average: 245.73 m³; distillation drying zone: 459.38–464.77 m³; and average amount of coal: 462.17 m³), as shown in Figure 9c. The difference between the average temperatures of the roof and floor is small (ATR: 293.35–293.36 K, averages are 293.35, 294.45–294.65, and 294.48 K). However, because of its density and specific heat capacity, there is a significant difference in the heat absorption, which shows the difference in the heat loss rate (12.37–25.12%, average: 17.56%), as shown in Figure 9d. When the floor is fine sandstone, the heat loss rate is the lowest, regardless of the roof lithology. When the floor is mudstone, the heat loss rate is the highest, regardless of the roof lithology. When the roof is fine sandstone or mudstone, the heat loss rate is different but not obvious, which indicates that the specific heat capacity of the floor has a greater influence on the heat loss rate of the gasifier than that of the roof.

The abovementioned analysis shows that during gasification with different surrounding rock types, there are differences in the coal quantity of the “three zones” and warming zone, gasifier temperature, and heat loss rate. Owing to the large number of parameters and roof and floor types involved, it is impossible to evaluate the roof and floor types helpful for UCG directly and effectively. Therefore, the TOPSIS method is introduced to evaluate the gasification effect of the different roof and floor types. Six parameters are involved for this purpose: coal quantity in the oxidation, reduction, dry distillation, and warming zones, average temperature of the gasifier, and heat loss rate.

To evaluate the surrounding rock types helpful for UCG directly and effectively, the TOPSIS method is introduced to evaluate the gasification effect of the different roof and floor types. Six parameters are involved for this purpose: coal quantity in the oxidation, reduction, dry distillation, and warming zones, average temperature of the gasifier, and heat loss rate.

3.3.2. Evaluation of the Gasification Effects of Surrounding Rock Types Based on TOPSIS. TOPSIS is a method of ranking based on the proximity of limited evaluation objects to the most idealized goals. Based on the normalized original data matrix, the optimal and worst schemes are found in the limited scheme (expressed by the optimal and worst vectors, respectively). Subsequently, the distances between the evaluation objects and the optimal and worst schemes are calculated. The relative closeness between each evaluation object and the optimal scheme is obtained, which can be used as the basis for evaluating the advantages and disadvantages.

According to TOPSIS, the Euclidean distance between each parameter, the positive and negative ideal solutions (D⁺, D⁻), and the comprehensive evaluation index (fi) are classified and presented in Table 6. The higher the fi value, the more favorable the roof and floor type for UCG. As presented in Table 6, the fi value ranges from 0.30 (BB) to 0.99 (CC), with an average of 0.6144. For siltstone, mudstone, fine sandstone, and sandstone mudstone, regardless of the roof lithology, the lithology of the corresponding floor from large to small is the same, namely, fine sandstone, sandy mudstone, siltstone, and mudstone, as shown in Figure 10. Meanwhile, the order of the specific heat capacity of these rock types from small to large is fine sandstone, sandy mudstone, siltstone, and mudstone, as presented in Table 1. It is clear that the two change patterns are exactly the same. As mentioned above, the specific heat capacity has a significant influence on the heat loss rate of the gasifier. Among all the gasification parameters, the heat loss rate has the largest variation range and the greatest impact on the gasifier. Therefore, in addition to the coal rank, coal thickness, and gasification speed, the specific heat capacity of the surrounding rock is a factor affecting the UCG. Without considering the mechanical strength and permeability, the most favorable lithology for UCG is fine sandstone, followed by sandy mudstone, siltstone, and mudstone.

4. CONCLUSIONS

In this study, a three-dimensional heat conduction model of underground lignite gasification was evaluated, and the effects of different coal thicknesses, advance speeds of the flame working face, and surrounding rock types on the gasifier were analyzed. The conclusions are as follows:

1. When the gasification rate is a constant value (0.5, 1.0, and 1.5 m/d), with the increase in the coal thickness, the temperature along the gasification channel increases, the coal quantity in the three zones increases, and the heat loss rate of the gasifier decreases gradually.

Figure 10. fi index with different surrounding rock types.
(2) When the gasification rate is 0.5 m/d, the ideal gasification thickness range of lignite is between 2.5 and 17.5 m. When the coal seam is less than 2.5 m, the gasification rate can be increased. However, the heat loss rate can be reduced, and then the heat loss rate can be increased. When gasifying a coal seam with a thickness of more than 13 m, the optimal gasification rate is 0.5 m/d and must not be increased further.

(3) When only the heat transfer of surrounding rock is considered, fine sandstone is more favorable than other types of rocks.

■ AUTHOR INFORMATION

Corresponding Author
Caifang Wu – Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process, Ministry of Education, Xuzhou 221008 Jiangsu Province, China; School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221008 Jiangsu Province, China; Email: caifangwu@sina.com

Authors
He Zhou – Key Laboratory of Coalbed Methane Resources and Reservoir Formation Process, Ministry of Education, Xuzhou 221008 Jiangsu Province, China; School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221008 Jiangsu Province, China

Mingyang Du – School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221008 Jiangsu Province, China

Zhenzhi Wang – School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221008 Jiangsu Province, China; orcid.org/0000-0002-1897-1310

Xiuming Jiang – School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221008 Jiangsu Province, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c06559

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study was sponsored by the National Natural Science Foundation of China (grant nos. 41572140 and 41872170), the National Major Special Project of Science and Technology of China (grant nos. 2016ZX05044-001), and the Qing Lan Project.

■ REFERENCES

(1) Perkins, G. Underground coal gasification—Part I: Field demonstrations and process performance. Prog. Energy Combust. Sci. 2018, 67, 158–187.

(2) Kashyap, S.; Vairakanuru, P. Movable injection point-based syngas production in the context of underground coal gasification. Int. J. Energy Res. 2020, 44, 3574–3586.

(3) Laciak, M.; Vizi, L.; Kačur, J.; Durdán, M.; Flegner, P. Application of geostatistical methods in spatio-temporal modelling of temperature changes of UCG experimental trial. Meas 2020, 171, 108826.

(4) Xu, H.; Chen, Y.; Xin, F.; Dong, Z.; Yin, Z.; Chen, S.; Wang, Q. Challenges and technical countermeasures of underground coal gasification. Coal Sci. Technol. 2020, 1–11. https://kns.cnki.net/kcms/detail/11.2402.td.20201217.1040.003.html.

(5) Bhutto, A. W.; Bazmi, A. A.; Zahedi, G. Underground coal gasification: From fundamentals to applications. Prog. Energy Combust. Sci. 2013, 39, 189–214.

(6) Daggupati, S.; Mandapati, R. N.; Mahajan, S. M.; Ganesh, A.; Sapru, R. K.; Sharma, R. K.; Aghalayam, P.; Aghalayam, P. Laboratory studies on cavity growth and product gas composition in the context of underground coal gasification. Energy 2011, 36, 1776–1784.

(7) Wang, Z.; Liang, J.; Shi, L.; Xi, J.; Li, S.; Cui, Y. Expansion of three reaction zones during underground coal gasification with free and percolation channels. Fuel 2017, 190, 435–443.

(8) Hu, C.; Davies, P.; Wagner, N.; Kauchali, S. Investigation of cavity formation in lump coal in the context of underground coal gasification. J. South. Afr. Inst. Min. Metall. 2014, 114, 305–310.

(9) Harloff, G. J. Underground coal gasification cavity growth model. J. Energy 1983, 7, 410–415.

(10) Kačur, J.; Durdán, M.; Laciat, M.; Flegner, P. Impact analysis of the oxidant in the process of underground coal gasification. Measurement 2014, 51, 147–155.

(11) Su, F.-q.; Hamanaka, A.; Itakura, K.-i.; Zhang, W.; Deguchi, G.; Sato, K.; Takahashi, K.; Kodama, J.-i. Monitoring and evaluation of simulated underground coal gasification in an ex-situ experimental artificial coal seam system. Appl. Energy 2018, 223, 82–92.

(12) Perkins, G.; Sahajwalla, V. Numerical Study of the Effects of Operating Conditions and Coal Properties on Cavity Growth in Underground Coal Gasification. Energy Fuels 2006, 20, 596.

(13) Prabu, V.; Jayanti, S. Heat-affected zone analysis of high ash coals during ex situ experimental simulation of underground coal gasification. Fuel 2014, 123, 167–174.

(14) Samdani, G.; Aghalayam, P.; Ganesh, A.; Sapru, R. K.; Lohar, B. L.; Mahajani, S. A process model for underground coal gasification—Part-II growth of outflow channel. Fuel 2016, 181, 587–599.

(15) Jiang, L.; Chen, Z.; Farouq Ali, S. M. Heavy oil mobilization from underground coal gasification in a contiguous coal seam. Fuel 2019, 249, 219–232.

(16) Shirong, G. E. Chemical mining technology for deep coal resources. J. China Univ. Min. Technol. 2017, 46, 679–691.

(17) Shafirovich, E.; Varma, A. Underground Coal Gasification: A Brief Review of Current Status. Ind. Eng. Chem. Res. 2009, 48, 7865–7875.

(18) Hu, Z.; Peng, Y.; Sun, F.; Chen, S.; Zhou, Y. Thermodynamic equilibrium simulation on the synthesis gas composition in the context of underground coal gasification. Fuel 2021, 293, 120462.

(19) Konstantinou, E.; Marsh, R. Experimental study on the impact of reactant gas pressure in the conversion of coal char to combustible gas products in the context of Underground Coal Gasification. Fuel 2015, 159, 508–518.

(20) Stańczyk, K.; Howaniec, N.; Smoliński, A.; Świądrowski, J.; Kapusta, K.; Wiatrowski, M.; Rogut, J. Gasification of lignite and hard coal with air and oxygen enriched air in a pilot scale ex situ reactor for underground gasification. Fuel 2011, 90, 1953–1962.

(21) Wang, Z.; Wei, Y.; Hou, T.; Jin, Y.; Wang, C.; Liang, J. Large-scale laboratory study on the evolution law of temperature fields in the context of underground coal gasification. Chin. J. Chem. Eng. 2020, 28, 3126–3135.

(22) Liu, H.; Liu, S.; Chen, F.; Zhao, J.; Qi, K.; Yao, H. Mathematical modelling of underground coal gasification process in one gasification cycle. Energy Fuels 2019, 33, 979–989.

(23) Shabbir, S.; Janjareh, I. Thermodynamic equilibrium analysis of coal gasification using Gibbs energy minimization method. Energy Convers. Manage. 2013, 65, 755–763.

(24) Samdani, G.; Ganesh, A.; Aghalayam, P.; Sapru, R. K.; Lohar, B. L.; Mahajani, S. Kinetics of heterogeneous reactions with coal in context of underground coal gasification. Energy 2017, 199, 102–114.

(25) Xin, L.; Wang, Z.-t.; Wang, G.; Nie, W.; Zhou, G.; Cheng, W.-m.; Xie, J. Technological aspects for underground coal gasification in steeply inclined thin coal seams at Zhongliangshan coal mine in China. Fuel 2017, 191, 486–494.
(26) Wang, J.; Wang, Z.; Xin, L.; Xu, Z.; Gai, J.; Lu, X. Temperature field distribution and parametric study in underground coal gasification stope. *Int. J. Therm. Sci.* 2017, 111, 66–77.

(27) Cheng, W.; Xin, L.; Wang, G.; Liu, Z.; Nie, W. Analytical research on dynamic temperature field of overburden in goaf fire-area under piecewise-linear third boundary condition. *Int. J. Heat Mass Transfer* 2015, 90, 812–824.

(28) Luo, J. a.; Wang, L.; Tang, F.; He, Y.; Zheng, L. Variation in the temperature field of rocks overlying a high-temperature cavity during underground coal gasification. *Min. Sci. Technol.* 2011, 21, 709–713.

(29) Yang, L. The Dynamic Temperature Field of Two-Stage Underground Coal Gasification (UCG). *Energy Sources* 2006, 28, 667–680.

(30) Brown, J.; Vardy, A.; Zeng, Z. Influence of radial seepage on temperature distribution around a cylindrical cavity in a porous medium. *Int. J. Heat Mass Transfer* 1998, 41, 1531–1541.

(31) Xin, L.; Wang, Z.; Huang, W.; Kang, G.; Lu, X.; Zhang, P.; Wang, J. Temperature field distribution of burnt surrounding rock in UCG stope. *Int. J. Min. Sci. Technol.* 2014, 24, 573–580.

(32) Xin, L.; Cheng, W.; Xie, J.; Liu, W.; Xu, M. Theoretical research on heat transfer law during underground coal gasification channel extension process. *Int. J. Heat Mass Transfer* 2019, 142, 118409.

(33) Kapusta, K.; Wiadowski, M.; Stańczyk, K. An experimental ex-situ study of the suitability of a high moisture ortho-lignite for underground coal gasification (UCG) process. *Fuel* 2016, 179, 150–155.

(34) Liu, S.; Niu, M.; Yan, Y.; Jin, X.; He, Y.; Gao, B.; Wang, Z.; Li, J. Exploration of radial expansion of the gasification face from underground coal gasification. *J. China Coal Soc.* 2018, 43, 2044–2051.

(35) Vyas, D. U.; Singh, R. P. Worldwide Developments in UCG and Indian Initiative. *Procedia Earth Planet. Sci.* 2015, 11, 29–37.

(36) Yang, D.; Koukouzas, N.; Green, M.; Sheng, Y. Recent development on underground coal gasification and subsequent CO2 storage. *J. Energy Inst.* 2016, 89, 469–484.

(37) Yekta, A. E.; Manceau, J.-C.; Gaboreau, S.; Pichavant, M.; Audigane, P. Determination of hydrogen–water relative permeability and capillary pressure in sandstone: application to underground hydrogen injection in sedimentary formations. *Transp. Porous Media* 2018, 123, 333–356.

(38) Meng, T.; Guangwu, X.; Jiwei, M.; Yang, Y.; Liu, W.; Zhang, J.; Bosen, J.; Fang, S.; Ren, G. Mixed mode fracture tests and inversion of FPZ at crack tip of overlying strata in underground coal gasification combustion cavity under real-time high temperature condition. *Eng. Pract. Mech.* 2020, 239, 107298.

(39) Tang, F. Fracture Evolution and Breakage of Overlying Strata of Combustion Space Area in Underground Coal Gasification. Ph.D. thesis, China University of Mining and Technology, 2013; pp 1–187. (In Chinese).

(40) Zhao, M. Research on The Experiment and Numerical Simulation of Temperature and Fracture in Overlying Strata in UCG; China University of Mining and Technology: Beijing, 2017; pp 1–128. (In Chinese).

(41) Wasantha, P.; Guerrieri, M.; Xu, T. Effects of tunnel fires on the mechanical behaviour of rocks in the vicinity — A review. *Tunn. Undergr. Space Technol.* 2020, 108, 103667.

(42) Shi, L.; Qiu, M.; Teng, C.; Wang, Y.; Liu, T.; Qu, X. Risk assessment of water inrush to coal seams from underlying aquifer by an innovative combination of the TPN-AHP and TOPSIS techniques. *Arabian J. Geosci.* 2020, 13, 600.

(43) Yang, L. H. A review of the factors influencing the physicochemical characteristics of underground coal gasification. *Energy Sources, Part A* 2008, 30, 1038–1049.

(44) Wang, Z.; Xu, X.; Cui, Y. Effect of Fixed and Removable Gas-Injection Patterns on the Expansion of Reaction Zones during Underground Coal Gasification. *Energy fuels* 2019, 33, 4740–4747.

(45) Yang, L.; Liu, Y. Characteristics of “Three Zones” in Underground Coal Gasification and Its Study of Influence Variables. *J. Nanjing Univ. Sci. Technol.* 2001, 25, 533–537.

(46) Liu, X.; Guo, G.; Li, H. Study on the propagation law of temperature field in surrounding rock of underground coal gasification (UCG) combustion cavity based on dynamic thermal parameters. *Results Phys.* 2019, 12, 1956–1963.

(47) Lán, Y. Study on moving velocity of burning front in underground coal gasification. *J. China Coal Soc.* 2000, 5, 496–500.

(48) Leiss, B.; Molli, G. ‘High-temperature’texture in naturally deformed Carrara marble from the Alpi Apuane, Italy. *J. Struct. Geol.* 2003, 25, 649–658.

(49) Xin, L.; Li, C.; Liu, W.; Xu, M.; Xie, J.; Han, L.; An, M. Change of sandstone microstructure and mineral transformation nearby UCG channel. *Fuel Process. Technol.* 2021, 211, 106575.