

Modeling and Control of Energy Conversion during Underground Coal Gasification Process

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1. Introduction

The underground coal gasification (UCG) technology is an unconventional method of coal mining, and its approaches represent new scientific knowledge. This continually evolving technology is a large energy source that can be obtained at a lower cost than convection mining and is also safer. The UCG process transforms the coal's energy into the gas produced (i.e., syngas). The coal is converted into syngas during the underground coal gasification process in the coal seam (i.e., in situ). The gas is produced and extracted by a well drilled into the gasified coal seam. The injection well is used to inject oxidants, i.e., air, oxygen, vapor, or their mixture. The injection well also serves to ignite the coal seam at the beginning of the UCG process. Production wells are used to transport the product gas to the Earth's surface (Figure 1) [1,2]. High-pressure gasification is carried out at a temperature of 700–900 °C, but under certain conditions, a temperature of up to 1500 °C can be achieved [2,3]. The coal is decomposed and mainly produces carbon dioxide (i.e., CO₂), hydrogen (i.e., H₂), carbon monoxide (i.e., CO), small amounts of methane (i.e., CH₄), and hydrogen sulfide (i.e., H₂S) in the UCG process [3,4].



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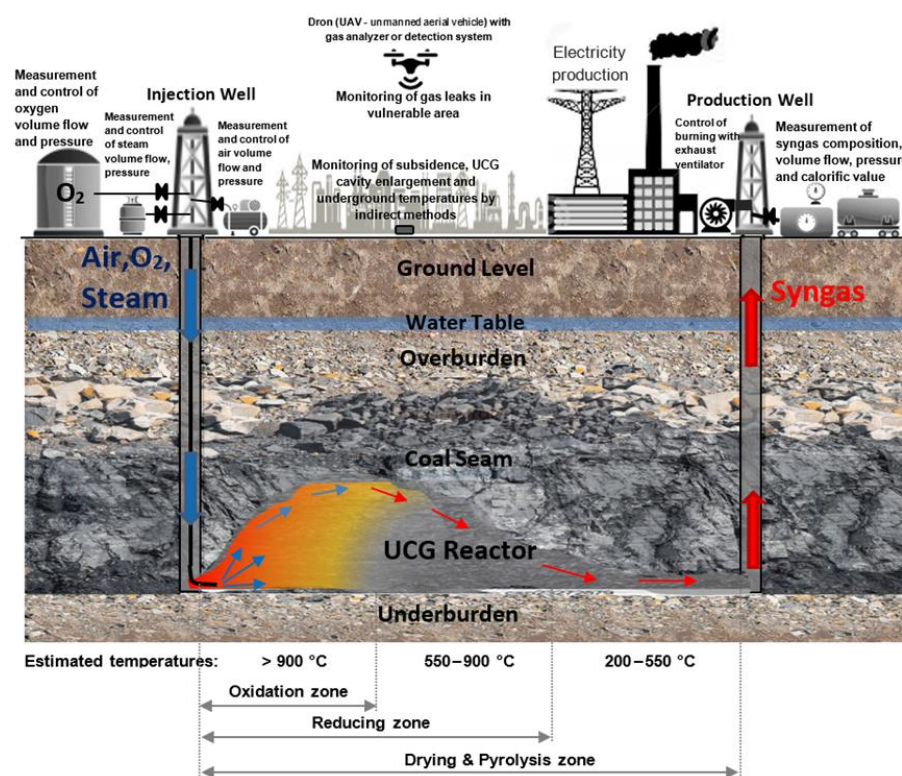


Figure 1. Principle of the UCG process [5].

For successful energy conversion, i.e., obtaining the syngas with a higher calorific value, it is essential to develop new modeling methods and control this process. Modeling methods will make it possible to identify the individual stages of the UCG process more precisely, and thus improve the knowledge of this process. Recently, various UCG models, e.g., models based on CFD, machine models for syngas composition, or temperature prediction, were investigated. By synthesizing suitable algorithms and mathematical models, it is possible to obtain simulation models of the process. These simulation models can be used to design the control systems and the optimal setting of process parameters. In the control of UCG, the significant issue is to ensure sufficient underground temperature and the calorific value of syngas. This issue can be solved by advanced control methods and optimization of operating variables.

This Special Issue (SI) of *Energies* journal focused on the energy conversion processes in underground coal gasification and the modeling and control of this process. A brief review of the articles published in the SI “Modeling and Control of Energy Conversion during Underground Coal Gasification Process” will be presented in the next section.

2. Special Issue Articles’ Short Review

Articles published in *Energies* as a part of this Special Issue can be divided into the three thematic parts of research in the field of underground coal gasification technology. The first part is the impact of technology on the environment, the second is research (studies) the coal areas and coal properties for UCG technology, and the third is the monitoring, modeling, and control of UCG processes.

This study [6] provides an overview of the systematic methods of the in situ coal gasification process. In the paper, it has been presented the model of the porous structure of coal and the gas movement taking place in the carbon matrix, which is part of the bed. The experimental tests were carried out with the use of air forced through the nozzle in the form of a gas stream spreading in many directions in a porous bed under bubbling conditions. The gas flow resistance coefficient was determined as a function of the Reynolds number in relation to the diameter of the gas flow nozzle. The evaluation showed that the models available in the literature have a limited scope of application to skeletal media, characterized by a significant internal structure of the porous material. The test results show that under bubbling conditions, it is possible to accurately assess the gas permeability, which makes it possible to comprehensively assess the properties of the porous material in terms of the process for UCG technology.

The main purpose of the study described in the article [7] was a qualitative and quantitative characterization of the UCG wastewater produced during four different UCG experiments. The experiments were carried out in an ex situ UCG installation located in the Clean Coal Technology Centre of the Central Mining Institute (Mikołów, Poland). One of the most important issues during UCG process is wastewater production and treatment. Condensed gasification wastewater is contaminated by many hazardous compounds. The composition of the generated UCG-derived wastewater may vary depending on the type of gasified coal and conditions of the gasification process. The conducted studies revealed significant relationships between the physicochemical composition of the wastewater and the coal properties, as well as the gasification pressure. The strongest impact is noticeable in the case of organic pollutants, especially phenols, BTEX and PAHs. The most abundant group of pollutants were phenols. The experimental studies have shown that concentrations of phenols, BTEX, and PAHs decrease with increasing pressure.

The conducted research has shown that UCG wastewater contains many hazardous pollutants and requires the selection of an appropriate treatment method, for example, for coking wastewater. The presented results in the paper [7] can help in the development of an appropriate UCG wastewater treatment strategy depending on the coal used and gasification parameters.

Article [8] presents the results of laboratory tests regarding the influence of high temperatures on changes in the strength and structural parameters of rocks that are present

in the immediate vicinity of a gasification channel. Sandstone and claystone samples were heated at 300 °C, 600 °C, 900 °C, and 1200 °C. Additionally, the heated samples were placed in water for 24 h. Strength tests regarding sandstone and claystone were carried out in a hydraulic press at the laboratory of the Faculty of Civil Engineering and Resource Management at the University of Science and Technology in Krakow.

The results of the laboratory tests were used in the numerical simulation using RS2 software. The main goal of modeling was to determine the extent of the rock destruction zone around the gasification channel for dry and wet rock masses. On the basis of the obtained results, it was found that the extent of rock destruction, both in the roof and in the floor, is greater by several percent for a wet rock mass. For the first time, this research presents the effect of water on heated rock samples in terms of the underground coal gasification process. The results of laboratory tests and numerical simulations clearly indicate a reduction in strength, deformation, and structural parameters for the temperature of 1200 °C. Based on numerical results of the research, it can be concluded that, for the width of the gasification channel equal to 10, 20, and 30 m, the maximum extent of rock destruction for dry rock mass does not exceed 5, 10, and 15 m, but an increase in the extent of rock destruction occurs for wet rock mass [8].

Another paper [9] of this Special Issue was focused on the effect of lignite properties on its suitability for the implementation of UCG process. Two experimental simulations of UCG processes, using large bulk samples of lignites, were conducted in a surface laboratory setup. Two different lignite samples were used for the oxygen-blown experiments, i.e., “Velenje” meta-lignite (Slovenia) and “Oltenia” ortho-lignite (Romania). The average moisture content of the samples was 31.6 wt.% and 45.6 wt.% for the Velenje and Oltenia samples, respectively. The main aim of the study was to assess the suitability of the tested lignites for the UCG process. The gas composition and its production rates, as well as the temperatures in the artificial seams, were continuously monitored during the experiments. The average calorific value of gas produced during the Velenje lignite experiment (6.4 MJ/Nm³) was much higher compared to the result obtained for the experiment with Oltenia lignite (4.8 MJ/Nm³). The Velenje lignite test was also characterized by significantly higher energy efficiency, i.e., 44.6%, compared to the gasification of Oltenia lignite (33.4%). The gasification experiments carried out showed that the physicochemical properties of the lignite used considerably affect the in situ gasification process. The results of the study indicate that underground gasification may be a feasible option for the extraction of lignite deposits, especially in the case of Velenje lignite, which was characterized by a relatively higher calorific value, and lower moisture and ash content.

The research presented in paper [10] is based on experimental studies UCG process as in most articles of this Special Issue. The experimental equipment is designed and patented at Dnipro University of Technology, and manufactured by Naftomash RMA under financial support of the Ministry of Education and Science of Ukraine. A gas generator model consists of four systems:

- An experimental stand;
- A system of supply of separated and mixed blow mixture;
- A gas outlet system;
- A system of control and measuring equipment (temperature control and control of input and output gas mixtures).

This paper represents the results of experimental studies of physical modeling of the underground coal gasification process in terms of implementation of design and technological solutions aimed at intensification of a gasification process of thin coal seams. A series of experimental studies were performed in terms of a stand unit with the provided criteria of similarity to field conditions as well as the kinetics of thermochemical processes occurring within a gas generator. Hard coal (high volatile bituminous coal) was selected as the raw material to be gasified, as that coal grade prevails in the Ukrainian energy balance, since it is represented by rather great reserves. Five blow types were tested during the research (air, air–steam, oxygen–steam, oxygen-enriched, and carbon dioxide and oxygen). As a result,

the effect of the tightness of a gas generator on the quantitative and qualitative parameters of coal gasification while varying the blow by reagents and changing the pressure in a reaction channel has been identified. Special attention was paid to the design solutions involving blow supply immediately into the combustion face of a gas generator. The experimental results demonstrate maximum efficiency of the applied gas generator design involving flexible pipelines and activator in the reaction channel and a blow direction onto the reaction channel face combined with blow stream reversing, which will make it possible to improve calorificity of the generator gas up to 18% (i.e., from 8.4 to 12.8 MJ/m³ depending upon a blow type). Consideration of the obtained results of physical modeling can be used with sufficient accuracy to establish modern enterprises based on the underground coal seam gasification; this will help develop more efficiently the substandard coal reserves to generate heat energy as well as power-producing and chemical raw material. The research conclusions can provide technical references for developing a new generation of UCG technology [10].

Paper [11] researches the possibility of the model's utilization for temperature prediction in UCG process. Within experimental research, several regression models were proposed that differed in their structures, i.e., the number and type of selected controllable variables as independent variables. The goal was to find an optimal regression model structure, where the underground temperature is predicted with the greatest possible accuracy. The regression model structure proposal was realized on data obtained from two laboratory measurements realized in the ex situ UCG reactor. These experiments differed by the volume of gasified coal and thus also in the duration of the experiment. The proposal of regression coefficients was performed on the data from the first experiment, but the verification of the proposed regression models was performed mainly on the data from the second experiment. The results of temperature models were evaluated using the multiple coefficient of determination R^2 . The values of this coefficient were during the verification of models on the second experiment lower than their values in the first experiment. The maximum value of the multiple coefficient of determination was reached at the temperature T_8 ($R^2 = 0.87$). The behavior of the measured and predicted temperature T_8 by the model is shown in Figure 2.

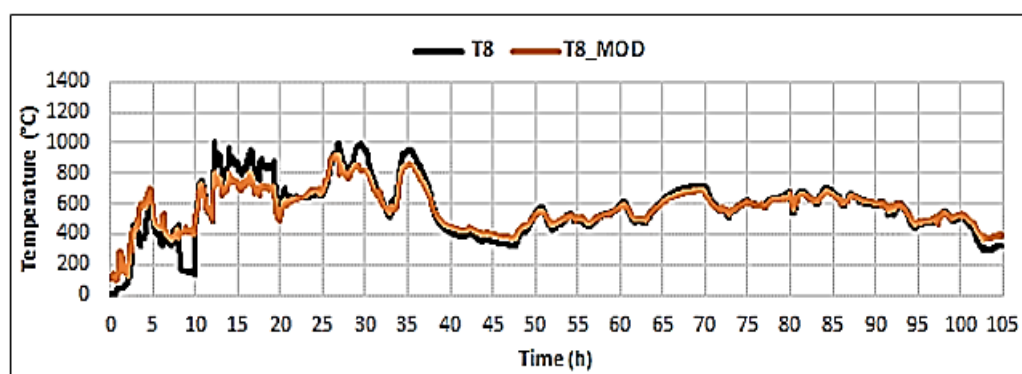


Figure 2. The measured (T) and modeled (T_{MOD}) temperature behavior [11].

The proposed models should contribute to developing a methodology for predicting temperatures in a gasified coal seam. Improving the prediction of these temperatures with higher accuracy makes it possible to identify places in the coal seam where coal to gas is transformed, and the underground cavity is formed. In addition, the prediction of coal seam temperatures allows the development of methods to control the UCG process based on modeled temperatures in the coal seam [11].

Paper [12] presents an experimental study of optimization of operating variables (airflow, oxygen flow, and syngas exhaust) during gasification in ex situ reactor. Optimization aims to maximize syngas calorific value. The proposed optimization algorithm was based on a simple gradient method that optimizes by experimental way of operating

variables. The novelty and originality of the proposed solution of UCG control rests on a model-free approach. This approach of automated control of UCG process to maximize calorific value has not been investigated to date. Most of the research in the world focuses on the model-based stabilization of calorific value and mathematical modeling of UCG processes. However, research is lacking in improving the direct automated control of the UCG process that is often controlled only blindly.

The proposed control algorithm has been implemented on a PLC; it does not require a process model, and only online measured process data are needed. The algorithm, in four tests, was able to increase the calorific value by optimizing the operating variables. Better algorithm performance, i.e., higher syngas calorific value, was achieved by optimizing three operating variables, i.e., when additional oxygen flow was optimized [12].

Article [13] investigated the possibility of using coal in situ, using UCG technology. The authors of the paper focused on verified geological, hydrogeological, and tectonic information about the selected brown coal deposit in Slovakia. Based on the analysis and obtained information, possible adverse factors were evaluated. These factors affect the rock environment around the underground generator by UCG activity. The article also draws attention to the possible impact of pollution, taking into account the geological, hydrogeological, and tectonic conditions in the selected locality. Attention was focused on pollution from UCG process after experimental gasification, taking into account the amounts of gasified coal based on analyses of tar.

3. Conclusions

The articles presented in the Special Issue “Modeling and Control of Energy Conversion during Underground Coal Gasification Process” reflect current research trends in the field of underground coal gasification. Most of the results reported in the articles are based on experiments performed in laboratory conditions (ex situ reactor). These experiments are significant for verifying the technology and its implementation in real conditions. Based on experiments in laboratory conditions, the following is possible:

- Assess the suitability of the coal deposit for UCG technology;
- Assess the impact of UCG technology on the environment;
- Design and verify mathematical models that can use for the control and optimization of the UCG process.

We firmly believe that the articles presented in the Special Issue will help in the advancement of UCG technology and will be an inspiration for experts in this field.

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