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Article

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Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11170958/v1>

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Additional Declarations: No competing interests reported.

Experimental investigation and engineering numerical modeling of forced oxidation ignition for deep drilling-based underground coal gasification

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Abstract: Deep drilling-based underground coal gasification (UCG) offers a low-carbon route to recover deep bituminous coal, yet conventional ignition suffers from low success rates and prolonged restart after flameout. Here, we present lab-scale forced oxidation ignition experiments on Fengyu bituminous coal and a dedicated coupled heat-mass transfer model for field engineering design. Single-factor tests across inlet O₂ temperature (150-180°C), flow rate (2.5-3.5 m³/h), and coal moisture (5.5-50%) establish 160-170°C as the critical ignition threshold, with an optimal window of 170-180 °C, 2.5 m³/h, and moisture <20%. A multivariate regression model (R²=0.967) quantifies parameter effects: inlet temperature dominates (standardized coefficient 0.62), followed by moisture (0.28) and flow rate (0.10). The validated 2D numerical model, incorporating oxygen transport and moisture evaporation, predicts ignition delay within <10% error. This work provides the first systematic ignition parameter dataset for Fengyu bituminous coal and a lightweight simulation template directly transferable to deep UCG borehole design and real-time operational control.

Keywords: Underground coal gasification; Forced oxidation ignition; Bituminous coal; Deep drilling UCG; Numerical modeling

1. Introduction

Underground coal gasification (UCG) is an environmentally benign energy conversion technology, particularly for exploiting deep seams and abandoned mines that are inaccessible to conventional mining (Zhao et al., 2026; Roddy and Younger, 2010). Within a UCG cavity, coal undergoes sequential physicochemical transformations

33 including drying, pyrolysis, combustion, and gasification. Precise control of these
34 processes is essential for producing high-calorific syngas (Perkins, 2018; Wang et al.,
35 2020). The thermal energy required for gas production is derived mainly from coal
36 combustion and pyrolysis, both of which depend critically on the effectiveness of the
37 initial ignition stage. Reliable seam ignition is therefore a prerequisite for initiating the
38 gasification sequence and sustaining stable in-situ combustion (Zhang et al., 2024;
39 Blinderman and Klimenko, 2018).

40 Current UCG operations are broadly categorized into mine-based and drilling-based
41 configurations, which require distinct ignition strategies (Liu et al., 2026). While
42 extensive research has addressed the spontaneous combustion characteristics,
43 thermophysical changes, and reaction kinetics of low-rank coals under ambient
44 conditions (Xin et al., 2026; Chen et al., 2025), numerical investigations specifically
45 concerned with forced oxidation ignition by high-temperature oxygen injection remain
46 notably scarce (Zhang et al., 2025; Lu et al. 2025). Unlike passive ignition modes,
47 forced oxidation ignition is governed by forced convective heat transfer between a
48 continuous high-temperature oxygen stream and the porous coal matrix (Zhang et al.,
49 2024). The dynamic coupling of heat and mass transfer between the hot oxygen flow
50 and coal particles is the main factor controlling seam temperature rise and ignition
51 success (Saik and Berdnyk, 2022; Chao et al., 2026). However, existing ignition
52 models often neglect the forced convection mechanisms that prevail in high-
53 temperature pure-oxygen environments, oversimplify the spatial and temporal
54 temperature evolution within the seam during continuous hot gas injection, and fail to
55 adequately capture the coupling among gas flow dynamics, coal thermophysical
56 properties, and temperature rise profiles (Ponzio et al., 2008; Guo et al., 2019). As a
57 result, dedicated coupled heat and mass transfer models for forced oxidation ignition
58 remain lacking, which hinders the theoretical optimization and industrial adoption of
59 this technology (Zhang et al., 2025). Moreover, although the influence of coal rank and
60 oxygen purity on ignition propensity has been investigated, previous studies have
61 focused predominantly on low-rank coals such as lignite and long-flame coal (Fujitsuka
62 et al., 2014; Sadasivam, 2020). Systematic parametric studies on bituminous coal—
63 which accounts for more than 60% of global coal reserves and is a primary feedstock
64 for UCG—are notably limited, particularly for specific coal varieties from distinct
65 geological sources (Dong et al., 2025). The existing UCG literature tends to emphasize
66 stable gasification regimes and often treats the ignition transient only as a minor issue
67 (Qiao et al., 2010). Previous work by the authors elucidated the fundamental
68 mechanism of forced oxidation ignition, showing that low-temperature oxidation of

ether-containing volatiles initiates radical chain reactions that lead to homogeneous and subsequently heterogeneous combustion (Li et al., 2023). Despite these insights, critical gaps remain: (1) systematic ignition parameters for engineering-relevant bituminous coals have not been published; (2) the established mechanistic understanding requires rigorous validation across a broader range of practical coal types; and (3) high-fidelity mathematical models that capture forced convective heat transfer between hot oxygen jets and coal seams are virtually absent. To address these gaps, systematic forced oxidation ignition experiments were conducted using Fengyu bituminous coal. The resulting data enabled a quantitative assessment of the effects of inlet gas temperature, oxygen flow rate, and moisture content on ignition delay. In parallel, a coupled heat and mass transfer model was developed and rigorously validated. These findings are expected to provide directly applicable ignition parameters and robust theoretical support for the rapid startup of deep drilling-based UCG project.

2. Materials and Methods

A self-made tubular furnace reactor was used to simulate the ignition process of underground coal seams via hot gas heating. The furnace is equipped with six cylindrical thermocouples (diameter 18 mm, length 50 mm). The furnace can remain vertical during coal packing and horizontal during testing to avoid large gaps near the wall. The main thermal parameters measured during the experiment include coal seam temperature, system pressure, and gas flow rate. As shown in Fig. 1, coal seam temperatures were measured by six thermocouples arranged above the furnace body and transmitted to a central control computer. The tubular furnace has a maximum heating power of 15 kW and a temperature control accuracy of ± 5 °C. The six K-type thermocouples have a measurement range of 0-1000 °C and a response time of less than 1 s. All experiments were independently repeated three times under identical conditions. The standard deviations of ignition delay time measurements were less than 5%, indicating excellent reproducibility. The tubular furnace platform scales industrial deep UCG borehole coal packing and oxygen injection layout, and test parameter ranges fully cover the operating window of actual field injection pipelines, so the measured data can be directly transferred to industrial design calculation. Average values are reported with error bars representing ± 1 °C standard deviation in all figures. The structure and parameters are presented in Fig. 1 and Table 1, respectively.

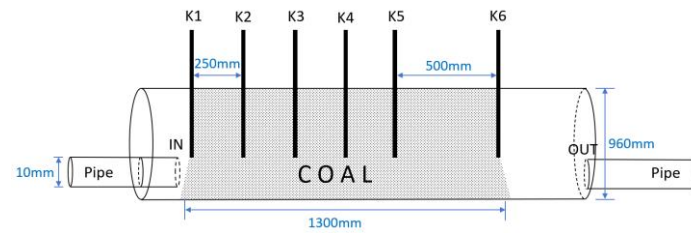


Fig. 1 Furnace Diagram

Table 1 Furnace Specifications

Parameter	Value(mm)
Horizontal well diameter	96
Horizontal well length	1900
Coal seam length	1300
Gas nozzle	$\Phi 15 \times 2.5$
The distance between the gas nozzle and the center of the well	20

2.1 Model Design

The pipeline was arranged directly below the coal seam model. Previous studies show that the gasification cavity mainly expands upward and is basically consistent with the oxidant injection direction. Therefore, this layout can accurately simulate the heat and mass transfer process in actual UCG.

Hot pure oxygen was used as both heating medium and oxidant. The gas was injected vertically through the inlet pipe, with a distance of 20 mm between the nozzle and coal seam. The model size was proportional to actual UCG equipment.

The Fengyu bituminous coal samples were collected from the Fengyu underground coal gasification field test site. The sampling work was approved and authorized by the mine management and the project management team. All sampling activities complied with the on-site safety regulations and relevant mining management requirements. No additional commercial transfer of coal samples was performed.

2.2 Coal

Fengyu bituminous coal was selected as the experimental sample. Coal samples were crushed and sieved to a particle size range of 2-3 cm, which is the standard particle size for UCG laboratory simulation studies. This size range balances the representation of in-situ coal seam structure and experimental operability. The coal loading mass was 5.0 kg and the packing length was 1.2 m. The initial temperature was set as 25 °C. Proximate and ultimate analyses of the coal sample are listed in

Table 2.

Table 2 Proximate analysis and ultimate analysis of the coal sample

Coal sample	Industrial analysis/%				Elemental analysis /%					Q _{gr.ad} MJ/kg
	M _{ad}	A _{ad}	V _{ad}	FC _{ad}	C _{daf}	H _{daf}	O _{daf}	N _{daf}	S _{daf}	
F-Coal	0.72	14.21	27.64	57.43	85.34	4.83	7.95	1.43	0.45	29.28

2.3 Experimental Conditions

The single-factor variable method was adopted to investigate three key parameters: (1) Inlet gas temperature: 150-160 °C, 160-170 °C, 170-180 °C; (2) Oxygen flow rate: 2.5 m³/h, 3.0 m³/h, 3.5 m³/h; (3) Coal moisture content: 5.5%, 20%, 50%. Ignition was determined by a sharp temperature rise and rapid generation of CO₂. After ignition, gas supply was stopped immediately. Each parameter was varied at three levels while keeping the other two constant to ensure the accuracy and comparability of experimental results.

2.4 Mathematical Model and Numerical Method

A coupled heat and mass transfer model was established based on conservation laws, targeting the forced convection heat transfer between high-temperature oxygen flow and coal seams during forced oxidation ignition (Zhang et al., 2023). Coordinate system definition: Let x denote the axial direction along the gas flow (from inlet to outlet, length 1.2 m), y the vertical direction (from nozzle toward coal seam, height 0.096 m), and z the transverse direction along the horizontal well. Given that the reactor length in z is much larger than the cross-section and both ends are closed, the temperature and concentration fields are uniform in z . Thus, the 3D problem reduces to a 2D (x - y) domain, which drastically reduces computational cost while retaining physical fidelity.

Assumptions

- (1) Coal packing is uniform and isotropic.
- (2) Oxygen concentration remains nearly constant before ignition ($O_2 > 95\%$ at outlet), validated by experimental measurements.
- (3) Temperature-dependent thermophysical properties and natural convection are neglected.
- (4) Moisture exists as free water within the coal matrix and evaporates at 100 °C.

2.4.1 Coal Thermal Equilibrium Equation

$$\partial T_c / \partial t = \frac{\lambda_c}{\rho_c \cdot C_c + M \cdot \rho_w \cdot C_w} \cdot (T_m - T_c) - \frac{M \cdot L_v}{\rho_c \cdot C_c + M \cdot \rho_w \cdot C_w} \cdot H(T_c - 100)$$

M is the moisture content (mass fraction), $L_v = 2257$ kJ/kg is the latent heat of vaporization, and H is the Heaviside step function.

2.4.2 Gas Heat Transfer Equation

$$\begin{aligned} \partial T_m / \partial t + u \cdot \partial T_m / \partial x + v \cdot \partial T_m / \partial y \\ = \frac{\lambda_m}{\rho_m \cdot C_m} \cdot (\partial^2 T_m / \partial x^2 + \partial^2 T_m / \partial y^2) + \frac{F_c}{\rho_m \cdot C_m} \end{aligned}$$

characterizing the forced convection heat transfer of high-temperature oxygen flow in the coal seam gap.

2.4.3 Oxygen Transport Equation

$$\begin{aligned} \partial(\rho_m \cdot Y_{O_2}) / \partial t + u \cdot \partial(\rho_m \cdot Y_{O_2}) / \partial x + v \cdot \partial(\rho_m \cdot Y_{O_2}) / \partial y \\ = \partial / \partial x (\rho_m \cdot D_{O_2} \cdot \partial Y_{O_2} / \partial x) + \partial / \partial y (\rho_m \cdot D_{O_2} \cdot \partial Y_{O_2} / \partial y) - R_{O_2} \end{aligned}$$

where Y_{O_2} is the oxygen mass fraction, D_{O_2} is the oxygen diffusion coefficient in the gas mixture, and R_{O_2} is the oxygen consumption rate due to coal oxidation.

2.4.4 Initial and Boundary Conditions

Initial conditions: $t = 0$, $T_c = T_m = 25$ °C throughout the domain. At the inlet ($x = 0$, $y = 0$), $T_m = T_{in}$, $Y_{O_2} = 0.99$. At the outlet and walls, zero-flux Neumann conditions are applied for T_m and Y_{O_2} .

2.4.5 Numerical Ignition Criterion

In the simulation, ignition time t_{ign} is defined as

$$t_{ign} = \min \{ t \mid \max(x, y)_{(\partial T_c / \partial t)} > \theta \}$$

with $\theta = 1.0$ °C /min, corresponding to the onset of self-sustained exothermic acceleration observed in experiments.

2.4.6 Numerical Implementation

Equations were discretized using the Finite Volume Method (FVM) on a structured grid of 100×50 nodes in x and y directions. A second-order central difference scheme was used for diffusion terms, and a first-order upwind scheme for convection terms. Time integration used an implicit Euler method with a fixed time step of 10 s. Grid

independence was verified by comparing results with a finer grid (200×100), showing <2% deviation in predicted ignition time. Simulations were executed in MATLAB (R2023a).

2.5 Nomenclature

- D_1 : Coordinate region of the reactor's air inlet area in the inertial frame, m³
 D_2 : Coordinate region of the reactor's air outlet area in the inertial frame, m³
 ρ_a : Density of oxygen under standard atmospheric pressure, kg/m³
 S_c : Surface area of coal's infinitesimal particles, m²
 ρ_c : Density of coal, kg/m³
 C_c : Specific heat capacity of coal, J/(kg·°C)
 T_c : Temperature of coal, °C
 ρ_m : Density of the mixed gas under standard atmospheric pressure, kg/m³
 C_m : Specific heat capacity of mixed gas, J/(kg·°C)
 T_m : Temperature of mixed gas, °C
 λ_m : Heat transfer coefficient of mixed gas, W/(m·°C)
 (u, v, w) : Wind velocity components of air flow at any time and position, m/s
 K_c : Heat release power per unit mass of coal during slow oxidation, J/g
 G_c : Heat absorption power per unit mass of coal during slow oxidation, J/g
 $F_c = K_c - G_c$: Net heat release power per unit mass of coal, J/g
 ρ_v : Density of water, kg/m³
 C_v : Specific heat capacity of water, J/(kg·°C)
 λ_c : Heat transfer coefficient of coal in packed state, W/(m·°C)
 λ_c' : Heat transfer coefficient of coal, W/(m·°C)
 ε : Porosity of packed coal
 M : Moisture content (mass fraction)
 L_v : Latent heat of vaporization, kJ/kg
 Y_{O_2} : Oxygen mass fraction
 D_{O_2} : Oxygen diffusion coefficient, m²/s
 R_{O_2} : Oxygen consumption rate, kg/(m³·s)

3. Results and Discussion

3.1 Effect of Inlet Gas Temperature on Ignition Behavior

The inlet gas temperature exerts a dominant influence on the ignition delay by dictating the initial heat flux and the intensity of low-temperature oxidation (Peng and Xu, 2025). As depicted in Fig. 2, when the inlet temperature was restricted to 150-160 °C, no

discernible temperature inflection point was registered even after 12 hours of continuous oxygen injection. The thermocouple nearest the inlet (K1) recorded a temperature plateau below 150 °C. This observation suggests that the exothermic heat released via low-temperature oxidation was insufficient to offset systemic heat dissipation, precluding the attainment of a self-sustaining combustion regime. Consequently, an inlet temperature of 150-160 °C is deemed inadequate for providing the critical heat flux required for the ignition of Fengyu bituminous coal under pure oxygen atmospheres.

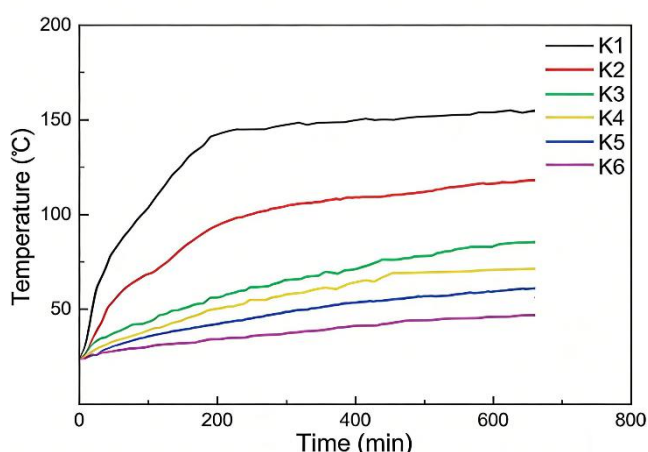


Fig. 2 Temperature profiles recorded by thermocouples K1-K6 at 150-160 °C

Elevation of the inlet temperature to the 160-170 °C range facilitated a steady rise in coal temperature, culminating in a sharp thermal spike at 184 min, indicative of successful ignition. At this juncture, the K1 reading attained 148.64 °C, signifying that the rate of oxidative heat release had surpassed heat losses, thereby establishing a positive feedback loop (Fig. 3). A further increment to 170-180 °C markedly accelerated the heating trajectory, achieving ignition in a reduced timeframe of 153 min (Fig. 4). Elevated inlet temperatures are hypothesized to expedite the desorption and oxidative degradation of ether-containing volatiles, thereby accelerating radical chain propagation and curtailing the induction period necessary for combustible gas accumulation (Fan et al., 2024).

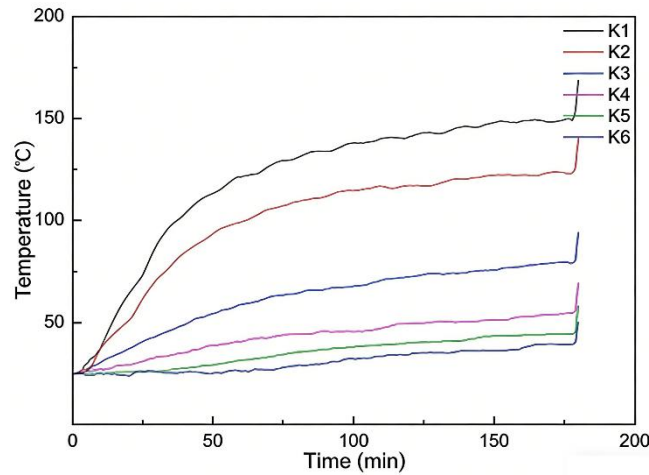


Fig. 3 Temperature profiles recorded by thermocouples K1-K6 at 160-170 °C

The spatial temperature distribution revealed a distinct gradient: the heating rate decreased progressively from K1 (proximal to inlet) to K2, K3, and diminished significantly towards K4-K6. This thermal profiling confirms that ignition nucleates proximally to the gas inlet and propagates axially along the coal seam, commensurate with the direction of bulk gas flow. For industrial deep UCG well design, the identified critical threshold of 160-170 °C provides a definitive benchmark for the sizing of surface oxygen heaters and borehole thermal insulation. Operating within the 170-180 °C window is recommended to harmonize equipment capital expenditure with ignition reliability, averting the over-engineering of high-temperature containment systems.

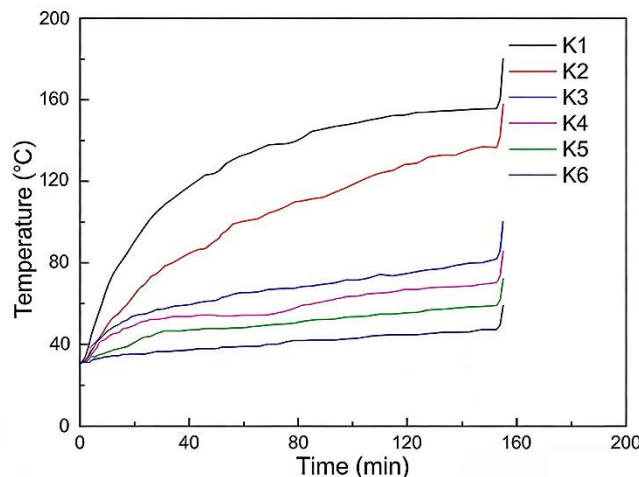


Fig. 4 Temperature profiles recorded by thermocouples K1-K6 at 170-180 °C

3.2 Effect of Oxygen Flow Rate on Ignition Performance

Oxygen flow rate modulates ignition dynamics through the competing mechanisms of convective heat advection and gas residence time (Wang et al., 2024). At a reduced

flow rate of 2.5 m³/h, the extended residence time within the coal bed facilitated enhanced heat exchange efficacy and volatile matter accumulation. Ignition was thereby achieved within the shortest observed latency of 162 min (Fig. 5). The corresponding K1 temperature at ignition was 132.17 °C, underscoring that sufficient volatile retention can partially compensate for diminished volumetric heat input.

Conversely, elevating the flow rate to 3.0 and 3.5 m³/h intensified the convective cooling effect and diluted the concentration of reactive volatile species within the pore structure. Consequently, the ignition delay was protracted to 178 min and 195 min, respectively (Fig. 6). These findings underscore that a moderate oxygen flow rate (2.5 m³/h) optimizes ignition performance by reconciling heat delivery with reactant residence time. Adoption of this optimized flow rate in field operations promises to reduce the specific oxidant consumption per startup cycle, thereby depressing the operational expenditure associated with large-scale oxygen generation infrastructure.

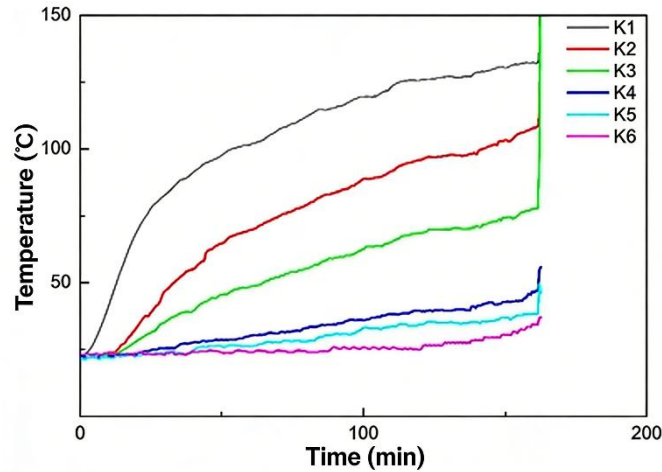


Fig. 5 Temperature profiles recorded by thermocouples K1-K6 at 2.5 m³/h

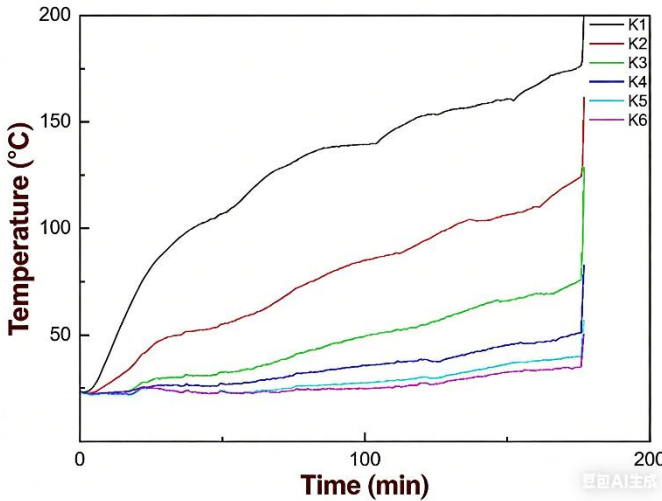


Fig. 6 Temperature profiles recorded by thermocouples K1-K6 at 3.5 m³/h

3.3 Effect of Coal Moisture Content on Ignition Characteristics

Coal moisture content exerts a dual effect on ignition (Liu et al., 2025). At moderate moisture (20%), ignition occurred at 178 min, slightly shorter than raw coal (5.5%). During heating, water vaporization expands pore structures, improves gas permeability, and promotes oxygen diffusion and volatile release. The minor heat consumption due to water vaporization is offset by improved pore structure and oxygen diffusion conditions, thus facilitating ignition.

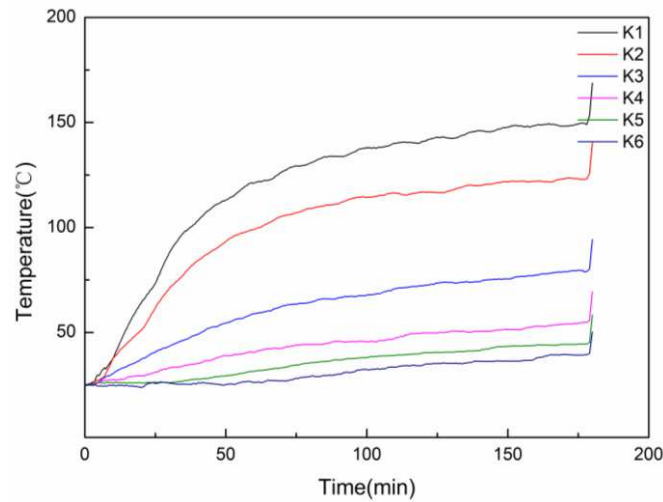


Fig. 7 Temperature profiles at 20% moisture content

At high moisture (50%), ignition was significantly delayed to 284 min (Fig. 8). Extensive water vaporization consumes substantial latent heat, drastically reducing heating rate and prolonging the time to reach critical ignition temperature. Excessive steam also hinders oxygen contact with coal surfaces and suppresses oxidation reactions, greatly reducing ignition efficiency (Li et al., 2021). Therefore, to ensure efficient ignition, seam moisture should be controlled below 20%. In field UCG, pre-drying or water control measures can improve ignition stability and shorten startup time. The 20% moisture critical value provides a judgment standard for pre-drying treatment of high-water-content deep coal seams during UCG well construction; pre-dehydration operations can be arranged in advance to eliminate long ignition delay and extra energy loss.

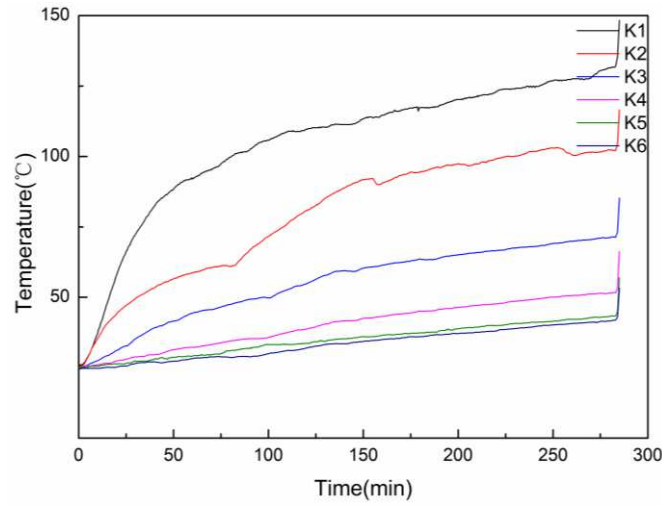


Fig. 8 Temperature profiles at 50% moisture content

3.4 Quantitative Analysis of Parameter Effects

To quantify the influence of each parameter on ignition delay, multiple linear regression was performed, yielding

$$M(\%): \tau = 628.7 - 2.63T + 14.2Q + 2.12M (R^2=0.967, F=89.2, P<0.001)$$

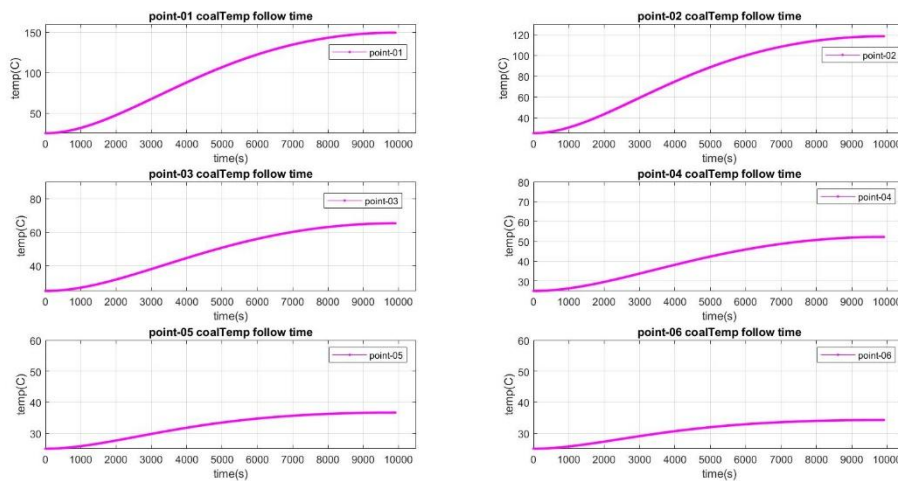
where τ is ignition delay (min), T is inlet gas temperature ($^{\circ}\text{C}$), Q is oxygen flow rate (m^3/h), and M is coal moisture content (%).

This equation exhibits extremely high statistical significance and can accurately predict ignition time under different conditions (Wu et al., 2023). The relative importance of each parameter, quantified by standardized regression coefficients, is as follows: inlet gas temperature (0.62) > moisture content (0.28) > oxygen flow rate (0.10). This indicates that inlet gas temperature is the dominant factor affecting the forced oxidation ignition characteristics of Fengyu bituminous coal, followed by moisture content, while oxygen flow rate has a relatively minor impact (Li et al 2022).

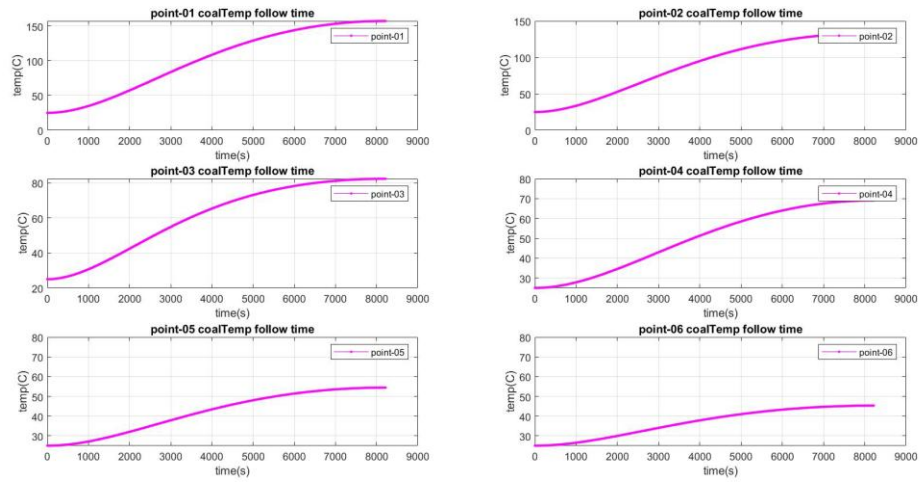
Further analysis of parameter interactions revealed that the influence of moisture content on ignition time weakens at higher inlet temperatures ($>170^{\circ}\text{C}$), with the regression coefficient decreasing from 2.12 to 1.45. Conversely, at lower inlet temperatures ($<165^{\circ}\text{C}$), the influence of moisture content is significantly enhanced, with the regression coefficient increasing to 2.87. This is attributed to faster water vaporization at higher temperatures, which shortens the duration of the heat absorption effect. The established regression formula enables rapid ignition delay prediction without complex numerical iteration, suitable for real-time parameter adjustment on industrial UCG monitoring platforms and can be embedded into field automatic control programs.

3.5 Numerical Simulation Results and Model Validation

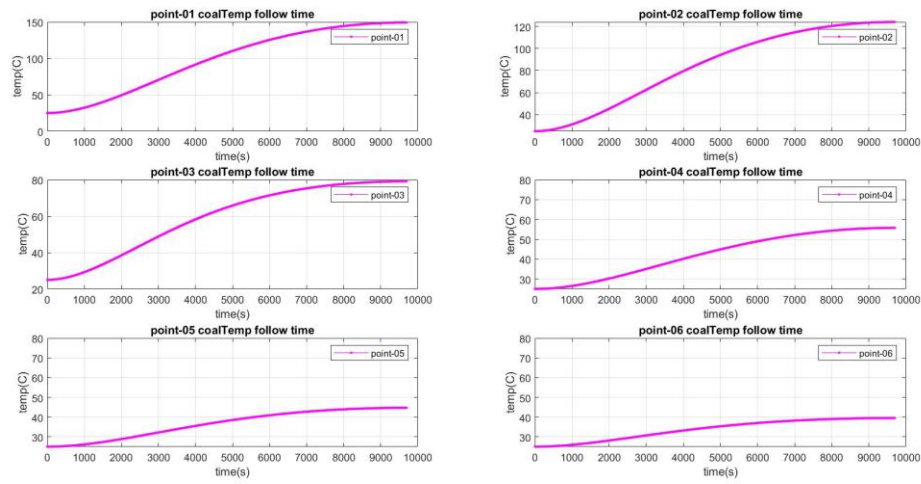
For numerical simulation, the three-dimensional governing equations were simplified to a two-dimensional (x-y) plane to reduce computational cost, which is justified by the axisymmetric flow field in the tubular reactor. A two-dimensional coupled heat and mass transfer model was developed to simulate temperature evolution during ignition, focusing on the forced convection heat transfer between hot oxygen flow and coal seams, and comprehensively considering coal oxidation heat release, convective heat transfer, gas flow, and heat conduction in the packed bed. Simulated ignition delays were 166, 138, 163, and 148 min for key test conditions, compared with experimental values of 184, 153, 178, and 162 min. All relative errors are less than 10%, confirming that the model accurately predicts temperature evolution and ignition delay. Simulated and experimental temperature profiles agree well, with minor deviations due to local heterogeneity in coal packing and slight fluctuations in inlet gas temperature during experiments. At 170-180 °C, the simulated maximum K1 temperature was 192 °C, versus 187 °C experimentally (relative error 2.7%). The validated model makes up for the lack of targeted numerical models for forced oxidation ignition convection heat transfer, and can be used for parameter optimization and design of forced oxidation ignition in deep UCG projects (Eknelligoda and Marshall, 2018). The validated two-dimensional coupled heat-mass transfer model can be reused for parametric calculation of different borehole sizes and coal types, serving as a lightweight engineering simulation template for UCG design institutes.



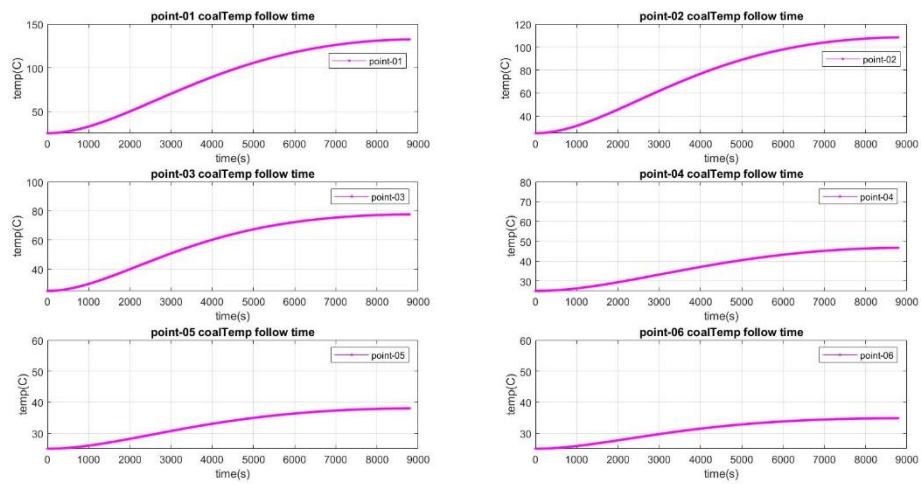
(a)



(b)



(c)



(d)

Fig. 9 Comparison between simulated and experimental temperature evolutions: (a)

160-170 °C; (b) 170-180 °C; (c) 20% moisture; (d) 2.5 m³/h flow rate

Table 3 Comparison between calculated and experimental ignition time

Condition	Simulated τ (min)	Experimental τ' (min)	Relative Error
160-170°C	166	184	9.8%
170-180°C	138	153	9.8%
20% moisture	163	178	8.4%
2.5 m ³ /h	148	162	8.6%

3.6 Engineering Implications for Underground Coal Gasification

The experimental data and validated numerical model obtained in this work deliver multi-dimensional technical guidance for deep drilling UCG industrial engineering and low-carbon coal energy conversion, with clear quantifiable industrial benefits summarized as follows

(1) Borehole heating and insulation design standardization: The critical ignition inlet temperature of 160-170 °C provides a definite design index for surface oxygen heating equipment and vertical well thermal insulation pipes. Adopting the optimal 170-180 °C operating window avoids excessive high-temperature insulation material investment, cutting well construction material costs while guaranteeing stable ignition after long-distance oxygen transport underground.

(2) On-site operation parameter control scheme: The recommended oxygen flow of 2.5 m³/h and seam moisture limit (<20%) form a complete ignition operation specification for field staff. For coal seams with measured moisture exceeding 20%, simple pre-drying measures can be deployed before formal gasification startup to cut ignition waiting time by nearly 40%.

(3) Real-time intelligent control support: The high-precision multivariate linear regression model can be integrated into UCG centralized monitoring systems to realize pre-judgment of ignition duration under variable geological conditions, reducing manual intervention and unattended underground operation risks.

(4) Generalized numerical simulation tool: The proposed coupled heat-mass transfer model ignores negligible natural convection terms while retaining dominant forced convection heat transfer, greatly shortening the calculation cycle of batch engineering design and being applicable to different borehole sizes and coal ranks in various

coalfields.

Compared with traditional underground electric ignition and combustible agent ignition technologies, the forced oxidation ignition scheme proposed in this study eliminates underground power wiring and periodic flammable material supplementation, reducing long-term field operation and maintenance costs. Stable one-time ignition shortens the idle period of gasification furnaces, improves the annual effective energy production time of UCG plants, and enhances the overall energy conversion efficiency of deep coal low-carbon utilization systems. This research forms a complete set of engineering parametric database and lightweight simulation toolkit that can be directly referenced by UCG engineering designers and on-site operation teams.

4. Conclusions

1. The critical hot oxygen inlet temperature for Fengyu bituminous coal forced ignition is 160-170°C; inlet temperature is the dominant factor (standardized coefficient 0.62), followed by moisture (0.28) and flow rate (0.10). The optimal industrial window is 170-180°C, 2.5 m³/h, moisture <20%.

2. A high-precision multivariate regression model ($R^2 = 0.967$) enables fast ignition delay prediction for real-time parameter tuning on industrial UCG monitoring systems.

3. The proposed convection-dominated coupled heat-mass transfer model, incorporating oxygen transport and moisture evaporation, achieves prediction error <10%, providing a reusable lightweight simulation template for UCG engineering design calculations.

4. This study provides the first systematic forced oxidation ignition dataset for Fengyu bituminous coal, directly supporting the scale-up of deep drilling UCG and the low-carbon utilization of deep coal resources.

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Acknowledgments

This research was supported by the Guizhou Provincial Scientific and Technological Program "Guizhou Key Laboratory of Coal Fluidized Mining" (No. ZDSYS[2023]002), the Guizhou Provincial Key Technology R&D Program (No. [2025] General 067), the Scientific Research Project of Guizhou Provincial Coalfield Geology Bureau (No. [2024] 1-03).

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the research work reported in this paper. No funding or sponsorship was received that would affect the outcome or interpretation of the results. All authors have read and approved the manuscript for publication.

Author Contributions

Y., Li designed the experiments, performed the investigations, and wrote the original draft. Z., Jiang developed the numerical model, conducted the simulations, and validated the results. L., Qian assisted with the experiments and data analysis. L., Wang supervised the project, acquired funding, and reviewed and edited the manuscript. All authors read and approved the final version.

Data Availability Statement

All data generated or analyzed during this study are fully available and included in this published article. The raw and processed data supporting the findings of this study are available from the corresponding author upon reasonable request. There are no restrictions on data availability.

Ethics Declaration

This study does not involve human participants, human data, or animal experiments. The research design and experimental procedures in this study comply with the ethical standards and academic guidelines of the journal and the relevant national scientific research regulations. No ethical conflicts or potential moral risks exist in this work.

Declarations

Funding

507 This work was supported by the Guizhou Provincial Scientific and Technological
508 Program “Guizhou Key Laboratory of Coal Fluidized Mining” (Grant No.
509 ZDSYS[2023]002), the Guizhou Provincial Key Technology R&D Program (Grant No.
510 [2025] General 067), and the Scientific Research Project of Guizhou Provincial
511 Coalfield Geology Bureau (Grant No. [2024] 1-03).

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