

Article

A Fitting Study on the Growth Boundary of an Underground Coal Gasification Cavity Based on Numerical Simulation

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Abstract

Underground coal gasification (UCG) is a coal utilization technology that has attracted extensive attention over the years. In order to study the distribution and evolution law of the growth boundary of a coal gasification cavity under UCG, COMSOL numerical simulation software was used to conduct a multi-physical field-coupling numerical simulation of its growth process. In this study, we established a gasification reaction model of the cavity, and after simulation calculation, the growth boundary of the gasification cavity was obtained. Multiple data points were taken from the growth boundary of the gasification cavity for the fitting calculation, and the fitting function $y = F(x)$ of the gasification boundary growth was obtained. The core insight from this study is that a gasification boundary growth fitting function $y = F(x)$ was cross-fitted based on seven different gasification times t (5 d, 20 d, 40 d, 60 d, 80 d, 110 d, 150 d) and 10 different gasification agent inflow velocities v (0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s, 1 m/s, 2 m/s, 4 m/s, 6 m/s, 8 m/s, 10 m/s) as orthogonal independent variables. An innovative multi-parameter fitting equation was constructed, $y = F(x, t, v)$, with the gasification time t and the gasification agent inflow velocity v as independent variables. This fitting equation, $y = F(x, t, v)$, can dynamically depict the gasification cavity boundary during the UCG process when different gasification times t and gasification agent inflow velocities v are inputted. The novelty of this study lies in the fact that it breaks through the limitations of traditional numerical simulation models that rely on a single variable, have limited adaptability, and focus on gasification cavities that lie mostly in the side-view direction. Moreover, through a multi-physics field-coupling numerical simulation in the top-view direction of the gasification cavity, we have improved the construction of the UCG numerical simulation model and cross-fitted the gasification boundary with respect to the gasification time t and gasification agent inflow velocity v to construct a fitting equation, achieving the quantitative representation of the nonlinear relationship between variables.

Keywords: underground coal gasification; numerical simulation; gasification cavity; boundary curve; fitting function



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1. Introduction

UCG technology, a cutting-edge technology that converts coal resources into synthetic gas in situ underground, was first proposed by German scientist William Siemen in 1868. Since then, after more than 150 years of research and practice by scholars across various countries, five mainstream gasification processes have been established, and industrial trials

have been conducted in at least 40 regions around the world [1–4]. This technology does not require underground mining operations. It fundamentally avoids potential accidents such as roof collapses and gas explosions caused by underground mining. At the same time, it retains waste materials such as ash and slag underground, significantly reducing surface subsidence and environmental issues such as solid waste emissions. It achieves true green coal mining, demonstrating unique advantage in terms of harnessing difficult-to-access coal resources and promoting clean coal conversion. It is regarded as one of the most promising coal utilization technologies in the 21st century [5–7].

Since the UCG technology concept was proposed, scholars from various countries have conducted extensive research on its reaction mechanism, process optimization, numerical simulation, and engineering applications. The UCG process is essentially a complex multi-physics field-coupled process involving heat transfer, mass transfer, chemical reactions, and fluid flow. The formation and dynamic evolution of the gasification cavity are the core links that determine the gasification efficiency, product gas quality, and engineering safety. The gasification cavity is the main site for coal thermal decomposition and gasification reactions. The distribution characteristics of its growth boundary directly affect the contact area between the gasification agent and the coal, the efficiency of heat transfer, and the migration path of the syngas. If the evolution law of the cavity growth boundary can be accurately determined, then key parameters such as the gasification time and gasification agent injection speed can be dynamically regulated to maximize the coal conversion rate and gasification efficiency. Conversely, if the evolution law of the cavity growth boundary is not well understood, this is very likely to cause a series of engineering problems, such as excessive expansion of the cavity, leading to instability and collapse in the stratum and leakage of the gasification channel. This wastes the gasification agent and dilutes the product gas or leads to an insufficient local reaction, which seriously restricts the large-scale and commercial application of UCG technology [8–10].

Currently, research on the growth boundary of UCG cavities mainly follows three technical approaches: field experiments, physical simulation, and numerical simulation. Field experiments can most directly reflect the actual growth state of the cavities, but they pose problems such as high cost, long cycles, and high testing difficulty. Moreover, due to the complexity of geological conditions, the universality of the test results is poor, making it difficult to conduct systematic studies on the evolution laws of cavities under different conditions [11–15]. Physical simulation involves constructing similar models to simulate UCG. It can, to some extent, reveal the basic laws of cavity growth; however, due to limitations in model scale and the difficulty in completely reproducing the complex geological and thermodynamic conditions underground, the simulation results show certain deviations from the actual engineering reality, and it is difficult to achieve precise quantitative analysis of the growth boundary of cavities [16–19]. In contrast, numerical simulation technology, with its advantages of low cost, high efficiency, and strong repeatability, can precisely characterize the multi-physics field-coupling effects in the UCG process. By constructing mathematical models and solving governing equations, it enables dynamic tracking and quantitative analysis of the cavity growth process and has become the mainstream technical means for UCG cavity evolution research. Scholar Greg Perkins proposed a planar cavity development sub-model, which is based on the concept of surface reactions and comprehensively considers physical factors such as water evaporation, water intrusion, and coal pyrolysis. Through laboratory experiments and field tests, it has been shown to be able to estimate the cavity development rate under reasonable input parameters. However, this model focuses on the calculation of cavity growth rate well and fails to achieve precise fitting of the growth boundary and multi-factor coupling analysis. Some scholars have mainly used FLUENT 2023 or MATLAB R2020b software to simulate the fluid flow and

heat and mass transfer characteristics during gasification, and analyze the effects of the gasification agent flow rate, oxygen concentration, etc., on cavity morphology. However, this type of research does not comprehensively consider the multi-physics field-coupling effects and is insufficient to accurately reflect the real process of cavity growth [20–27]. Currently, UCG technology is evolving toward more quantitative and intelligent control. Constructing a precise model for predicting the growth boundary of cavities is the core prerequisite in achieving this goal. By accurately predicting the expansion trend of cavities, it will be possible to effectively avoid engineering risks such as the development of water-conducting fractures, layer collapse, and gas channel leakage caused by excessive cavity expansion [28–33]. Research by Guo Guangli [34] and others has confirmed that the parameters of the gasification furnace are highly directly related to the development of water-conducting fractures. Precise boundary prediction can provide a basis for parameter regulation, and at the same time, based on the prediction results, the supply amount of the gasification agent can be reasonably matched, significantly improving the coal conversion rate and gasification efficiency, and reducing energy waste and production costs.

The main objective in this study is to conduct multi-physics field simulations of the UCG process, analyze the simulation results, and then construct an equation, $F(x, t, v)$, for the growth boundary of the gasification cavity that integrates variables such as the time t (5 d, 20 d, 40 d, 60 d, 80 d, 110 d, 150 d) and gasification agent injection speed v (0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s, 1 m/s, 2 m/s, 4 m/s, 6 m/s, 8 m/s, 10 m/s) as independent variables. This equation can predict the shape of the coal seam gasification cavity and provide a theoretical basis and methodological support for achieving precise control and safety optimization in the UCG process. At the same time, it can be combined with coal seam geological parameters (such as coal seam thickness, permeability, or porosity) to modify the multi-physics field simulation model, enhancing its applicability in different geological conditions.

2. Establishment of Numerical Model

2.1. Model Establishment

This study focuses on the establishment of a numerical model for coal seams that are challenging to extract and have low economic mining value. Here, “challenging to extract” refers to deep burial depths, typically reaching several thousand meters, while “low economic mining value” indicates thin seams combined with significant depth, making conventional underground mining economically unviable. Therefore, a thin coal seam (with a thickness of 1 m) is selected as the modeling target in this study. The coal type chosen was lignite, which is suitable for UCG, and the x-direction size of the coal seam was 90 m, while the y-direction size was 60 m. There was an agglomeration channel along the x-direction in the middle of the coal seam, which ran through the entire coal seam and had a width of 3 m. An initial heat source was set 6 m away from the right boundary of the model to simulate the ignition point at the beginning of the agglomeration process. The initial heat source temperature was set at 873.15 K, and its size was 3 m × 3 m. The right boundary of the agglomeration channel was set as the inlet for the agglomeration agent, and the left boundary was set as the outlet for the gas produced (coarse gas). The agglomeration direction (the growth direction of the agglomeration cavity) was from right to left. The numerical model grid arrangement was selected as “finer” and ultra-fine was chosen at the agglomeration channel. A schematic diagram of the numerical model’s geometry and grid division is shown in Figure 1. To explore the relationship between the boundary growth trend of the ellipsoidal agglomeration cavity during the UCG process and the time and gas introduction speed, this model used 10 gas introduction speeds as the first independent variable, i.e., 0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s, 1 m/s, 2 m/s, 4 m/s, 6 m/s, 8 m/s, and

10 m/s; seven time points were used as the second independent variable, i.e., 5 d, 20 d, 40 d, 60 d, 80 d, 110 d, and 150 d; and the boundary growth trend of the ellipsoidal agglomeration cavity was used as the dependent variable for orthogonal simulation.

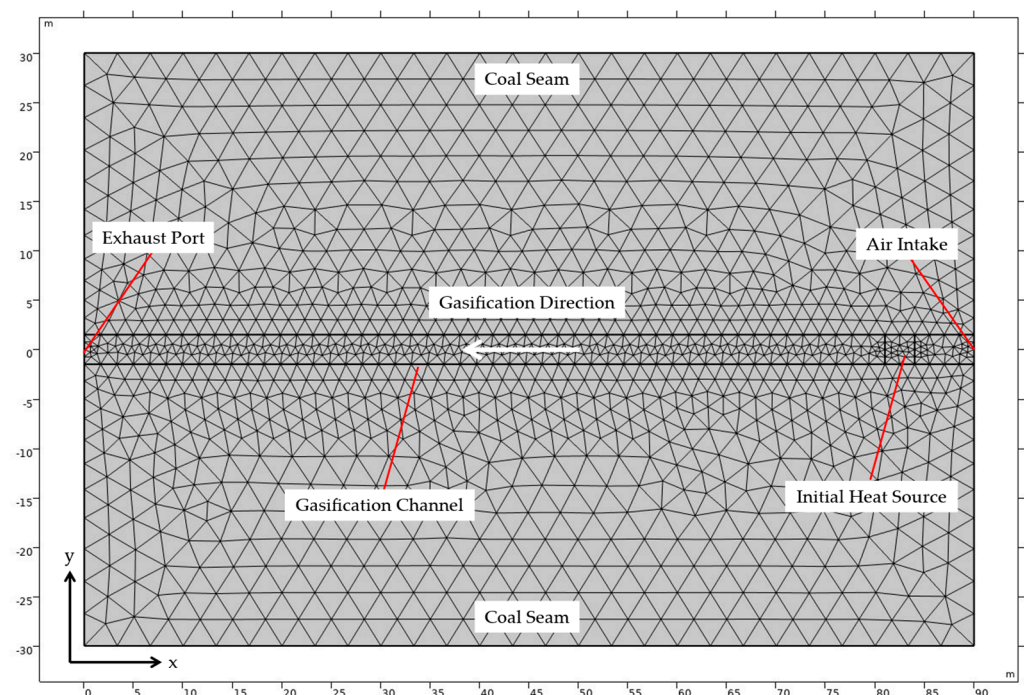


Figure 1. Geometric illustration and mesh division diagram of the numerical model.

2.2. Material Parameters

Since the coal quality considered in this model is lignite with a high moisture content, a mixed gas with a water vapor-to-oxygen ratio of 1:1 was selected as the gasification agent. To simplify the numerical model calculation, in this study, we assume that before ignition and gasification, the gasification agent has been introduced into the gasification channel and stabilized. The material parameters of the coal layer are set as shown in Table 1. It is worth noting that this chapter only provides the settings of some material properties for the subsequent physical field invocation; for the specific setting of the control equations and boundary conditions, please refer to Section 2.3.

Table 1. Coal seam parameter settings.

Attribute	Value
Permeability	$5 \times 10^{-17} \text{ m}^2$
Porosity	0.15
Constant-pressure heat capacity	$C_{coal}(T)$
Thermal conductivity	$\lambda_{coal}(T)$
Density	1150 kg/m^3

The constant-pressure heat capacity and thermal conductivity of the coal seam both change with temperature. The values of these numerical model parameters are taken from the fitting formula in the measurement experiment literature for lignite [35]; and are denoted as $C_{coal}(T)$ and $\lambda_{coal}(T)$, respectively, as shown in Equations (1) and (2).

Constant-pressure heat capacity:

$$C_{coal}(T) = 10^{-13}T^5 - 3 \times 10^{-10}T^4 + 2 \times 10^{-7}T^3 - 8 \times 10^{-5}T^2 + 1.16 \times 10^{-2}T + 0.8341 \quad (1)$$

Thermal conductivity:

$$\lambda_{coal}(T) = 2 \times 10^{-14}T^5 - 6 \times 10^{-11}T^4 + 5 \times 10^{-8}T^3 - 2 \times 10^{-5}T^2 + 1.5 \times 10^{-3}T + 0.2248 \quad (2)$$

The parameters for the gasification agent are set as shown in Table 2.

Table 2. Parameters for gasification agent settings.

Attribute	Value
Dynamic viscosity	$\mu_{mix}(T)$
Constant-pressure heat capacity	$C_{p,mix}(T)$
Specific heat capacity	$Y_{mix}(T)$
Thermal conductivity	$\lambda_{mix}(T)$
Density	$\rho_{mix}(T)$

All of its physical parameters change with the variation in temperature. Therefore, for the dynamic viscosity, specific heat rate, constant-pressure heat capacity, thermal conductivity, and density of the gasifier, the following settings are used:

Dynamic viscosity:

According to the Sutherland law proposed by William Sutherland [36], the relationship between the dynamic viscosity of gases and temperature is as shown in Equation (3), where T_{ref} is a reference temperature, μ_{ref} is the viscosity at the T_{ref} , and S is the Sutherland temperature.

$$\mu = \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{\frac{3}{2}} \frac{T_{ref} + S}{T + S} \quad (3)$$

Take the T_{ref} value as 873.15 K, μ_{H_2O} as the dynamic viscosity of water vapor, which is set at 2×10^{-5} Pa·s, and μ_{O_2} as the dynamic viscosity of oxygen, which is set at 3×10^{-5} Pa·s. Substituting these values into Equation (3), the dynamic viscosities with respect to temperature changes are obtained as $\mu_{H_2O}(T)$ and $\mu_{O_2}(T)$; μ_{mix} is the dynamic viscosity of the gasifier and can be calculated using the semi-empirical formula proposed by Wilke and later modified by Bird, as shown in Equation (4). Since the dynamic viscosity of the gasifier near the inlet has a negligible overall impact on the model calculation, to simplify the equation and input the numerical model, this model calculates the mixture dynamic viscosity according to Equation (5).

$$\mu = \sum_{k=1}^K \frac{X_k \mu_k}{\sum_{j=1}^K X_j \Phi_{kj}} \quad (4)$$

$$\mu_{mix}(T) = 0.5\mu_{H_2O}(T) + 0.5\mu_{O_2}(T) \quad (5)$$

Constant-pressure heat capacity:

The heat transfer in the constant-pressure process and the heat transfer in the constant-volume process are given by Equation (6) and Equation (7), respectively. By transforming these two equations, the constant-pressure heat capacities $C_{p,H_2O}(T)$ for water vapor and $C_{p,O_2}(T)$ for oxygen are obtained as shown in Equation (8) and Equation (9), respectively. Here, T_0 is set to 293.15 K, and the values of T and Q are set according to the results of the heat transfer physical field. Thus, functional form coupling of the laminar physical field and the heat transfer physical field can be achieved, and the constant-volume heat capacities $C_{v,H_2O}(T)$ and $C_{v,O_2}(T)$ for water vapor and oxygen are obtained as shown in Equation (10) and Equation (11), respectively. n denotes the amount of substance of a specific material.

Since the mixture in the gasifier is a 1:1 mixture of water vapor and oxygen, the constant-pressure heat capacity $C_{p,mix}(T)$ of the gasifier is expressed by Equation (12).

$$Q_p = \int_{T_1}^{T_2} nC_p dT \quad (6)$$

$$Q_v = \int_{T_1}^{T_2} nC_v dT \quad (7)$$

$$C_{p,H_2O}(T) = \left. \frac{dQ_p}{dT} \right|_{T-T_0} \times \frac{1}{n} \quad (8)$$

$$C_{p,O_2}(T) = \left. \frac{dQ_p}{dT} \right|_{T-T_0} \times \frac{1}{n} \quad (9)$$

$$C_{v,H_2O}(T) = \left. \frac{dQ_v}{dT} \right|_{T-T_0} \times \frac{1}{n} \quad (10)$$

$$C_{v,O_2}(T) = \left. \frac{dQ_v}{dT} \right|_{T-T_0} \times \frac{1}{n} \quad (11)$$

$$C_{p,mix}(T) = 0.5C_{p,H_2O}(T) + 0.5C_{p,O_2}(T) \quad (12)$$

Specific heat capacity:

The heat capacity ratio Y can be expressed as Equation (13). Let $C_p = C_{p,mix}(T)$, and the value of C_v is determined according to Equation (14). Here, $C_{v,H_2O}(T)$ and $C_{v,O_2}(T)$ are calculated using Equation (10) and Equation (11), respectively. The final calculated gasification agent heat capacity ratio is denoted as $Y_{mix}(T)$, as shown in Equation (15).

$$Y = \frac{C_p}{C_v} \quad (13)$$

$$C_{v,mix}(T) = 0.5C_{v,H_2O}(T) + 0.5C_{v,O_2}(T) \quad (14)$$

$$Y_{mix}(T) = \frac{C_{p,mix}(T)}{C_{v,mix}(T)} \quad (15)$$

Thermal conductivity:

By slightly modifying Equation (16), the thermal conductivity $\lambda_{mix}(T)$ of the mixed gas can be calculated, as shown in Equation (19), where the thermal conductivities of water vapor and oxygen that vary with temperature are as given by Equations (17) and (18). In these equations, for water vapor, since it is in liquid form at room temperature, the value of T_0 is set to 473.15 K, and at this time, λ_0 is set as 0.04, and n is set as 0.9. $\lambda_{H_2O}(T)$ represents the thermal conductivity of water vapor at temperature T ; for oxygen, λ_0 is the thermal conductivity of oxygen at room temperature, which is set as 0.02, and $\lambda_{O_2}(T)$ is the thermal conductivity of oxygen at temperature T , with n being 0.8.

$$\lambda = \lambda_0 \left(\frac{T}{T_0} \right)^n \quad (16)$$

$$\lambda_{H_2O}(T) = 0.04 \left(\frac{T}{473.15} \right)^{0.9} \quad (17)$$

$$\lambda_{O_2}(T) = 0.02 \left(\frac{T}{293.15} \right)^{0.8} \quad (18)$$

$$\lambda_{mix}(T) = 0.5\lambda_{H_2O}(T) + 0.5\lambda_{O_2}(T) \quad (19)$$

Density:

According to the ideal gas state equation, $PV = nRT$, but water vapor is not in a gaseous state at normal temperature and pressure but in a liquid state. Therefore, the ideal gas state equation is transformed to obtain Equation (20) as the density $\rho_{mix}(T)$ of the gasifying agent, where $M = 0.5 \times 18 + 0.5 \times 32 = 25 \text{ g/mol} = 0.025 \text{ kg/mol}$. The universal gas constant R is set as $8.314 \text{ J/(mol}\cdot\text{K)}$, and the pressure P is set as 10^5 Pa (0.1 MPa).

$$\rho_{mix}(T) = \frac{PM}{RT} \quad (20)$$

2.3. Setting of Physical Field Control Equations

This section will explain the equations used in physical environments. Some of the material properties and coupling methods of the physical fields were described in Section 2.2 and will not be repeated here.

2.3.1. Laminar Physical Field

The laminar physical field acts on the entire model, and its calculation is mainly based on the Navier–Stokes momentum conservation equation, as shown in Equations (21) and (22) [28,37–39].

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot [-pI + K] + F \quad (21)$$

$$K = \mu [\nabla u + (\nabla u)^T] \quad (22)$$

In the equation, ρ represents the fluid density, u is the velocity vector, t is the time, $(u \cdot \nabla)u$ is the convective term, p is the pressure, I is the unit tensor, K is the viscous stress tensor, F is the volume force per unit volume, μ is the dynamic viscosity coefficient, and $(\nabla u)^T$ is the transpose of the velocity gradient, ensuring tensor symmetry. Boundary pressure constraints are set at the inlet and outlet, and the flow is suppressed at the outlet to prevent backflow. Except for the model inlet and outlet, no-slip boundary conditions $u = 0$ are set on the outer walls.

2.3.2. Heat Transfer Physical Field

In this model, the calculation is based on the energy conservation equation and is as shown in Equation (23) [40,41].

$$d_z \rho c_p \frac{\partial T}{\partial t} + d_z \rho c_p u \cdot \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_p + d_z Q_{vd} + d_z Q_{geo} \quad (23)$$

In the equation, $d_z \rho c_p \frac{\partial T}{\partial t}$ represents the change in internal energy per unit volume over time, $d_z \rho c_p u \cdot \nabla T$ represents the heat transport caused by the fluid, $\nabla \cdot q$ represents the net heat flow change in heat conduction, where $q = -d_z k_{eff} \nabla T$ describes the heat flux density in a multiphase medium, k_{eff} is the effective thermal conductivity, d_z is a correction factor related to the geometric structure of the medium, and the right side of the equation is the superimposed term of all volume heat sources and external heat sources. At the initial heat source, an initial temperature of 873.15 K is set to simulate the initial state of ignition. For the model boundary, it is defined as heat insulation and set to a temperature of 293.15 K. It is worth noting that the entire model is defined as a model heat source reaction $Q = Q_0$, where Q_0 originates from the heat of chemical reactions, indicating that in addition to the initial heat source, subsequent dynamic heat generated by chemical reactions is used to simulate the dynamic process of coal seam combustion.

2.3.3. Physical Field of Matter Transfer

The governing equations for component transport based on Fick's first law are set up as in Equations (24) and (25). These equations describe the variation patterns in the concentration of a certain component i ($i = \text{C}, \text{CO}, \text{CO}_2, \text{H}_2\text{O}, \text{H}_2, \text{O}_2$) over time and space. They are mathematical expressions of processes such as convection, diffusion, reaction, and inter-phase mass transfer [42–44].

$$\frac{\partial c_i}{\partial t} + \nabla \cdot J_i + u \cdot \nabla c_i = R_i \quad (24)$$

$$J_i = -D_i \nabla c_i \quad (25)$$

In the equation, $\frac{\partial c_i}{\partial t}$ represents the rate of change in component i 's concentration c_i with respect to time, $\nabla \cdot J_i$ represents the divergence of the diffusion flux J_i , $u \cdot \nabla c_i$ represents the convective transport term caused by the velocity field u , R_i represents the chemical reaction source term of component i , D_i represents the molecular diffusion coefficient of component i , c_i represents the concentration of component i , and this model regards the coal seam as a porous medium. By performing a multiphase extension on $\frac{\partial c_i}{\partial t}$, it can be written as $\frac{\partial(\theta_{ci})}{\partial t} + \frac{\partial(\rho c_{p,i})}{\partial t}$, and on the right side of Equation (24), a source term corresponding to solid mass transfer S_i is added. Substituting this into Equation (24) yields the multiphase mass transfer equation as Equation (26).

$$\frac{\partial(\theta_{ci})}{\partial t} + \frac{\partial(\rho c_{p,i})}{\partial t} + \nabla \cdot J_i + u \cdot \nabla c_i = R_i + S_i \quad (26)$$

In the equation, θ represents the non-steady term of the concentration of the fluid phase, ρ is the density of the solid phase, $c_{p,i}$ is the concentration change caused by the adsorption or reaction of the solid in relation to component i , and the diffusion flux J_i can be expanded as $J_i = -(D_{d,i} + D_{e,i}) \nabla c_i$, where $D_{d,i}$ is the molecular diffusion coefficient and $D_{e,i}$ is the diffusive diffusion caused by the flow of the fluid around the solid particles in the porous medium coal layer.

2.3.4. Physical Field of Chemical Reaction

To simplify the model calculation, this numerical simulation employs three of the most significant chemical reaction equations to set up the physical field for chemical reaction kinetics as shown in Equations (27)–(29). These three reaction equations include six of the most primary substance components: $i = \text{C}, \text{CO}, \text{CO}_2, \text{H}_2\text{O}, \text{H}_2$, and O_2 . The gasification kinetics process is defined by the Arrhenius equation; (Equation (30)) [45,46].



$$k = A \left(\frac{T}{T_{ref}} \right)^n \exp \left(-\frac{E_a}{RT} \right) \quad (30)$$

In the equation, k is the reaction rate constant defined by the Arrhenius equation, A is the pre-exponential factor of the reaction, T is the thermodynamic temperature of the system, E_a is the apparent activation energy, n is the exponent of the temperature index term used to correct the simple Arrhenius equation, and r_i is defined as $k_z c_i$, where k_z is the reaction rate constant defined by the Arrhenius equation in the three chemical reaction equations ($z = 1, 2, 3$). The different chemical reaction parameters of UCG are shown in Table 3.

Table 3. Different chemical reaction parameters of UCG [47].

Reaction Rate r_i	n	Antecedent Factor A (1/s)	Apparent Activation Energy E_a /(kJ/mol)	Reaction Enthalpy (kJ/mol)
$r_1 = k_1 c_{O_2}$	1	2.503×10^{17}	179.4	−393.8
$r_2 = k_2 c_{CO_2}$	0.5	0.8593	211	+172.4
$r_3 = k_3 c_{H_2O}$	0.5	85.93	231	+131.4

3. Results and Fitting Analysis

3.1. Results

We performed transient calculations on the numerical model, selecting 10 gas injection velocities as the first independent variable, i.e., 0.1 m/s, 0.3 m/s, 0.5 m/s, 0.7 m/s, 1 m/s, 2 m/s, 4 m/s, 6 m/s, 8 m/s, and 10 m/s, and seven time points as the second independent variable: 5 d, 20 d, 40 d, 60 d, 80 d, 110 d, and 150 d. The model calculates the boundaries of 70 elliptical gasification cavities. Under the condition of a gas injection velocity of 4 m/s, the shapes of the gasification cavities at time variables of 5 d, 20 d, 40 d, 60 d, 80 d, 110 d, and 150 d are shown in Figure 2. The black part in Figure 2 represents the coal seam, and the blue part represents the boundary of the gasification cavity. From Figure 2, it can be observed that as the reaction time is prolonged, the gasification cavity shows a continuous expansion trend and gradually approaches an elliptical shape. This phenomenon can be explained by combining reaction kinetics and heat transfer theory. The essence of coal gasification combustion is a multiphase reaction process, and the reaction rate is determined by the contact efficiency of the fuel (coal seam) and the gasification agent, as well as the efficiency of heat transfer. In the initial stage (5 days to 20 days), the expansion rate of the cavity is relatively slow, because at this time, the heat accumulation in the reaction area is insufficient and the gasification reaction is mainly surface oxidation. The heat conduction rate limits the rapid consumption of the coal seam [48–50]. As the reaction continues (after 40 days), the heat accumulates in the coal seam around the cavity through conduction and convection, causing the temperature in the reaction area to increase, accelerating the thermal decomposition and gasification reactions of the coal seam. At the same time, the expanded cavity provides a larger space for the diffusion of the gasification agent, further enhancing the probability of gas–solid contact, forming a positive feedback loop of “heat accumulation–reaction acceleration–cavity expansion”, and ultimately presenting an elliptical expansion form. This form is essentially the thermodynamic equilibrium result of the synergistic effect of the reaction rate of the gas–solid reaction and the diffusion path of the gasification agent.

Figure 3 shows the velocity distribution of the cavity flow field under the same gasification agent velocity (4 m/s) (the red arrows indicate the direction of the gas vector). Through analysis and comparison and analyzing with Figure 2, it can be concluded that the gasification cavity is not an ideal symmetrical structure. From the perspective of fluid dynamics principles, after the gasification agent is ejected from the pipeline and breaks free from constraints, it forms a free jet. In the area far from the inlet, due to the shear effect between the jet and the cavity boundary, as well as the development of wake vortices, tail oscillation and swirling phenomena occur. This asymmetric flow field directly changes the spatial distribution of the gas–solid interaction. The area with jet oscillation has a higher concentration of gasification agent, more gas–solid contact, and a faster reaction rate, resulting in a higher coal layer consumption rate in this area than the symmetrical side. The swirling area is prone to form local vortices, causing gasification agent stagnation and product accumulation, reducing the local reaction efficiency and ultimately causing the cavity boundary to exhibit non-symmetrical evolution characteristics. This discovery suggests that in actual UCG engineering, the non-symmetrical reaction induced by the jet may lead to the biased expansion of the cavity [51,52].

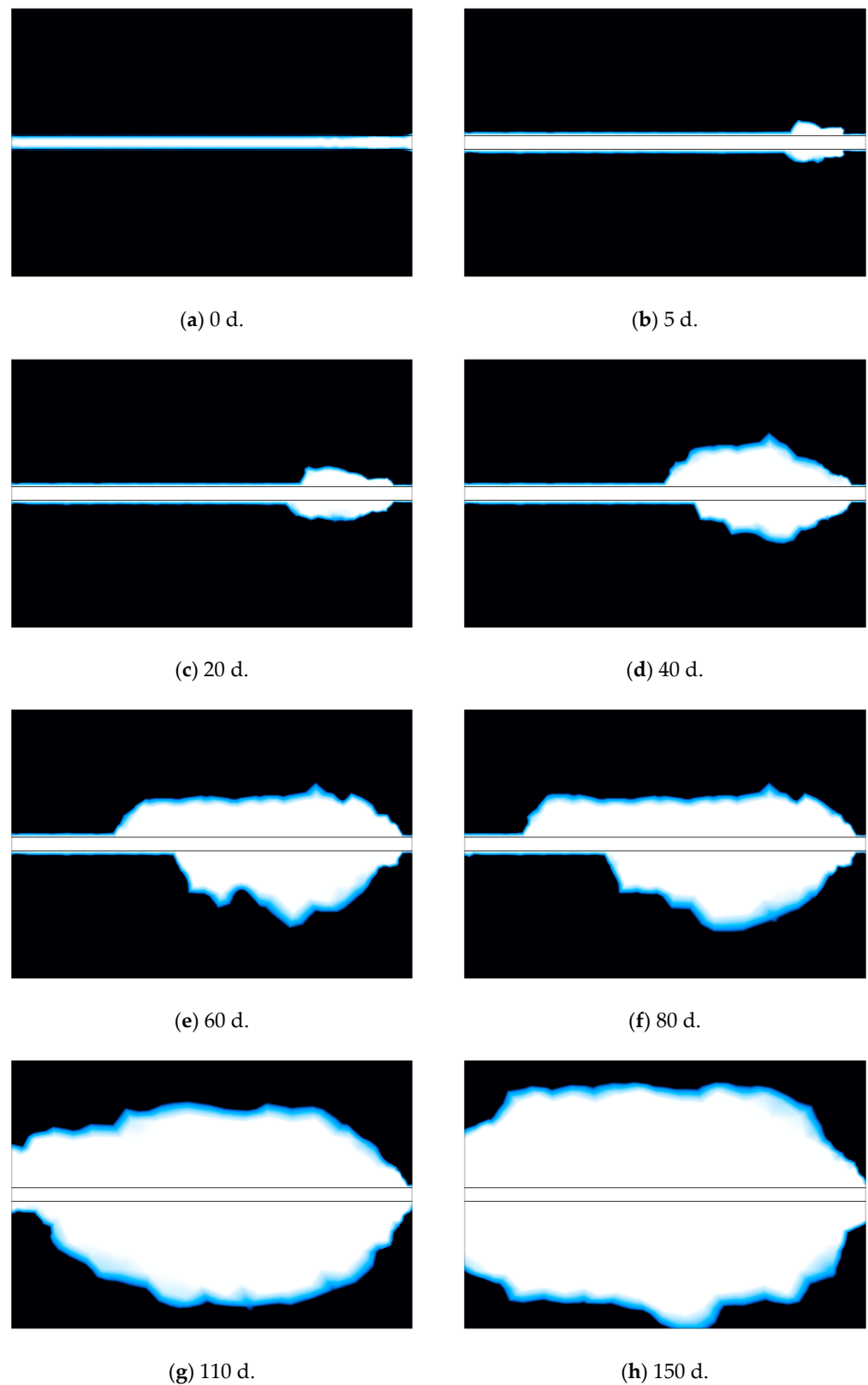


Figure 2. Shape of the gasification cavity boundary (inlet gas velocity of 4 m/s). In this figure, the black part represents the coal seam, the white part represents the gasification cavity, the blue part indicates the boundary of the coal seam being gasified, and the two horizontal lines in the middle are the modeling construction lines for the gasification channel in the initial modeling process.

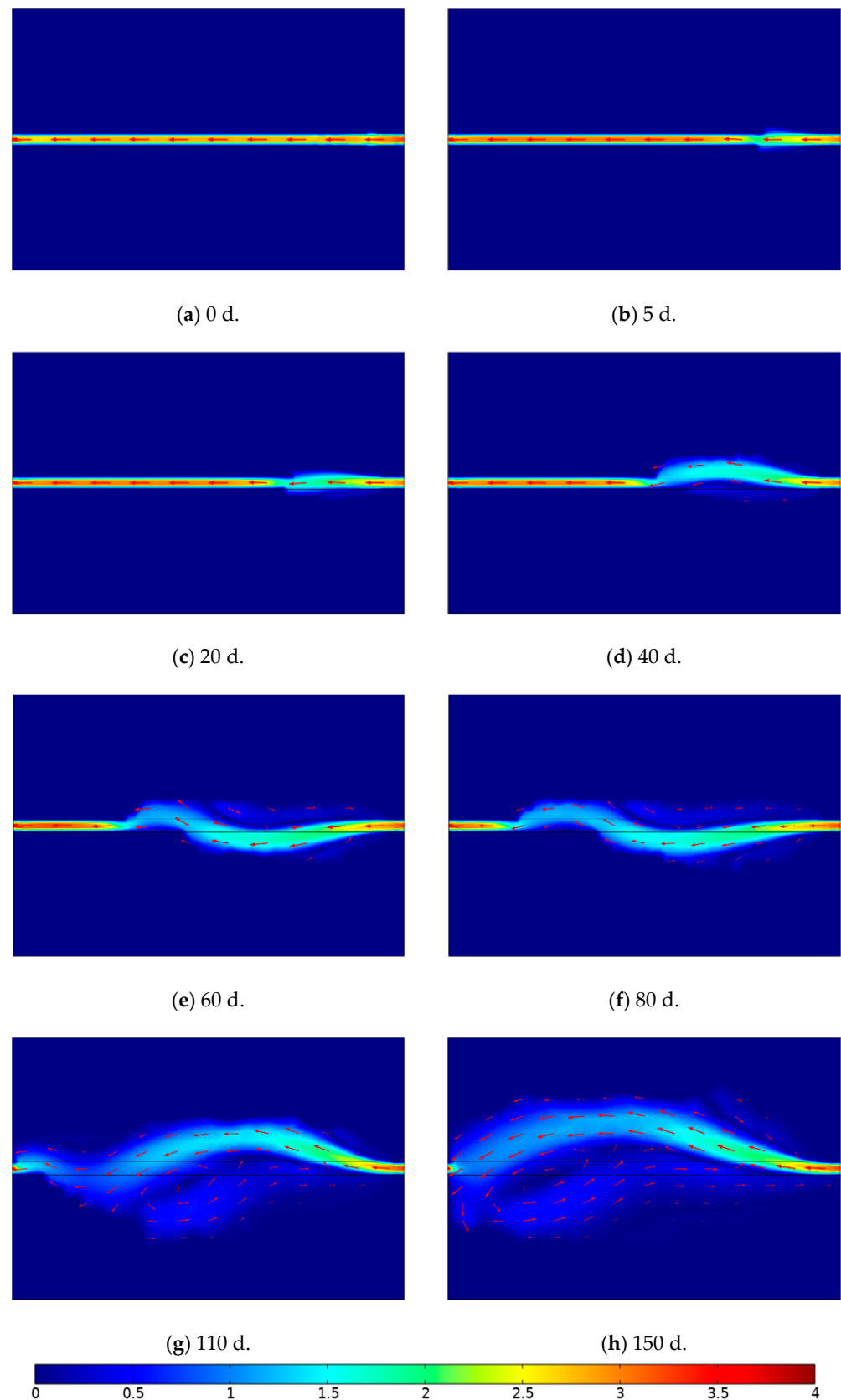


Figure 3. Velocity map of the gasification cavity flow field (m/s). In this figure, the arrows indicate the flow direction of the gasifying agent, and the two black horizontal lines in the middle represent the modeling construction lines of the gasification channel in the initial modeling process.

This model is specifically designed for thin coal seams. Based on the thermal transfer characteristics, the calculation dimensions are reasonably simplified. In the thickness direction (z direction) of the thin coal seam, heat transfer is uniform and there is no obvious temperature gradient, allowing the coal seam in this direction to be approximately completely vaporized. The top of the cavity is constrained by the roof cooling, while the bottom is less affected by the bottom insulation. Together, these two factors limit the evolution of the cavity in the z direction. Therefore, the model focuses on the growth trend of the cavity in the perspective view. This simplification not only conforms to the actual working conditions of coal seam vaporization but also reduces the computational complexity while ensuring the accuracy of the core evolution laws.

To clarify the influence of the gasification agent speed on the cavity size, this study selected 40 days as the characteristic time point and analyzed the differences in cavity size under different gasification agent speeds (as shown in Figure 4). The results indicated that there was a positive correlation between the two. This trend can be largely explained through the coupling mechanism of mass transfer and reaction kinetics. The gasification agent introduction speed directly determines the amount of gasification agent supplied to the reaction area within a unit time. When the speed increases, the concentration gradient of the gasification agent (such as O_2 or H_2O) in the cavity increases. According to Fick's law, the mass transfer rate increases, effectively alleviating the mass transfer resistance of the gasification reaction. At the same time, the higher introduction speed enhances the convective heat transfer effect, accelerates the discharge of reaction products (such as CO_2 or H_2), avoids the product inhibition effect, and continuously increases the gasification reaction rate. From the perspective of reaction kinetics, the increase in reactant concentration promotes the reaction rate according to the Arrhenius equation, and the consumption rate of the coal seam increases. Eventually, the cavity size expands with the increase in gasification agent speed. It should be noted that when the speed exceeds the critical value (in this study, it is close to 6 m/s), the expansion rate of the cavity may tend to level off. This is because the excessive speed causes the gasification agent not to fully participate in the reaction before being discharged, resulting in a decrease in the utilization rate of the gasification agent.

3.2. Fitting Analysis

In this section, we will describe the quantitative fitting of the UCG cavity, as shown in Figure 5. With an inlet gas velocity of 4 m/s and a duration of 40 days, the gasification cavity will form two gasification boundary growth curves, A and B. The gasification channel boundaries are denoted as L_1 and L_2 , respectively. A total of 15 data points are selected from the growth curves of the A and B gasification boundaries for plotting. For the A gasification boundary growth curve, the vector distance from the data points to L_1 is recorded as h_1 , and the path distance from the data points to the right boundary of the model is recorded as d_1 ; for the B gasification boundary growth curve, the vector distance from the data points to L_2 is recorded as h_2 , and the path distance from the data points to the right boundary of the model is recorded as d_2 . It is worth noting that the principle for selecting the vertical expansion coordinate interval (x -coordinate) of the 15 data points is as follows: the average value of the vertical expansion of the gasification cavity is taken.

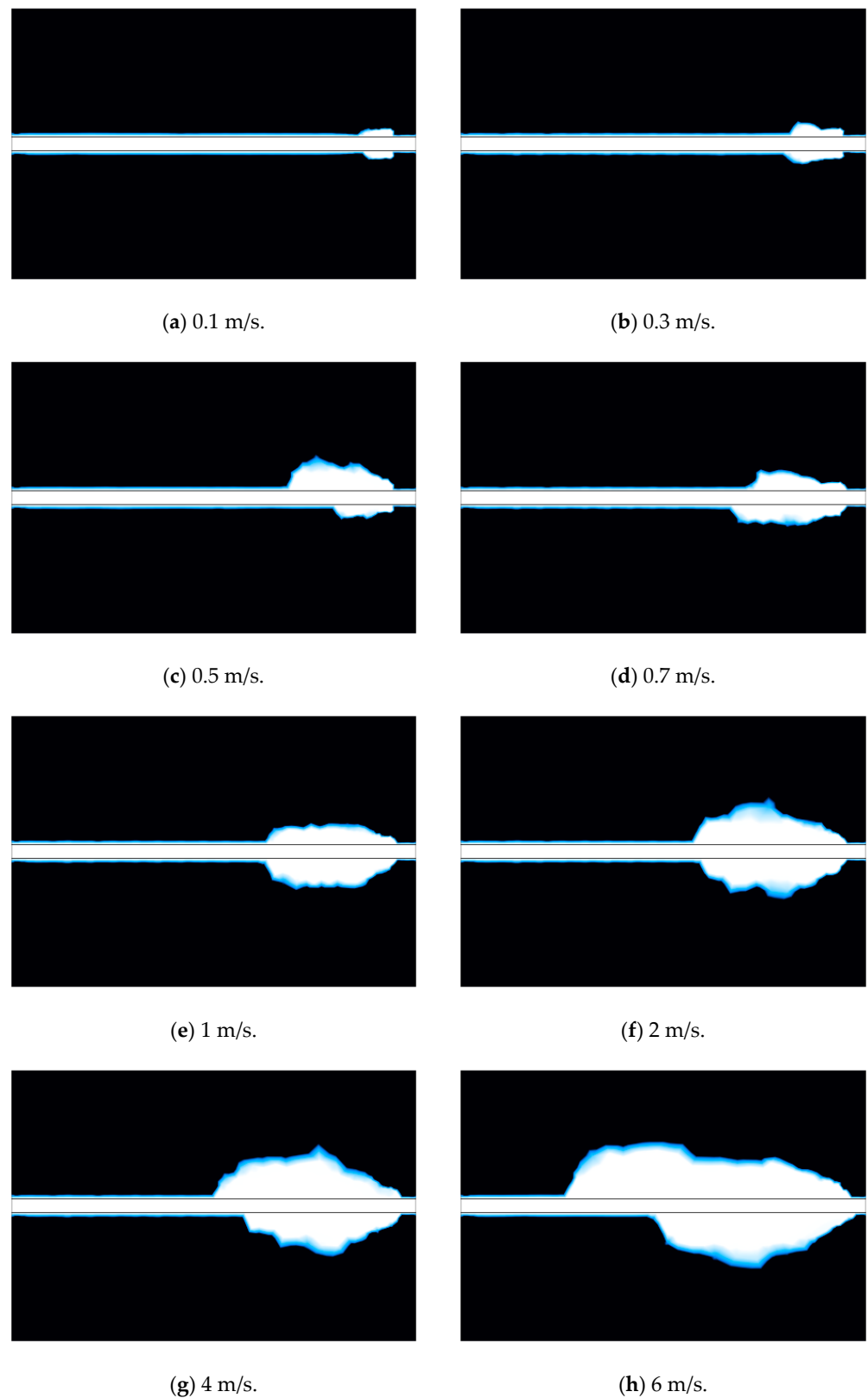


Figure 4. *Cont.*

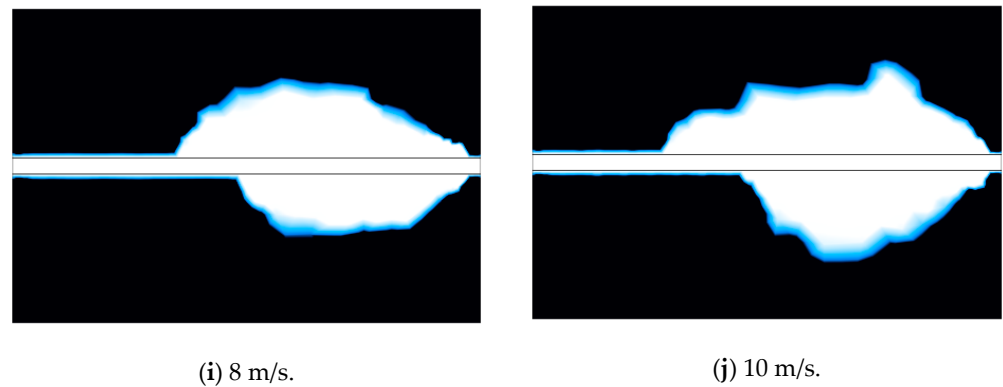


Figure 4. Shape of the gasification cavity boundary (at 40 d time point).

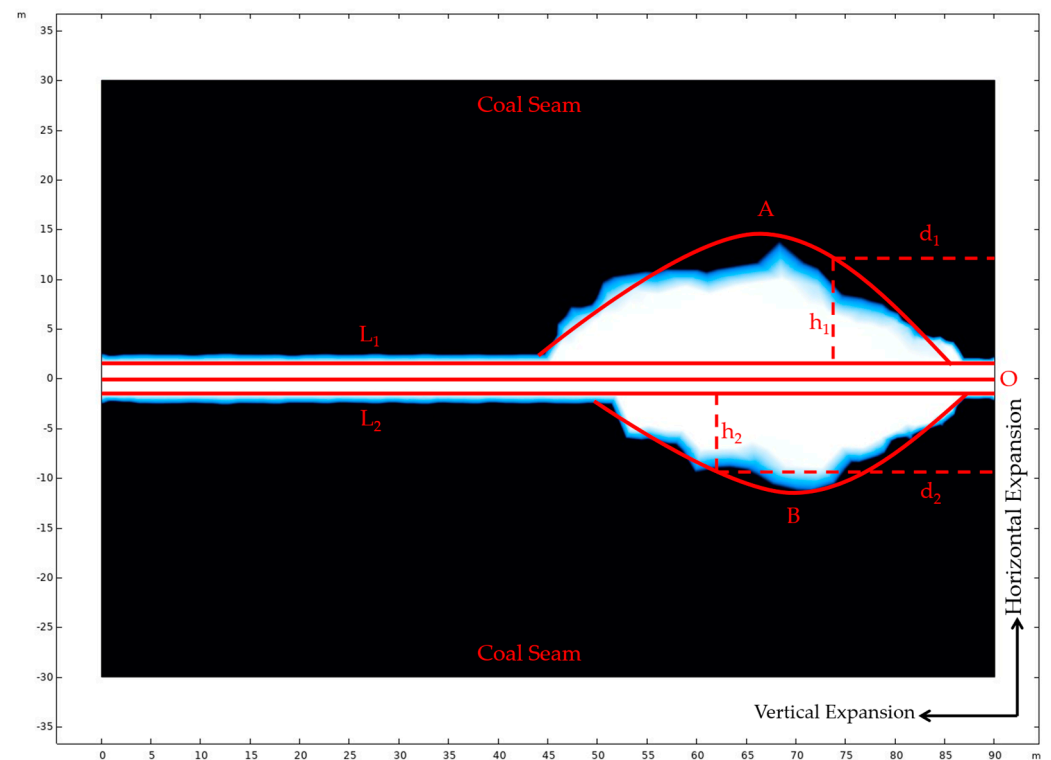


Figure 5. Symbolic schematic diagram of the gasification cavity.

For ease of understanding, in this study, the growth curves A and B of the vaporization boundary at different time points with an inlet gas velocity of 4 m/s will be plotted as line graphs. The origin of the coordinate system is point O, the x-axis coordinates are data points d_1 and d_2 , and the y-axis coordinates are data points h_1 and h_2 . Thus, we can determine the vaporization boundary growth curves A and B of the vaporization cavity under the condition of an inlet gas velocity of 4 m/s at different times, as shown in Figures 6 and 7, respectively. Then, cubic and quartic polynomial fitting (this study involves the use of cubic polynomials and quartic polynomials for fitting) is performed on the vaporization boundary curves A and B, as shown in Figures 8 and 9, respectively.

The fitting equations for the gasification boundary growth curves A with an inlet gas velocity of 4 m/s at 5 d, 20 d, 40 d, 60 d, 80 d, 110 d, and 150 d are given as Equations (31)–(37), respectively. The fitting equations for the gasification boundary growth curve B with an inlet gas velocity of 4 m/s at 5 d, 20 d, 40 d, 60 d, 80 d, 110 d, and 150 d are given as Equations (38)–(44), respectively.

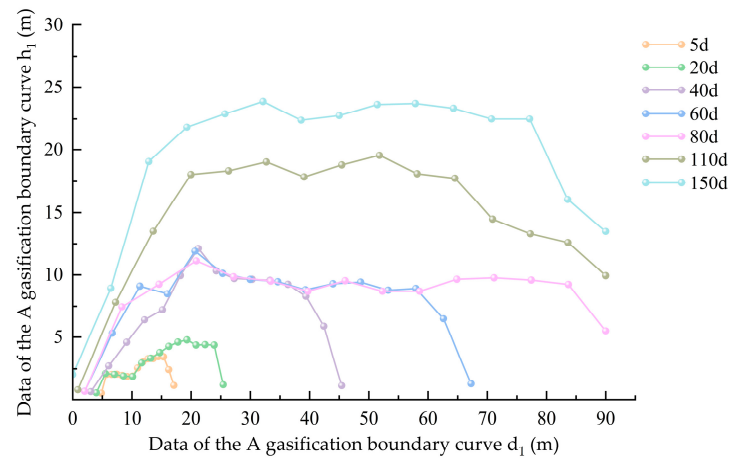


Figure 6. Growth curve of the vaporization boundary at an inlet gas velocity of 4 m/s (Graph A).

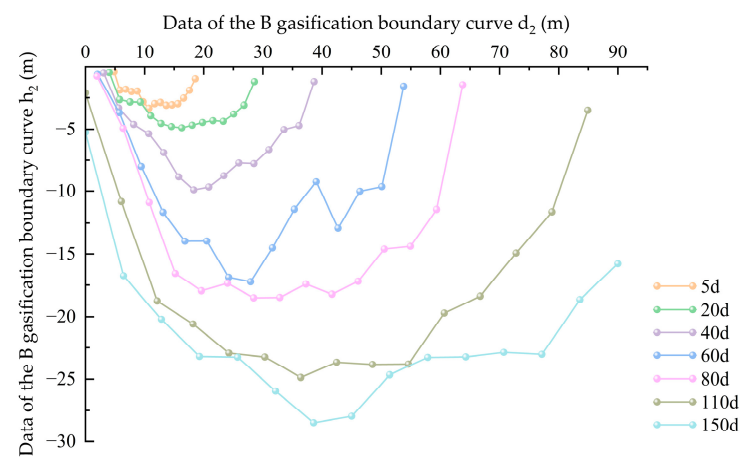


Figure 7. Growth curve of the vaporization boundary at an inlet gas velocity of 4 m/s (Graph B).

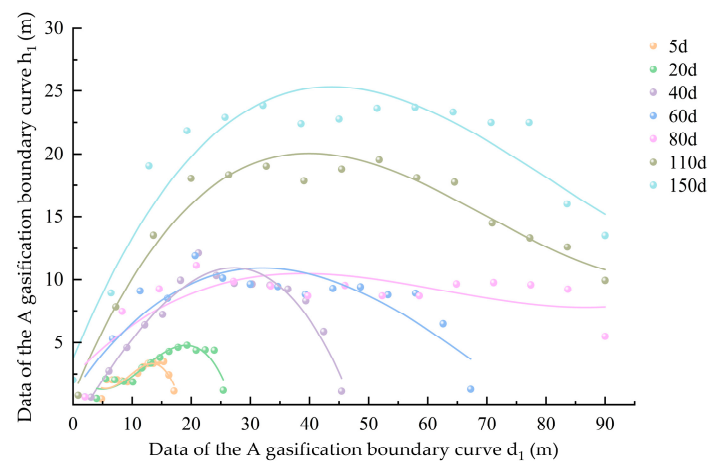


Figure 8. Fitting curve of the gasification boundary growth at an inlet gas velocity of 4 m/s (Graph A).

$$y = F(x) = -0.007x^3 + 0.224x^2 - 1.747x + 5.495 \quad (31)$$

$$y = F(x) = -0.002x^3 + 0.088x^2 - 0.697x + 2.870 \quad (32)$$

$$y = F(x) = -2.082 \times 10^{-4}x^3 - 0.005x^2 + 0.769x - 1.673 \quad (33)$$

$$y = F(x) = 5.645 \times 10^{-5}x^3 - 0.013x^2 + 0.675x + 1.013 \quad (34)$$

$$y = F(x) = 4.895 \times 10^{-5}x^3 - 0.009x^2 + 0.495x + 2.275 \quad (35)$$

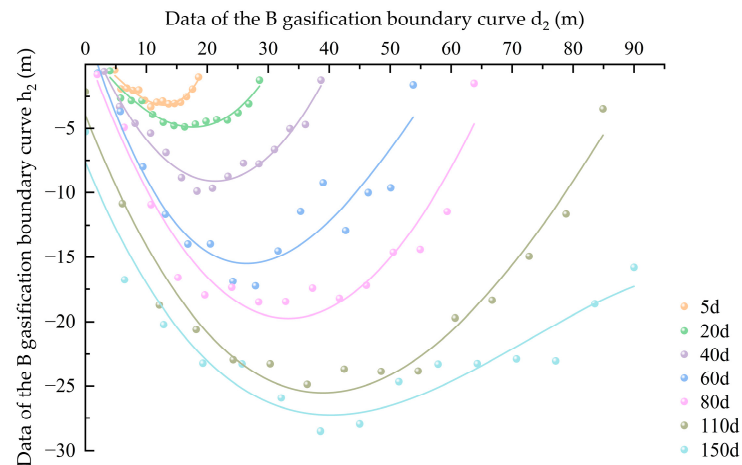


Figure 9. Fitting curve of the gasification boundary growth at an inlet gas velocity of 4 m/s (Graph B).

$$y = F(x) = 9.267 \times 10^{-5}x^3 - 0.019x^2 + 1.110x + 0.818 \quad (36)$$

$$y = F(x) = 7.295 \times 10^{-5}x^3 - 0.017x^2 + 1.127x + 3.717 \quad (37)$$

$$y = F(x) = 0.002x^3 - 0.030x^2 - 0.284x + 0.959 \quad (38)$$

$$y = F(x) = 2.581 \times 10^{-4}x^3 + 0.010x^2 - 0.618x + 1.276 \quad (39)$$

$$y = F(x) = -3.034 \times 10^{-5}x^3 + 0.027x^2 - 1.114x + 2.601 \quad (40)$$

$$y = F(x) = -2.063 \times 10^{-4}x^3 + 0.037x^2 - 1.538x + 2.938 \quad (41)$$

$$y = F(x) = -4.212 \times 10^{-5}x^3 + 0.021x^2 - 1.303x + 1.177 \quad (42)$$

$$y = F(x) = -5.551 \times 10^{-5}x^3 + 0.018x^2 - 1.190x - 3.977 \quad (43)$$

$$y = F(x) = -8.969 \times 10^{-4}x^3 + 0.019x^2 - 1.119x - 7.651 \quad (44)$$

Then, the gasification boundary growth curves A and B are fitted as functions of time t , denoted as $y_i = F_i(x, t)$, where i takes the value A or B (indicating curve A or curve B), and the range of t is from 0 d to 150 d, as shown in Equations (45) and (46). To ensure the selection of the required data in the fitting equations, it is determined that $y_A = F_A(x, t) \geq 0$ in curve A and $y_B = F_B(x, t) \leq 0$ in curve B.

$$\begin{aligned} F_A(x, t) = & (-2.204 \times 10^{-10}t^4 + 7.971 \times 10^{-8}t^3 - 1.005 \times 10^{-5}t^2 + 5.206 \times 10^{-4}t - 0.009)x^3 \\ & + (5.461 \times 10^{-9}t^4 - 2.051 \times 10^{-6}t^3 + 2.734 \times 10^{-4}t^2 - 0.015t + 0.296)x^2 \\ & + (-6.774 \times 10^{-8}t^4 + 2.419 \times 10^{-5}t^3 - 0.003t^2 + 0.163t - 2.608)x \\ & + (3.603 \times 10^{-7}t^4 - 1.196 \times 10^{-4}t^3 + 0.013t^2 - 0.592t + 8.663) \end{aligned} \quad (45)$$

$$\begin{aligned} F_B(x, t) = & (6.581 \times 10^{-11}t^4 - 2.562 \times 10^{-8}t^3 + 3.337 \times 10^{-6}t^2 - 1.701 \times 10^{-4}t + 0.003)x^3 \\ & + (-1.122 \times 10^{-9}t^4 + 4.832 \times 10^{-7}t^3 - 7.196 \times 10^{-5}t^2 + 0.004t - 0.049)x^2 \\ & + (-2.409 \times 10^{-8}t^4 + 5.783 \times 10^{-6}t^3 - 2.073 \times 10^{-4}t^2 - 0.024t - 0.136)x \\ & + (2.712 \times 10^{-7}t^4 - 7.324 \times 10^{-5}t^3 + 0.005t^2 - 0.059t + 1.116) \end{aligned} \quad (46)$$

In this study, 70 curves (with ten different inlet gas velocities and seven different time points) will be fitted using the aforementioned method. A total of ten empirical fitting equations for the A-type curves, denoted as $y_A = F_A(x, t)$, and ten corresponding empirical fitting equations for the B-type curves, denoted as $y_B = F_B(x, t)$, all with the 10 inlet velocities as independent variables. It is worth noting that when the inlet gas velocity of the gasifier is too high, the gasification process completely combusts the 60 m × 90 m coal seam within 150 days. Therefore, this study will no longer fit data exceeding the

model size. Thus, when the inlet gas velocity is too high, the range of the independent variable t in the fitting equation changes. The value of the independent variable t is selected according to the piecewise function Formula (47), where v is the gasifier inlet velocity and t is the time.

$$t = \begin{cases} 0 \text{ d} \leq t \leq 150 \text{ d}, & 0.1 \text{ m/s} \leq v \leq 4 \text{ m/s} \\ 0 \text{ d} \leq t \leq 80 \text{ d}, & 4 \text{ m/s} < v \leq 8 \text{ m/s} \\ 0 \text{ d} \leq t \leq 60 \text{ d}, & 8 \text{ m/s} < v \leq 10 \text{ m/s} \end{cases} \quad (47)$$

If we consider that curves A and B are approximately equal in the UCG process, meaning that we only want to obtain one boundary growth curve, and we believe that the other side is also this curve, then we need to process curve B. It is worth noting that the y-axis coordinate of the gasification boundary curve B is negative. Therefore, we need to take the absolute value of the fitting equation of curve B and then fit it with curve A. Finally, we obtain the uniquely fitted curve C, and the fitting equation of curve C is denoted as $y_c = F_c(x, t)$, as shown in Table 4.

Table 4. Results of the fitted equation $y_c = F_c(x, t)$.

The Rate of Gasification Agent Injection	$F_c(x, t)$
0.1 m/s	$\begin{aligned} & (-1.108 \times 10^{-9}t^4 + 3.372 \times 10^{-7}t^3 - 3.067 \times 10^{-5}t^2 + 0.728 \times 10^{-3}t + 0.013)x^3 \\ & + (3.226 \times 10^{-8}t^4 - 0.980 \times 10^{-5}t^3 + 0.880 \times 10^{-3}t^2 - 0.084t - 0.239)x^2 \\ & + (-2.928 \times 10^{-7}t^4 + 0.892 \times 10^{-4}t^3 - 0.008t^2 + 0.165t + 2.863)x \\ & + (0.789 \times 10^{-6}t^4 - 2.410 \times 10^{-4}t^3 + 0.021t^2 - 0.451t - 7.837) \end{aligned}$
0.3 m/s	$\begin{aligned} & (0.769 \times 10^{-9}t^4 - 2.964 \times 10^{-7}t^3 + 4.003 \times 10^{-5}t^2 - 0.002t + 0.034)x^3 \\ & + (-1.415 \times 10^{-8}t^4 + 0.615 \times 10^{-5}t^3 - 0.001t^2 + 0.056t - 1.004)x^2 \\ & + (4.826 \times 10^{-8}t^4 - 3.138 \times 10^{-5}t^3 + 0.006t^2 - 0.443t + 8.923)x \\ & + (1.608 \times 10^{-7}t^4 - 2.021 \times 10^{-5}t^3 - 0.004t^2 + 0.676t - 20.473) \end{aligned}$
0.5 m/s	$\begin{aligned} & (2.558 \times 10^{-10}t^4 - 0.897 \times 10^{-7}t^3 + 1.047 \times 10^{-5}t^2 - 0.436 \times 10^{-3}t + 0.003)x^3 \\ & + (-0.610 \times 10^{-8}t^4 + 2.355 \times 10^{-6}t^3 - 3.099 \times 10^{-4}t^2 + 0.015t - 0.185)x^2 \\ & + (3.288 \times 10^{-8}t^4 - 1.506 \times 10^{-5}t^3 + 0.001t^2 - 0.127t + 2.266)x \\ & + (-0.660 \times 10^{-7}t^4 + 3.280 \times 10^{-5}t^3 - 0.005t^2 + 0.317t - 6.064) \end{aligned}$
0.7 m/s	$\begin{aligned} & (0.638 \times 10^{-9}t^4 - 2.106 \times 10^{-7}t^3 + 2.267 \times 10^{-5}t^2 - 0.001t + 0.007)x^3 \\ & + (-2.162 \times 10^{-8}t^4 + 7.211 \times 10^{-6}t^3 - 0.001t^2 + 0.030t - 0.276)x^2 \\ & + (1.930 \times 10^{-7}t^4 - 6.636 \times 10^{-5}t^3 + 0.007t^2 - 0.296t + 3.078)x \\ & + (-0.543 \times 10^{-6}t^4 + 1.892 \times 10^{-5}t^3 - 0.021t^2 + 0.839t - 8.315) \end{aligned}$
1 m/s	$\begin{aligned} & (-0.601 \times 10^{-10}t^4 + 2.763 \times 10^{-8}t^3 - 4.544 \times 10^{-6}t^2 + 3.282 \times 10^{-4}t - 0.008)x^3 \\ & + (-0.887 \times 10^{-9}t^4 + 3.600 \times 10^{-8}t^3 + 4.495 \times 10^{-5}t^2 - 0.006t + 0.175)x^2 \\ & + (0.519 \times 10^{-7}t^4 - 1.338 \times 10^{-5}t^3 + 0.001t^2 + 0.020t - 0.916)x \\ & + (-2.680 \times 10^{-7}t^4 + 0.677 \times 10^{-4}t^3 - 0.004t^2 - 0.014t + 2.486) \end{aligned}$
2 m/s	$\begin{aligned} & (-1.744 \times 10^{-10}t^4 + 6.331 \times 10^{-8}t^3 - 8.050 \times 10^{-6}t^2 + 4.242 \times 10^{-4}t - 0.007)x^3 \\ & + (4.516 \times 10^{-9}t^4 - 1.614 \times 10^{-6}t^3 + 2.046 \times 10^{-4}t^2 - 0.010t + 0.217)x^2 \\ & + (-13.005 \times 10^{-9}t^4 + 5.896 \times 10^{-6}t^3 - 0.838 \times 10^{-3}t^2 + 0.085t - 1.538)x \\ & + (-0.601 \times 10^{-7}t^4 + 0.764 \times 10^{-5}t^3 + 0.002t^2 - 0.221t + 4.637) \end{aligned}$
4 m/s	$\begin{aligned} & (-1.431 \times 10^{-10}t^4 + 5.266 \times 10^{-8}t^3 - 6.693 \times 10^{-6}t^2 + 3.453 \times 10^{-4}t - 0.006)x^3 \\ & + (3.291 \times 10^{-9}t^4 - 1.267 \times 10^{-6}t^3 + 1.726 \times 10^{-4}t^2 - 0.010t + 0.172)x^2 \\ & + (-2.182 \times 10^{-8}t^4 + 0.920 \times 10^{-5}t^3 - 1.396 \times 10^{-3}t^2 + 0.093t - 1.236)x \\ & + (0.445 \times 10^{-7}t^4 - 2.318 \times 10^{-5}t^3 + 0.004t^2 - 0.266t + 3.773) \end{aligned}$
6 m/s	$\begin{aligned} & (-0.750 \times 10^{-9}t^4 + 1.555 \times 10^{-7}t^3 - 1.160 \times 10^{-5}t^2 + 3.752 \times 10^{-4}t - 0.004)x^3 \\ & + (2.951 \times 10^{-8}t^4 - 0.571 \times 10^{-5}t^3 + 3.910 \times 10^{-4}t^2 - 0.011t + 0.127)x^2 \\ & + (-4.205 \times 10^{-7}t^4 + 0.737 \times 10^{-4}t^3 - 0.004t^2 + 0.113t - 0.756)x \\ & + (2.534 \times 10^{-6}t^4 - 4.326 \times 10^{-4}t^3 + 0.024t^2 - 0.522t + 3.020) \end{aligned}$
8 m/s	$\begin{aligned} & (-0.720 \times 10^{-9}t^4 + 1.429 \times 10^{-7}t^3 - 0.999 \times 10^{-5}t^2 + 2.941 \times 10^{-4}t - 0.003)x^3 \\ & + (-0.838 \times 10^{-5}t^4 + 0.001t^3 - 0.070t^2 + 1.116t - 3.926)x^2 \\ & + (-0.523 \times 10^{-6}t^4 + 0.938 \times 10^{-4}t^3 - 0.005t^2 + 0.159t - 0.937)x \\ & + (2.835 \times 10^{-6}t^4 - 4.497 \times 10^{-4}t^3 + 0.029t^2 - 0.685t + 3.896) \end{aligned}$
10 m/s	$\begin{aligned} & (-0.653 \times 10^{-9}t^4 + 1.605 \times 10^{-7}t^3 - 1.288 \times 10^{-5}t^2 + 4.072 \times 10^{-4}t - 0.004)x^3 \\ & + (1.277 \times 10^{-8}t^4 - 4.699 \times 10^{-6}t^3 + 4.543 \times 10^{-4}t^2 - 0.015t + 0.149)x^2 \\ & + (1.874 \times 10^{-7}t^4 - 0.542 \times 10^{-5}t^3 - 0.002t^2 + 0.145t - 1.098)x \\ & + (-2.044 \times 10^{-7}t^4 - 0.503 \times 10^{-4}t^3 + 0.014t^2 - 0.619t + 4.497) \end{aligned}$

Finally, in order to dynamically monitor the growth of the boundary of the UCG cavity, an additional variable, v , is introduced. Variable v represents different gas injection velocities. The introduced variable v is fitted to the x^3 , x^2 , x , and constant terms of $F_C(x, t)$ and is denoted as $a(v, t)$, $b(v, t)$, $c(v, t)$, and $d(v, t)$, respectively, as shown in Table 5. Thus, the function expression $F(x, t, v)$ of the growth boundary of the UCG cavity with respect to the gas injection velocity v and the gasification time t is obtained, as shown in Equation (48).

$$F(x, t, v) = a(v, t)x^3 + b(v, t)x^2 + c(v, t)x + d(v, t) \quad (48)$$

Table 5. Coefficient fitting equation of $F(x, t, v)$.

Coefficient Equation	Equation
$a(v, t)$	$\begin{aligned} & [(-2.4 \times 10^{-12}v^4 + 5.5 \times 10^{-11}v^3 - 4.0 \times 10^{-10}v^2 + 8.5 \times 10^{-10}v - 2.6 \times 10^{-10})t^4 \\ & + (7.6 \times 10^{-10}v^4 - 1.6 \times 10^{-8}v^3 + 1.1 \times 10^{-7}v^2 - 2.1 \times 10^{-7}v + 4.4 \times 10^{-8})t^3 \\ & + (-6.3 \times 10^{-8}v^4 + 1.3 \times 10^{-6}v^3 - 7.6 \times 10^{-6}v^2 + 1.1 \times 10^{-5}v + 2.9 \times 10^{-6})t^2 \\ & + (9.4 \times 10^{-7}v^4 - 1.3 \times 10^{-5}v^3 + 1.3 \times 10^{-5}v^2 + 3.8 \times 10^{-4}v - 6.4 \times 10^{-4})t \\ & + (6.0 \times 10^{-5}v^4 - 1.4 \times 10^{-3}v^3 + 1.1 \times 10^{-2}v^2 - 3.6 \times 10^{-2}v + 2.5 \times 10^{-2})] \end{aligned}$
$b(v, t)$	$\begin{aligned} & [(2.9 \times 10^{-8}v^4 - 5.0 \times 10^{-8}v^3 + 2.5 \times 10^{-6}v^2 - 3.8 \times 10^{-6}v + 1.1 \times 10^{-6})t^4 \\ & + (-3.4 \times 10^{-6}v^4 + 6.1 \times 10^{-5}v^3 - 3.1 \times 10^{-4}v^2 + 4.6 \times 10^{-4}v - 1.3 \times 10^{-4})t^3 \\ & + (2.4 \times 10^{-4}v^4 - 4.3 \times 10^{-3}v^3 + 2.2 \times 10^{-2}v^2 - 3.2 \times 10^{-2}v + 9.0 \times 10^{-3})t^2 \\ & + (-4.0 \times 10^{-3}v^4 + 7.1 \times 10^{-2}v^3 - 3.6 \times 10^{-1}v^2 + 5.6 \times 10^{-1}v - 1.6 \times 10^{-1})t \\ & + (1.2 \times 10^{-2}v^4 - 2.1 \times 10^{-1}v^3 + 9.5 \times 10^{-1}v^2 - 9.6 \times 10^{-1}v - 1.6 \times 10^{-1})] \end{aligned}$
$c(v, t)$	$\begin{aligned} & [(1.9 \times 10^{-10}v^4 + 4.7 \times 10^{-9}v^3 - 9.4 \times 10^{-8}v^2 + 3.0 \times 10^{-7}v - 1.4 \times 10^{-7})t^4 \\ & + (1.1 \times 10^{-7}v^4 - 3.8 \times 10^{-6}v^3 + 3.5 \times 10^{-5}v^2 - 9.0 \times 10^{-5}v + 3.3 \times 10^{-5})t^3 \\ & + (-1.9 \times 10^{-5}v^4 + 4.4 \times 10^{-4}v^3 - 3.3 \times 10^{-3}v^2 + 7.1 \times 10^{-3}v - 1.7 \times 10^{-3})t^2 \\ & + (2.8 \times 10^{-4}v^4 - 5.2 \times 10^{-3}v^3 + 2.3 \times 10^{-2}v^2 + 3.8 \times 10^{-2}v - 1.5 \times 10^{-1})t \\ & + (1.2 \times 10^{-2}v^4 - 2.9 \times 10^{-2}v^3 + 2.4v^2 - 7.8v + 6.5)] \end{aligned}$
$d(v, t)$	$\begin{aligned} & [(-1.7 \times 10^{-9}v^4 - 7.9 \times 10^{-9}v^3 + 3.6 \times 10^{-7}v^2 - 1.3 \times 10^{-6}v + 5.9 \times 10^{-7})t^4 \\ & + (-3.7 \times 10^{-7}v^4 + 1.4 \times 10^{-5}v^3 - 1.4 \times 10^{-4}v^2 + 3.8 \times 10^{-4}v - 1.6 \times 10^{-4})t^3 \\ & + (4.9 \times 10^{-5}v^4 - 1.3 \times 10^{-3}v^3 + 1.1 \times 10^{-2}v^2 - 2.7 \times 10^{-2}v + 9.2 \times 10^{-3})t^2 \\ & + (-1.2 \times 10^{-3}v^4 + 2.6 \times 10^{-2}v^3 - 1.7 \times 10^{-1}v^2 + 2.2 \times 10^{-1}v + 1.7 \times 10^{-1})t \\ & + (-2.9 \times 10^{-2}v^4 + 7.2 \times 10^{-1}v^3 - 6.0v^2 + 19.8v - 16.3)] \end{aligned}$

The ranges of the gas velocity v and the gasification time t are based on the piecewise function Formula (47). The fitting function $F(x, t, v)$ can predict the growth boundary of the gasification cavity in the UCG process. By adjusting the gas introduction speed and gasification time, the size of the gasification cavity can be controlled to ensure the smooth progress of the UCG process.

4. Conclusions

This study constructed a multi-physics field-coupling simulation model integrating heat transfer, laminar flow, material transfer, and chemical reactions using COMSOL 6.2 software. It accurately revealed the dynamic evolution law of the gasification chamber boundary during the UCG process with respect to the injection speed (v) and gasification time (t) of the gasification agent. Through analysis, it was revealed that after the gasification agent breaks free from the pipeline constraint, it forms a free jet. In the area far from the inlet, due to the shear of the jet and the development of the wake vortex, oscillations and swirls are triggered, resulting in an uneven spatial distribution of the gas–solid reaction, ultimately causing the asymmetric expansion of the gasification chamber.

The core innovation of this study lies in the establishment of a multi-parameter coupled prediction model for the growth boundary of the vaporization chamber: using 7 time points (5 d, 20 d, 40 d, 60 d, 80 d, 110 d, 150 d) and 10 injection velocities of the vaporization agent (0.1 m/s–10 m/s) as orthogonal independent variables, through cubic/quartic polynomial

fitting of 70 sets of boundary data of ellipsoidal chambers, a dynamic fitting function $F(x, t, v) = a(v, t)x^3 + b(v, t)x^2 + c(v, t)x + d(v, t)$ was constructed. This function can quantitatively describe the nonlinear relationship between variables, and it can directly predict the morphology of the chamber under different working conditions.

The simulation and fitting results indicate that the gasification chamber continuously expands with the increase in reaction time and gradually approaches an ellipsoidal shape. After 40 days, due to the accumulation of heat, a positive feedback loop of “thermal accumulation–reaction acceleration–chamber expansion” is formed, entering a rapid expansion stage. The injection speed of the gasification agent is positively correlated with the chamber size. When the speed exceeds the critical value (approximately 6 m/s), the utilization rate decreases due to incomplete reaction of the gasification agent, and the expansion rate of the chamber slows down. In addition, the model can be adapted to different geological conditions by reconstructing coal seam parameters (porosity, permeability, etc.) and physical field parameters (formation temperature and pressure, etc.), forming an engineering application closed loop of “parameter adjustment–simulation iteration–equation update”.

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