energies

MDPI

Article

Physical Simulation Test of Underground Coal Gasification Cavity Evolution in the Horizontal Segment of U-Shaped Well

Yufeng Zhao [1], Zhen Dong [1,*], Yanpeng Chen [1], Hao Chen [1], Shanshan Chen [1], Mengyuan Zhang [1], Junjie Xue [1], Xinggang Wang [2] and Lixin Jiao [2]

[1] Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China; cnzhaoyufeng@petrochina.com.cn (Y.Z.)
[2] Research Institute of Exploration and Development, Tuha Oilfield Company, PetroChina, Hami 839009, China
* Correspondence: dongzhen69@petrochina.com.cn

Abstract: A key point in the underground coal gasification process is the cavity evolution in the horizontal segment. The morphological evolution law of the gasification cavity has not been clarified, which is the bottleneck restricting the analysis of its controllability. In this paper, a physical simulation system for cavity generation was developed, and the cavity evolution in a targeted coal seam with overburden pressure was duplicated in the laboratory. A set of temperature field synchronous monitoring devices was developed to realize temperature sampling within a cavity and the surrounding rock. By analyzing the relationship between the overall temperature distribution pattern and the gasification agent injection condition, the morphological propagation law of the cavity is verified to be water drop-shaped, and influencing factors including the injection flow rate and the gasification agent component ratio are investigated. The axial length and volume of the cavity increase with an increasing injection flow rate. Higher oxygen content results in increased size in all dimensions. The research results provide theoretical support and reference for applying controlled cavity formation in the horizontal segment of U-shaped wells.

Keywords: underground coal gasification; gasification cavity; cavity evolution; physical simulation; temperature field

check for updates

Citation: Zhao, Y.; Dong, Z.; Chen, Y.; Chen, H.; Chen, S.; Zhang, M.; Xue, J.; Wang, X.; Jiao, L. Physical Simulation Test of Underground Coal Gasification Cavity Evolution in the Horizontal Segment of U-Shaped Well. *Energies* **2023**, *16*, 3452. https://doi.org/10.3390/en16083452

Academic Editor: Changkook Ryu

Received: 6 March 2023
Revised: 9 April 2023
Accepted: 11 April 2023
Published: 14 April 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Due to the abundance of coal resources and the scarcity of oil/gas resources in China, coal occupies the dominant share in China's energy consumption. Current natural gas production is far from meeting this consumption and there is an urgent need to expand new sources of energy. Large quantities of deep, hard-to-use coal resources could be an important supplement to cover the energy shortage. Underground Coal Gasification (UCG) is of great strategic significance for developing the natural gas industry and is expected to establish a new approach for providing fast and efficient gas with Chinese characteristics. This technology can provide a technical basis for the era of a "hydrogen economy" by utilizing deep coal resources, alleviating the shortage of natural gas and conserving resources [1].

The basic process of underground coal gasification was developed by the German scientist Siemens and the Russian chemist Mendeleev [2]. Its technical feasibility has been verified by more than 30 field tests worldwide. Based on petroleum engineering technology, UCG has been innovated in three generations: underground roadway, shallow vertical well and horizontal well + CRIP (controlled retracting injection point).

The horizontal cavity along the coal seam is the basis of the UCG operation. The advantage of this is that the vertical propagation height of the cavity is limited by the thickness of the coal seam. However, since the cavity expands spontaneously, an inappropriate cavity volume has a significant impact on the gas production efficiency. Therefore, a

proper distance between the air inlet (injection point) and the gas outlet can be ensured by the CRIP process. Via multiple retreats and reignitions, the CRIP process is particularly suitable for controlling the shape and volume of the gasification cavities. The CRIP method is precisely designed to ensure structural integrity. For this reason, it has been widely used in field tests over the past few years. The research on this process will provide the technical reserves for the field tests and the engineering applications.

Currently, the basic theories and key techniques of UCG are not fully understood. The temperature field distributions inside the cavity and in the surrounding rock are affected by the flow of the mixed gasification agent in the cavity. The high temperature weakens the strength of the coal seam and adjacent strata. The interaction between the irregular temperature field and the overburden pressure leads to a complex cavity response. It is difficult to solve the above problems by theoretical derivation and using experimental methods based on conventional reservoir development.

Perkins classified the gasification reactions and provided a theoretical analysis of the internal wall spall behavior [3]. Scientists have conducted much research on how the gasifying cavity evolves. Other researchers have examined the temperature-influenced thermophysical properties of rocks [4–6]. Hettema and Wolf studied the thermodynamic behavior of rocks in the El Tremedal test area based on the influence of a high temperature on the physical properties of coal rock [7]. The analysis of cavity evolution based solely on the thermos-physical properties of coal and rock has obtained some results. However, most of them are limited to the effect of temperature and pressure and do not consider complex temperature and flow fields. Liu studied the characteristics of the temperature field around the combustion zone by means of similar simulation experiments [8]. During this simulation, bamboo charcoal was used as a similar material and was ignited in the model. Only the temperature field and collapse in the overlying rock were studied. Scholars used camphor, wood and coal for UCG combustion simulations (see Figure 1) and found that the formations of cavities after combustion are drop-shaped [9], the expansion rate and the final shape of gasification cavity are significantly affected by the flow rate of gasification agent, and a higher flow rate could transform a spherical cavity into an elongated cavity. Daggupati investigated the volume, the shape evolution and the vertical growth rate of the gasification cavity under different combustion conditions [10,11]. Otto established a two-dimensional thermomechanical coupling model with consideration of the influence of temperature [12]. The irregular growth rate and the shape of the gasification cavity were obtained by using the simplified two-dimensional gasification cavity numerical model to consider the combined effects of fluid, mass transfer and heat transfer [13]. According to the numerical simulation study performed by Akbarzadeh, significant deformations were found due to the elastic modulus changing with temperature by analyzing the thermo-hydro-mechanical coupling in the simplified cubic gasification cavity [14]. Kapusta et al. conducted experiments to study the temperature field in coal and gas production components during gasification under high-temperature and high-pressure conditions [15,16]. The experiments solely considered the effect of combustion and gasification on the expansion of the cavity, and the spalling behavior could not be realized experimentally due to pressure-bearing. In order to study the temperature field and stress field evolution processes in the coal seam, Liang established a physical simulation model for underground coal mine roadway gasification in the laboratory [17]. Physically similar simulation experiments based on the CRIP gasification process have not yet been conducted. Chen developed a physical simulation method for salt cavern gas storage for the real-time monitoring of cavity shape [18]. This work provides important inspiration for the research in this paper.

Theoretical analyses and physical simulations are performed based on the predetermined cavity morphology, and most previous studies are based on independent block models. There is a lack of experimental data concerning real boundary conditions in previous studies. Due to the limited number of field tests and incomplete monitoring technology, and because the current cavity measurement technology cannot obtain the complete cavity

morphology, a physical simulation in the laboratory is an appropriate method to study the evolution of gasification cavity morphology.

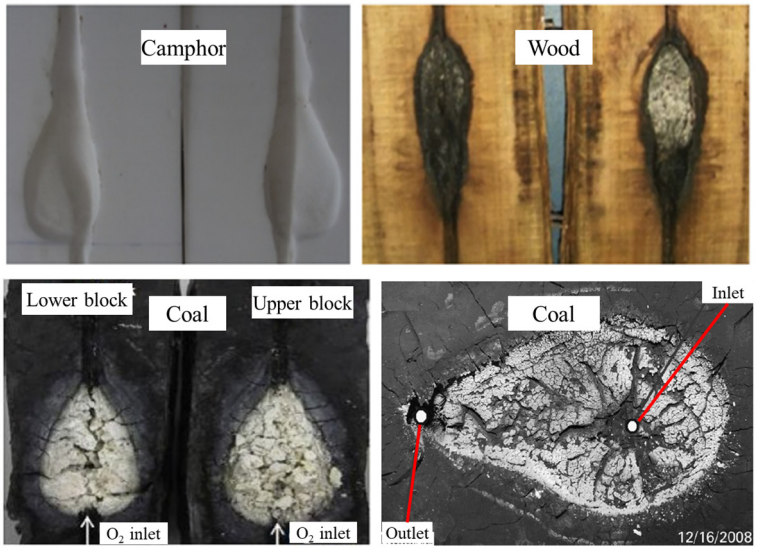


Figure 1. Cavity morphologies produced by gasification processes simulated with different materials.

In this paper, a newly developed physical simulation device is applied. Based on the CRIP process, the simulation test of the gasification cavity development in the horizontal section is carried out. The characteristics of the temperature field are measured on a real-time basis. The cavity evolution law is analyzed by the combination of cavity shape characteristics and temperature field characteristics.

2. Physical Simulation Tests

2.1. Experimental Devices

The key experimental device is designed by the China Petroleum Exploration and Development Research Institute (RIPED) to simulate the failure of combustion zone and fracture evolution in the surrounding rock. The evolution of the gasification cavity can be simulated in the self-configured coal seam material test, which adopts the simulation device, as shown in Figure 2. The flow rates of different injected gas components can be controlled. The position of the injection point can be adjusted to change the ignition location. Before the experiment, different raw material proportions of physical simulations are calibrated, and suitable proportions are selected for the processing of coal seam, bottom, roof and overburden materials. By comparison with geological data, the structure of each material layer is formed with a predefined geometric similarity ratio, and the strength of the mixed material is in accordance with the mechanical similarity ratio.

The overall dimensions of the test frame are 1800 mm × 200 mm × 1200 mm (length × width × height). To simulate a 120 m thick rock layer, the frame is filled to a height of 800 mm for this study.

2.2. Modeling

Based on the geological data of the Tiao-231 well in the Santanghu Basin, a physical simulation model is generated, as shown in Figure 3. Aggregate and binder are the main components of the similar material. The proportion of aggregate in the material is relatively high, and its proportion is the determinant of the physical and mechanical properties of the similar material. Fine sand is used as the aggregate material. Binder is used to form geometry and adjust mechanical properties. In this test, lime and gypsum are used as the binding agents. The material ratio of each layer is set according to the rock strength. Mica powder is used as artificial layering between adjacent layers. Under the premise of

ensuring the similarity of mechanical properties, pulverized coal and sawdust are used as coal seam material aggregate, which can participate in the combustion reaction.

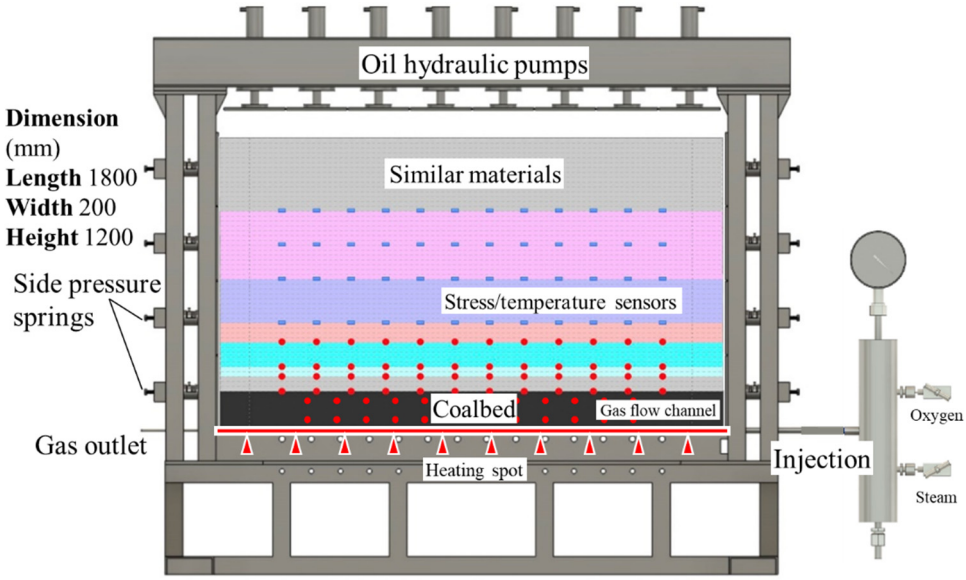


Figure 2. Frame parameters, loading devices and connection of combustion devices.

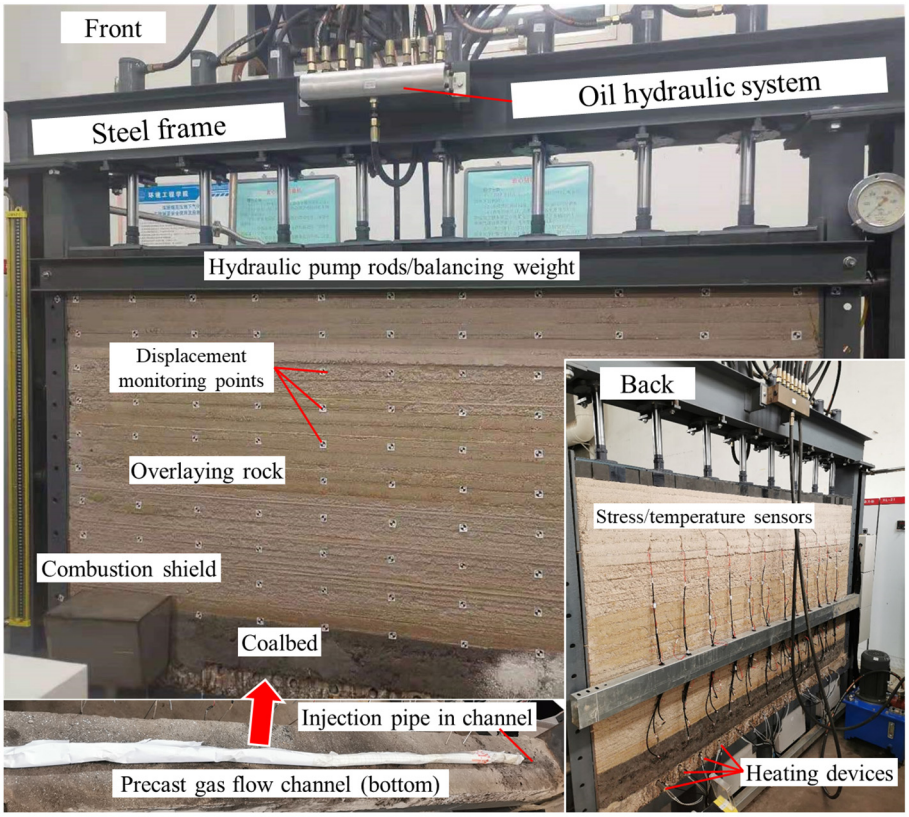


Figure 3. Photos of real devices and experiment preparation (including igniter/heating devices, gasification agent channel arrangement, pressure and temperature sensor installation, subsidence monitoring point arrangement and overburden pressure application).

A channel of hard paper rolls is placed at the bottom of the coal seam material before similar materials are placed. The channel has a good connection to mimic the horizontal section of the U-shaped well. To simulate the gasification agent injection pipe in the

flammable casing pipe, a gas injection pipe is installed in the channel. Electric heaters are installed under the paper channel to realize ignition function at different locations. Thermocouple sensors are placed in the coal seam materials. These sensors monitor and record the temperature field in real time.

2.3. Test Process

On the right side of the test frame, the injection pipe is connected to the gasification agent pump, and the mixed gasification agent is injected into the system in accordance with the specific water–oxygen ratio. On the left side, the air flow channel is connected to the flow meter and the pressure meter using a hose, and a gas sampling port is set up. A major part of the exhaust gas is purified and then discharged from the system. As shown in Figure 4, specific devices are connected to form the system for injecting the gasification agent and discharging the produced gas.

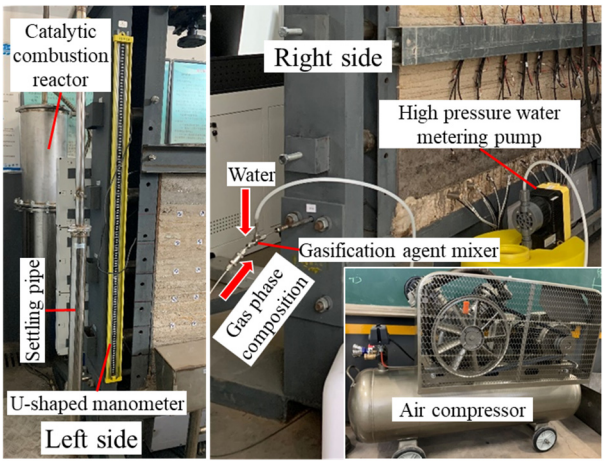


Figure 4. Gasification agent injection and produced gas discharge system.

After the start of the test, the ignition position is adjusted by moving the gas injection pipe in the channel, and the electric heater is activated at the corresponding position for approximately 4 h. This process is referred to as the activation phase. Once the coal seam material has been ignited, the electric heater can be turned off. With the help of the gasification agent, the coal seam material can spontaneously complete the cavity formation. Pure oxygen is used as the gasification agent. The flow rate is 5 L/min. The test enters the first cavity generation phase. The focus of this research is mainly on the development of the first gasification cavity. The temperature fields in the gasification cavity and the surrounding rock are monitored with the temperature sensors placed, as shown in Figure 5.

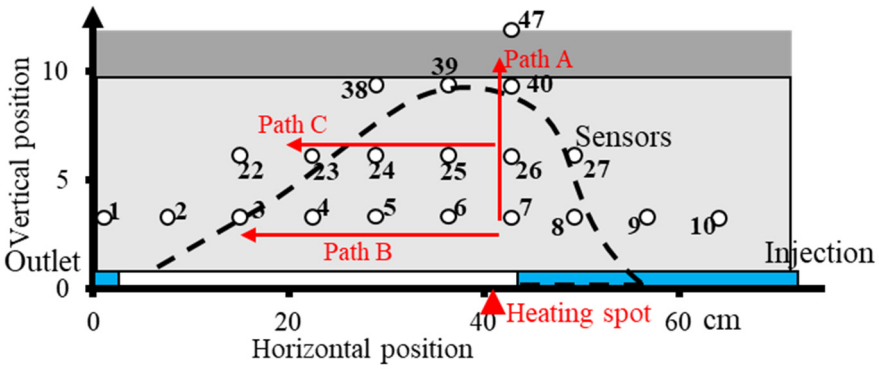


Figure 5. Temperature monitor layout in coal seam (Lower temperature points 1–10, middle temperature points 22–27, top temperature points 38–40 and roof plate temperature point 47 are set for monitoring the first gasification chamber).

In the early stage of the formation of the cavity, a combustion space is formed in the coal seam material. The inner surface of the cavity is subject to combustion and peeling due to the drastic reaction. This causes continuous cavity expansion until the first cavity is formed. The temperature data are monitored at one-minute intervals in order to obtain the true shape and size of the cavity throughout the test.

The cavity reaches its maximum size when the high-temperature zone reaches the top of the coal seam. The gas injection pipe is then retracted along the channel towards the inlet. The new gas injection point is located in the upstream direction of the gas flow and is surrounded by the fresh material of the coal seam. This step simulates the CRIP procedure. Generation of the second cavity is initiated from the new gas injection point. This is referred to as the continuous generation stage. Multiple cavities are formed in the coal seam by repeating the retraction process in this stage.

After creating cavities in the effective area of the test frame, gas injection stops, and the coal seam material stops burning. After the system cools down, expanding foam is injected into the cavity. After the foam blocks have solidified, they can be excavated from the coal seam material by hand. The shape of the foam block is a reflection of the final shape of the gasification cavity. Figure 6 shows the foam block representing the first cavity.

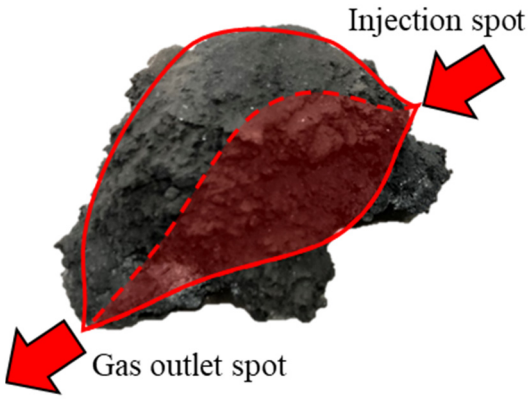


Figure 6. Final shape of gasification cavity (expanding foam).

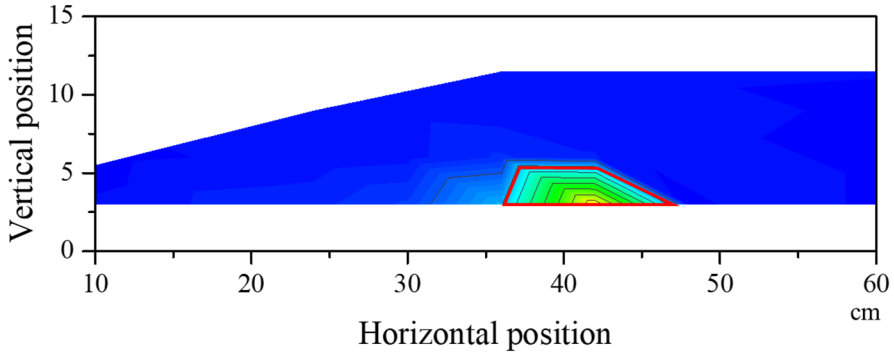
3. Results Analysis

The morphological expansion of the gasification cavity is essentially the burning and spalling of the coal surface. Different dimensions reflect different combustion and spalling rates in different parts of an irregular cavity. The temperature field is the most intuitive element to use to study the cavity. During the test, the overburden pressure and lateral pressure remain constant, and the mechanical constraints are fixed. Coal seams are sufficiently dense to prevent the reaction gases from communicating with the outside atmosphere. The influence of external temperature is negligible because the coal seam is covered with thermal insulation material.

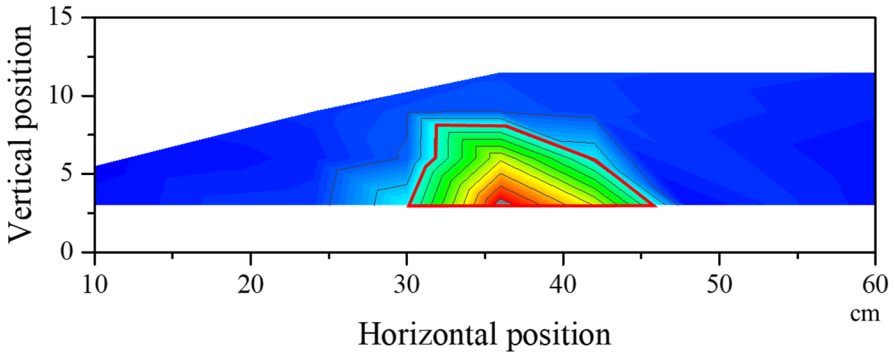
3.1. Morphological Evolution of Gasification Cavity

Gasification cavity shape is monitored in real time by collecting temperature data from sensors. The results are analyzed by the visual processing of temperature data at 20 min intervals. Temperature values and their corresponding coordinates are matched and plotted. By generating a two-dimensional temperature field, the cross-sectional structure of the cavity is reconstructed.

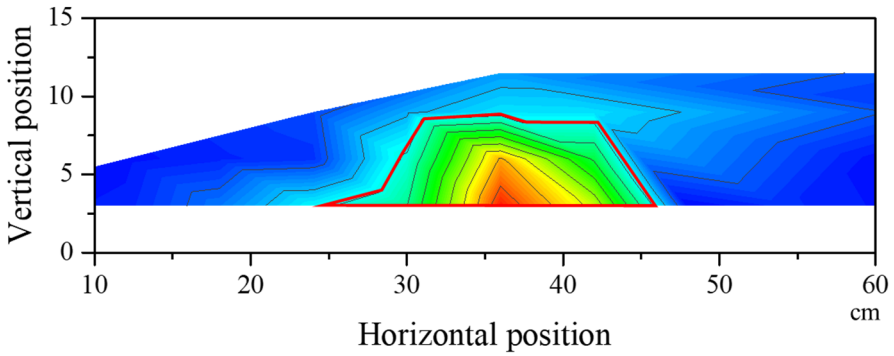
An approximate relationship between the temperature and the physical boundary is established by comparing the shape of the foam blocks with the temperature field diagrams at the appropriate time. Therefore, the internal cavity shape diagram is obtained by calculating the temperature field (see Figure 7).



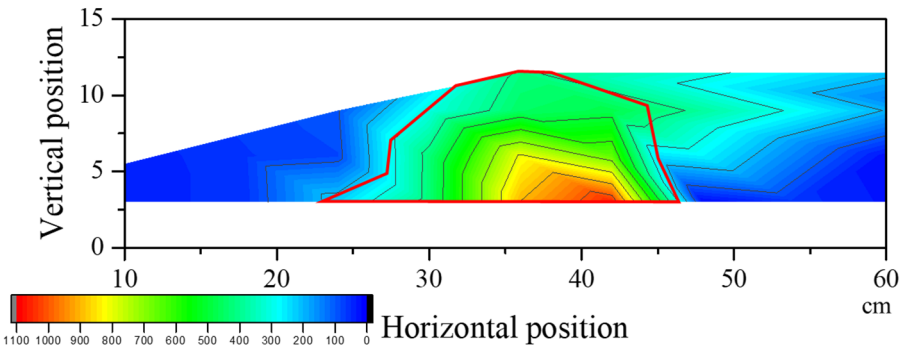
(**a**) t = 300 min



(**b**) t = 400 min



(**c**) t = 500 min



(**d**) t = 600 min

Figure 7. Temperature field and cavity shape at different stages.

In accordance with the shape diagram of the cross-section, the high-temperature zone above the ignition point expands rapidly. An arc-shaped gasification cavity is formed. The

high-temperature zone begins to expand downstream of the gas flow when the arc reaches a certain height. This condition continues for a certain period of time, and a water drop shape is formed, which gradually shrinks from the ignition point to the outlet. In the late stage of cavity formation, the air flow joints appear in the upper part of the coal seam layer so that the high-temperature zone expands into the layer. Because the bottom of the coal seam is mudstone, the similar material is not combustible and the gasification cavity can rarely expand downward.

By observing the cross-sectional shape at different stages, the evolution law of the cavity shape during the whole process is analyzed (see Figure 8). The evolution law is discussed in three aspects, including expansion around the ignition point, gas flow channel enlargement and the upward evolution to the roof.

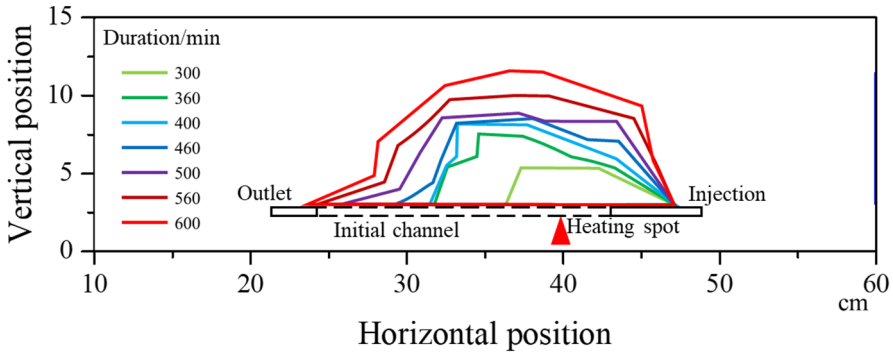


Figure 8. Shape variation of gasification cavity at different stages.

The internal space is limited in the early stage of the gasification process. A large amount of gasification agent enters the space in the form of gas. The coal material is ignited by the high temperature. The cavity expands slowly due to the narrow flow channel and limited gas discharge. The horizontal area of the cavity increases gradually. For a long time, the cavity body near the ignition point expands hemispherically. This hemispherical part dominates most of the volume expansion of the cavity and is the site of the gasification reaction.

In the next stage, the high-temperature gas migrates along the flow channel to the gas outlet point. The channel size expands to form an obvious dominant channel. At this point, the asymmetric distribution around the ignition point appears, and the space near the outlet point increases. As the reaction continues, the channel becomes conical, and the entire cavity begins to resemble a water droplet. The conical slanted plane connects the top of the cavity and the gas outlet point under the action of the high-temperature gas flow.

The expansion rate slows down due to the distance from the ignition point after the top of the cavity reaches a certain height. High-temperature gas penetrates the coal seam along the horizontal bedding due to the layer separation of the upper coal seam material. The temperature of the upper part increases sharply in the horizontal direction in the case of height limitation. Moreover, the stagnation time of the high-temperature atmosphere near the top of the cavity is longer, and the separation becomes considerable. Therefore, due to the change in the thermal-physical properties of the upper coal seam layers in the later stage of cavity development, large-scale caving damage may occur.

3.2. Distribution of Temperature Field

There is a dynamic equilibrium between the temperature field distribution in the gasification cavity and the surrounding rock. The temperature field is significantly affected when the test system is disturbed or the gasification agent injection conditions are changed. The internal gas flow field is also an important factor affecting the temperature field. Therefore, the adjustment of the injection condition is made gradually after the system is stable. The disturbance of a sudden change in the injection condition must be avoided.

During the cavity generation process, a stable gasification agent flow is maintained to stabilize the temperature. The temperature value from each sensor is loaded into the processing terminal. The monitoring of Path A is used to analyze the temperature changes in the vertical direction inside the cavity. Both Path B and Path C are used to study the temperature changes in the horizontal direction but at different heights (see in Figure 4). In this paper, the temperature changes along vertical Path A (points TP7, TP26, TP40 and TP47), horizontal Path B (points TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8 and TP9) and horizontal Path C (points TP22, TP23, TP24, TP25, TP26 and TP27) at different times are analyzed.

The temperature gradually decreases in a vertical direction from the bottom to the top of the cavity, as shown in Figure 9. Between the inside of the cavity and the surrounding material, there is a remarkable temperature difference. The highest temperature occurs at the bottom of the cavity near the ignition point. The top of the cavity expands successively through points TP7, TP26 and TP40 above the ignition point. The temperature increases rapidly after the sensor of the corresponding point is exposed into the cavity, and the maximum temperature monitored in the cavity is approximately 1150 °C.

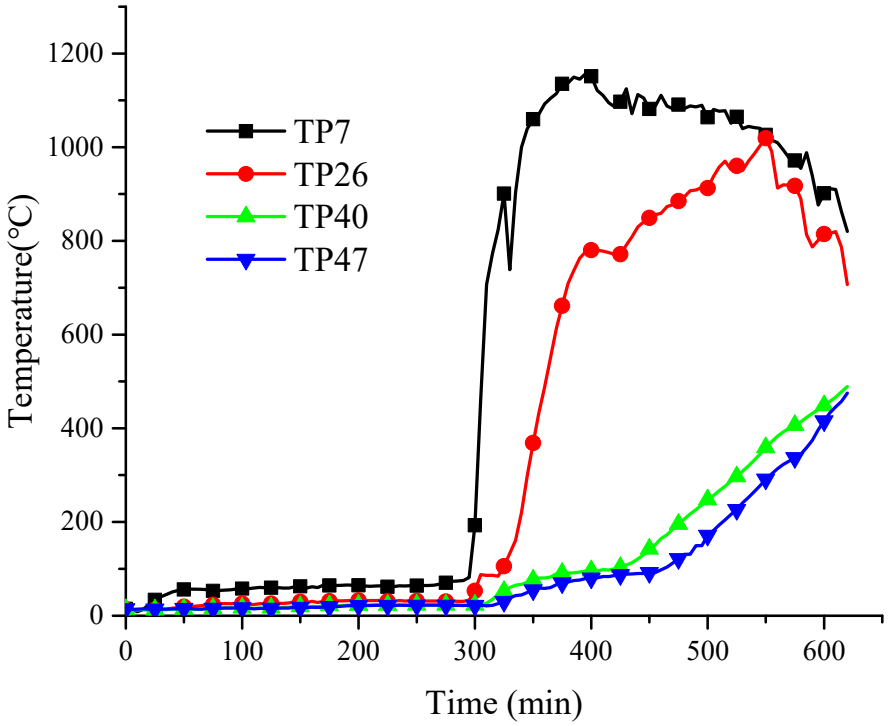


Figure 9. Temperature variation curves at different positions in vertical direction.

As shown in Figure 10, except for the ignition point, the temperature along Path B in the cavity changes relatively little in the horizontal direction. The temperature of the points along the flow direction increases sequentially because the gas flow pushes the heat toward the outlet point. The horizontal temperature gradient is small.

Path B is near the open gas flow channel; Path C is above Path B. Compared to those along Path B, points along Path C have lower temperatures. The temperature at the higher position is influenced by the irregular boundary of the cavity, and there is also an obvious difference in temperature between the inside of the cavity and the surrounding material (see Figure 11).

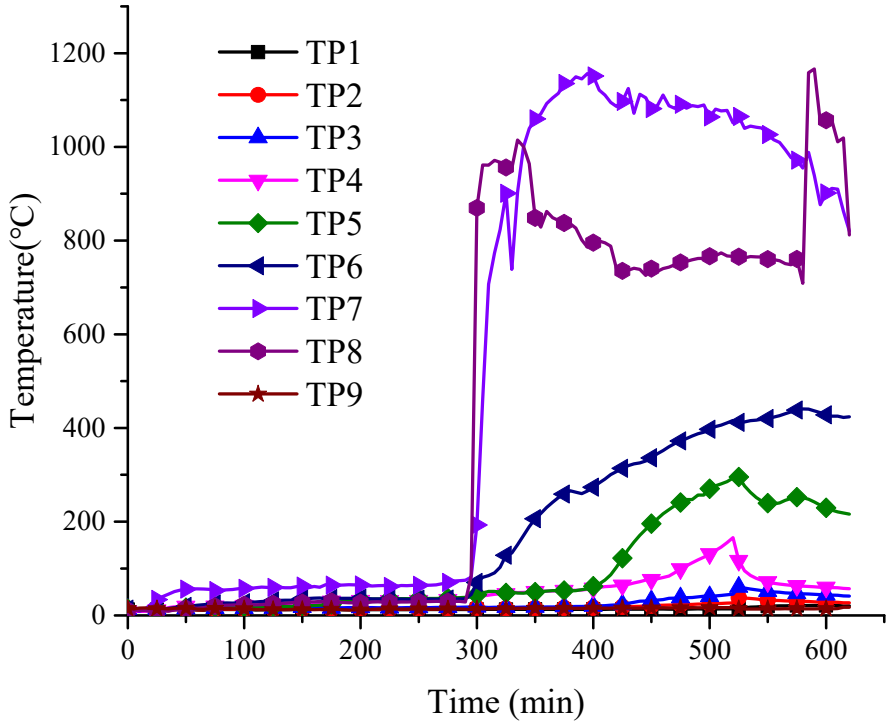


Figure 10. Temperature variation curves at different positions in horizontal direction (Path B close to bottom).

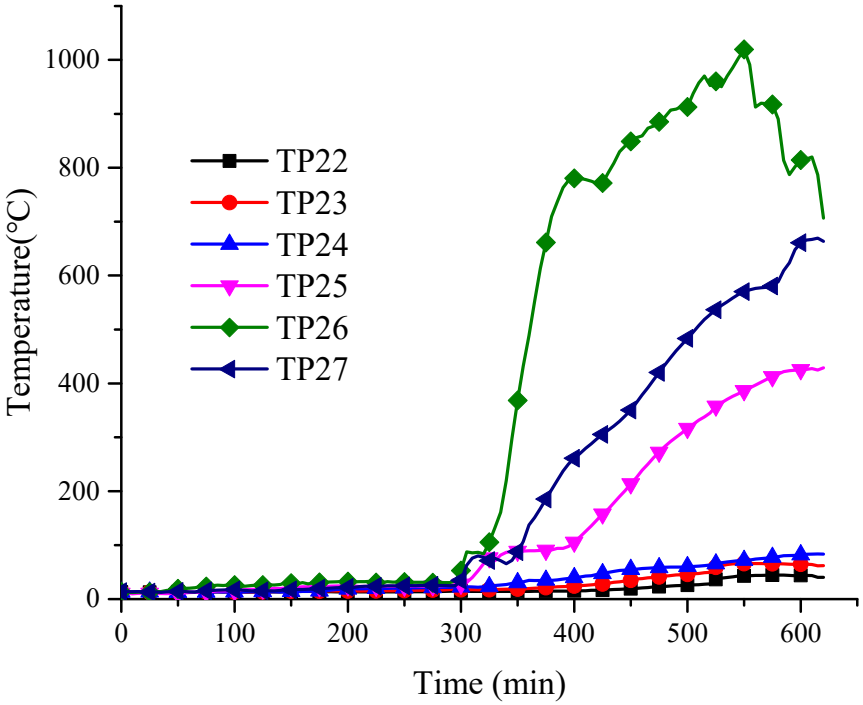


Figure 11. Temperature variation curves at different positions in horizontal direction (Path C in the middle).

Points TP5 and TP40 (see Figures 5, 9 and 10) are selected for comparison. Both points are located at a distance of 10 cm from the ignition point. TP5 is located downstream of the gas stream and TP40 is located directly above the ignition point. The temperature of the two points increases simultaneously at 420 min of test time. The temperature of TP5 reaches the peak of about 250 °C after the test lasts about 500 min, and the cavity extends

to the TP5 position. Since TP5 is close to the gas passage, the high-temperature gas is not retained in the cavity for a long time. The gas generated by the gasification and combustion is quickly discharged through the gas channel with an excessive amount of the gasification agent. As a result, the temperature of TP5 drops to a lower value of about 200 °C. On the other hand, TP40 is far from the outlet point, the residence time of the high-temperature gas is longer, and the temperature continues to rise to more than 400 °C until the end of the test. After the high-temperature region reaches the coal seam roof, the TP47 position set in the roof material also heats up simultaneously. In the late stage of cavity formation, the temperature of the points around the gas injection site is relatively higher, whereas the temperature of the areas toward the outlet point is severe.

In addition, the temperature field at the top of the cavity expands in a wide range after the test duration reaches 600 min (see Figure 7d). However, the temperature in the cavity decreases significantly. It can be concluded that a large amount of heat is diffusing into the separated layers of the coal seam and the exposed roofing.

3.3. Genetic Analysis

The expansion of the cavity is mainly due to the combination of coal combustion and spalling, according to the analysis of the evolution of the cavity and the distribution of the temperature field.

The first aspect of the combustion refers to the combustion and gasification reaction that takes place on the coal wall: the consumption of the coal body leads to the enlargement of the cavity. This occurs especially in the early stages, when the cavity size is small and the inner surfaces are close to the ignition point. The second aspect of spalling refers to the high temperature acting on the coal wall, which weakens the physical and mechanical properties of coal and rock materials. Coal fragments are separated from the massive coal block under the conditions of self-weight and the overburden pressure. The spalling effect is the main factor of the cavity development, and the cavity volume increases continuously. As the roof is increasingly exposed, the top coal spalling phenomenon becomes more pronounced. The combustion and gasification reactions continue as the small fragments fall into the cavity. The reactions take place at the bottom, close to the ignition point.

In the hemispherical cavity state, the high-temperature gas slowly flows to the outlet point, causing the additional erosion of the coal wall downstream. The upper arc of the cavity extends gradually to the outlet, and the radiant is gently tapered to a sloping surface. As more gasification agent is injected, the horizontal consumption becomes more significant, and the cavity axial length becomes longer.

The volume in the cavity increases rapidly when the dominant gas channel between the injection and the outlet points is wide enough. The gasification agent reacts sufficiently and flows out through the conical channel at a rapid rate. A part of the heat is taken away by the gas flow and the maximum temperature is reduced. Both lateral and upward expansions are observed while forming the conical sloped surface of the cavity. The vertical and horizontal temperature gradients inside the cavity are determined by gas flow conditions and affect the final cavity shape. As shown in Figure 12, the final cavity is the combined result of the temperature field, flow field and stress field in the coal seam.

The analysis of the temperature distribution shows large temperature gradients in the vertical direction, as shown in Figure 9. After the initial ignition, the temperature at the bottom of the chamber is much higher than the temperature in the top of the cavity and in the upper layer, and the expansion is slow. In the horizontal direction, the amount of high-temperature gas increases slowly along the direction of gas flow, and the expansion rate also increases accordingly so that the position of the strongest expansion moves toward the outlet point.

The final water drop shape is analyzed based on the foam reconstructed cavity model. Different injection flow rates are tested using pure oxygen as the gasification agent. As shown in Table 1, the cavity size is significantly affected. Increasing the injection flow rate helps to expand the cavity space under the same conditions.

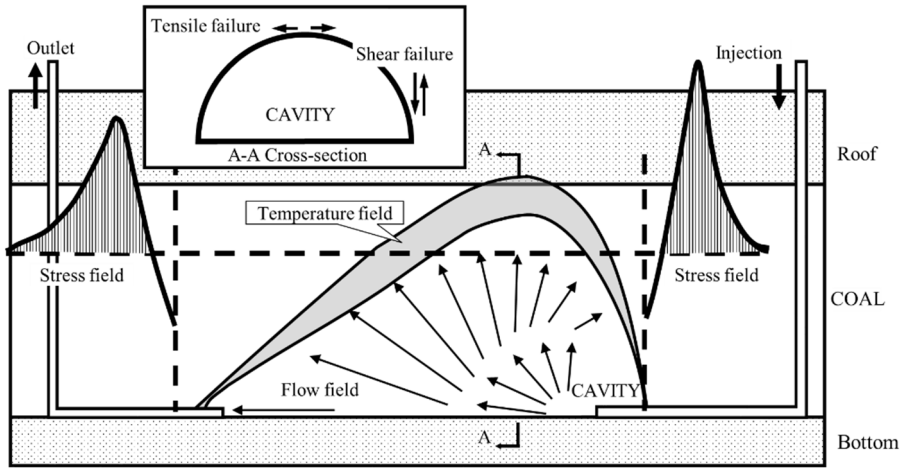


Figure 12. Multiple fields in a single cavity generation process.

Table 1. Relationship between flow rate of gasification agent and final cavity volume.

Flow Rate of Gasification Agent (Oxygen)/(L/min)	Cavity Volume/cm^3
1.6	273.6
2.4	332.7
3.2	361.4

Maintaining a constant gasification agent injection results in a smaller change rate of the height and a smaller slope of the cavity shape as the cavity expands; the inner surface area becomes larger, and the heat required for expansion becomes greater. When a certain volume is reached, the constant injection can no longer support the continuous expansion of the cavity. The shape of the cavity is basically stable and does not change any more.

Using a fixed injection flow rate of 2.4 L/min, gasification agents with different oxygen proportions are tested. The cavity shape is obtained, as shown in Figure 13 and Table 2. In the cross-section of the axial view, the cavity is centered on the prefabricated gas flow channel, which means that the empty space in the coal seam material expands in the radial direction. The initial sectional shape of the cavity is roughly semicircular. In the later stage, due to the severe spalling of coal material, the vertical height H_1 in the gas ignition point cross-section is greater than the transverse width W_1.



(**a**) side view (**b**) plan view

Figure 13. Shape and dimension of cavity (expanding foam).

Table 2. Dimension variation of cavity caused by different oxygen proportions (injection flow rate 2.4 L/min).

Oxygen Proportion	L_1/mm	L_2/mm	H_1/mm	H_2/mm	W_1/mm	W_2/mm
60%	48.3	99.7	60.4	36.2	47.7	34.8
80%	44.8	104.4	62.2	43.6	54.4	40.7
100%	41.6	106.5	62.4	45.7	63.3	42.8

The cavity space around the ignition point is significantly larger than the cavity space around the gas outlet point. Higher oxygen content results in a greater size in all dimensions. The gasification agent has the highest concentration at the gas injection point so the reaction is intense and the heat release is the largest. Therefore, in the process of cavity development control, reaction and expansion states around the ignition point should be adjusted to cover more coal seam area.

The development of the second cavity is more complicated due to the existence of a full-size cavity in the downstream direction when the gas injection point is retracted to the second ignition point. During the test, the gasification agent flow rate and the oxygen content are adjusted to control the temperature fields in the cavity and surrounding materials. This aims to maximize the high-temperature zone, increase gasification range and improve the exploitation rate of the coal seams.

The gasification agent is maintained in contact with the fresh coal wall by continuously moving the position of the gas injection point during the second cavity generation test. As the violent reaction continues and the temperature rises, the cavity expands to form a semi-elliptical cavity, as shown in Figure 14. The cavity height does not reach the roof, but more coal seam material is involved in the reaction.



Figure 14. Cavity shape generated by continuously moving gas injection point (the second cavity).

3.4. Experimental Method Limitations

The coal seam material is a mixture of coal dust, wood chips and a small amount of binder, and the material is uniform and isotropic. The real coal block is influenced by the internal presence of joints and other structures during the cavity forming process. In the next study, the authors plan to simulate the cavity building behavior due to heat-induced changes in physical mechanical properties by processing intact lumps of coal as a similar material for coal seams.

Real coal underground gasification occurs in a high-temperature and high-pressure environment. The gasification cavity in this experiment is directly connected to the atmosphere via a similar porous material and does not have high-pressure characteristics. Therefore, this setup is only used to simulate cavity evolution and overburden subsidence deformation, and the collected produced gas components are of no reference value.

4. Conclusions

In this paper, the cavity shape evolution law of a U-shaped well with the CRIP process is studied by an indoor physical similarity simulation test. The monitoring of the gasification space is typically not visually observable directly so it is inverted by the temperature field. The evolution law of the horizontal gasification cavity is analyzed based on the temperature field data and gas injection parameters. The temperature field distribution is summarized to reveal the basis of the cavity expansion, and the causes of the shape variation are analyzed.

Due to the combustion and gasification reaction in the limited space, the cavity expands rapidly during the process of cavity formation. Cavity expansion is a direct function of temperature. Therefore, the temperature of the combustion area is the main factor influencing the expansion rate. The physical and mechanical properties of coal seam material change after heating, and expansion occurs first in the high-temperature part.

The temperature inside the cavity decreases gradually from the bottom to the top, and the temperature gradient can be reduced by using a smaller amount of gasification agent. Horizontally, the temperature decreases gradually along the gas flow direction, and more gasification agent can reduce the temperature gradient. The gas flow rate modifies the shape of the temperature distribution area. The injection flow rate of the gasification agent can obviously affect the direction of cavity development. Most of the cavity volume is contributed by the space formed around the ignition point. The cavity shrinks to a minimum at the gas outlet point in the horizontal section. The angle of inclination of the conical channel is gradually reduced during the process, the cavity expands only in the coal seam, and the influences on the bottom are neglected. The test results provide several references for the design and control of cavities for underground coal gasification using the CRIP method.

Author Contributions: Conceptualization, Y.Z. and Z.D.; data curation, M.Z.; formal analysis, Z.D. and S.C.; funding acquisition, Z.D., H.C. and S.C.; investigation, Y.Z. and Z.D.; methodology, Y.Z., Z.D. and J.X.; project administration, Y.C. and L.J.; resources, Z.D. and X.W.; software, Y.Z.; supervision, Y.C. and L.J.; validation, Z.D., H.C. and J.X.; visualization, M.Z.; writing—original draft preparation, Y.Z. and M.Z.; writing—review and editing, Y.Z., Z.D. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: The present work is supported by Major Scientific and Technological Project of China National Petroleum Corporation (CNPC) (2019E-25), Soft Science Research Project of CNPC (20230118-4), International Cooperation Project of RIPED (YGJ2019-15). The financial supports are gratefully acknowledged.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Zou, C.; Chen, Y.; Kong, L.; Sun, F.; Chen, S.; Dong, Z. Underground Coal Gasification and Its Strategic Significance to the Development of Natural Gas Industry in China. *Pet. Explor. Dev.* **2019**, *46*, 205–215. [CrossRef]
2. Blinderman, M.S. Global Development of Commercial Underground Coal Gasification. *Earth Environ. Sci.* **2017**, *76*, 012003. [CrossRef]
3. Perkins, G. Underground Coal Gasification—Part II: Fundamental Phenomena and Modeling. *Prog. Energy Combust. Sci.* **2018**, *67*, 234–274. [CrossRef]
4. Ozguven, A.; Ozcelik, Y. Investigation of Some Property Changes of Natural Building Stones Exposed to Fire and High Heat. *Constr. Build. Mater.* **2013**, *38*, 813–821. [CrossRef]
5. Liu, S.; Xu, J. Study on Dynamic Characteristics of Marble under Impact Loading and High Temperature. *Int. J. Rock Mech. Min. Sci.* **2013**, *62*, 51–58. [CrossRef]
6. Liu, S.; Xu, J. An Experimental Study on the Physico-Mechanical Properties of Two Post-High-Temperature Rocks. *Eng. Geol.* **2015**, *185*, 63–70. [CrossRef]
7. Hettema, M.; Wolf, K.-H. Thermo-mechanical properties of roof rock of coal for underground gasification. In *Topics in Applied Mechanics*; Dijksman, J.F., Nieuwstadt, F.T.M., Eds.; Springer: Dordrecht, The Netherlands, 1993. [CrossRef]
8. Liu, J. *Study on the Combustion Cavity Growth and Stability of the Roof during Underground Coal Gasification*; China University of Mining and Technology: Beijing, China, 2014.
9. Prabu, V.; Jayanti, S. Simulation of Cavity Formation in Underground Coal Gasification Using Bore Hole Combustion Experiments. *Energy* **2011**, *36*, 5854–5864. [CrossRef]
10. Daggupati, S.; Mandapati, R.N.; Mahajani, S.M.; Ganesh, A.; Mathur, D.K.; Sharma, R.K.; Aghalayam, P. Laboratory Studies on Combustion Cavity Growth in Lignite Coal Blocks in the Context of Underground Coal Gasi Fi Cation. *Energy* **2010**, *35*, 2374–2386. [CrossRef]
11. Daggupati, S.; Mandapati, R.N.; Mahajani, S.M.; Ganesh, A.; Pal, A.K.; Sharma, R.K.; Aghalayam, P. Compartment Modeling for Flow Characterization of Underground Coal Gasification Cavity. *Ind. Eng. Chem. Res.* **2011**, *50*, 277–290. [CrossRef]
12. Otto, C.; Kempka, T. Thermo-Mechanical Simulations of Rock Behavior in Underground Coal Gasification Show Negligible Impact of Temperature-Dependent Parameters on Permeability Changes. *Energies* **2015**, *8*, 5800–5827. [CrossRef]

13. Sarraf, A.; Mmbaga, J.P.; Hayes, R.E. Modeling Cavity Growth during Underground Coal Gasification. In Proceedings of the 2011 Comsol Conference, Boston, MA, USA, 25 February 2011; p. 5.
14. Akbarzadeh, H.; Chalaturnyk, R.J. Structural Changes in Coal at Elevated Temperature Pertinent to Underground Coal Gasification: A Review. *Int. J. Coal Geol.* **2014**, *131*, 126–146. [CrossRef]
15. Kapusta, K.; Wiatowski, M.; Jerzy, S.; Stan, K.; Smolin, A.; Rogut, J.; Kotyrba, A. Experimental Simulation of Hard Coal Underground Gasification for Hydrogen Production. *Fuel* **2012**, *91*, 40–50. [CrossRef]
16. Kapusta, K.; Wiatowski, M.; Thomas, H.R.; Zagorščak, R.; Sadasivam, S.; Masum, S.; Kempka, T.; Otto, C.; Basa, W.; Szyja, M.; et al. Experimental Simulations of Methane-Oriented Underground Coal Gasification Using Hydrogen—The Effect of Coal Rank and Gasification Pressure on the Hydrogasification Process. *Int. J. Hydrogen Energy* **2023**, *48*, 921–932. [CrossRef]
17. Liang, J.; Li, Y.; Chen, S.; Yang, Y.; Zhao, Z.; Yuan, H.; Li, Z. Evolution Law of the Characteristic Field of Channel-Type Underground Coal Gasification Process. *J. China Coal Soc.* **2022**, *47*, 2218–2227. [CrossRef]
18. Chen, T.; Shi, X.; Li, J.; Yang, C.; Liu, J.; Li, Y.; Ma, H.; Wang, T. Simulation Test on the Horizontal-Well Leaching of Salt-Cavern Gas Storage. *Oil Gas Storage Transp.* **2019**, *38*, 1257–1264.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.