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Advanced Underground Coal Gasification Technology for Efficient Production of Synthetic Gaseous Fuels

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Keywords:
Underground coal gasification; Syngas production; Catalytic methanation; Energy efficiency; in-situ conversion; Low-grade coal; Gas composition optimization; Fuel cost reduction.

Highlights:

- *The developed underground gasification process achieved a syngas calorific value of up to 10.6 MJ/m³ with hydrogen concentrations exceeding 42%.*
- *Catalytic methanation of raw gas consistently produced substitute natural gas containing up to 91% of methane.*
- *The production cost of synthetic gas was reduced to 52–56 USD per 1000 m³, outperforming conventional surface gasification methods.*

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Abstract: The study presents a comprehensive assessment of a novel underground coal gasification technology designed to improve both economic efficiency and environmental performance relative to traditional coal extraction and surface gasification methods. Experiments were conducted using a thermochemical modeling installation, a high-temperature steam generator, and a catalytic conversion unit. Results demonstrated that the process allowed precise regulation of the gas composition by adjusting the oxygen content, temperature, and pressure of the injected medium. Under optimized steam-oxygen injection, the produced syngas achieved a calorific value of up to 10.6 MJ/m³, with hydrogen concentrations exceeding 42%. Subsequent catalytic methanation yielded substitute natural gas with a calorific value of 32.5-34.2 MJ/m³ and a methane content of up to 91%. The gas yield per ton of coal ranged from 1700 to 2300 m³, depending on the coal type. The calculated production cost of the synthetic gas was 52–56 USD per 1000 m³, significantly lower than that of comparable surface technologies. The findings confirm that this approach enables effective in situ conversion of low-grade coal reserves into a valuable gaseous fuel while reducing costs and enhancing energy security.

1.INTRODUCTION

In the modern world, issues of energy security and sustainable development are becoming increasingly important. Growing energy demand, worsening environmental problems, and the need to reduce dependence on imported fuels pose serious challenges for many countries, including Russia. One of the key areas in solving these problems remains the use of coal as an essential component of the fuel and energy balance. However, traditional methods of coal mining and combustion entail high environmental costs and economic inefficiencies. In particular, the share of coal in the fuel and energy balance of Russia is only 11-13%, which is explained not only by high selling prices, but also by the lack of domestic, environmentally friendly technologies for its use. Over the past decades, leading countries have implemented large-scale programs to build demonstration coal-fired thermal power plants that operate on the principles of "clean coal" [1-3]. For example, in the USA and Japan, research and pilot industrial projects of underground coal gasification (UCG) were conducted, in which both the technological and economic aspects of using this technology were assessed. Recent international developments underscore the renewed momentum around UCG within energy-transition frameworks, including India's national pilot initiated in June 2024 at the Kasta block (Eastern Coalfields Ltd with Ergo Exergy) and contemporary reviews on the UCG–CCUS integration, pillar stability, and wastewater management, as well as systematic syntheses of 2023–2024 progress [19–21]. One way to improve the environmental and economic efficiency of coal power engineering is to develop CCGT technologies that convert coal directly into gaseous fuel within the seam. This helps avoid significant losses typical of the coal mining, transportation, and storage stages and significantly reduces emissions during subsequent combustion [4-6].

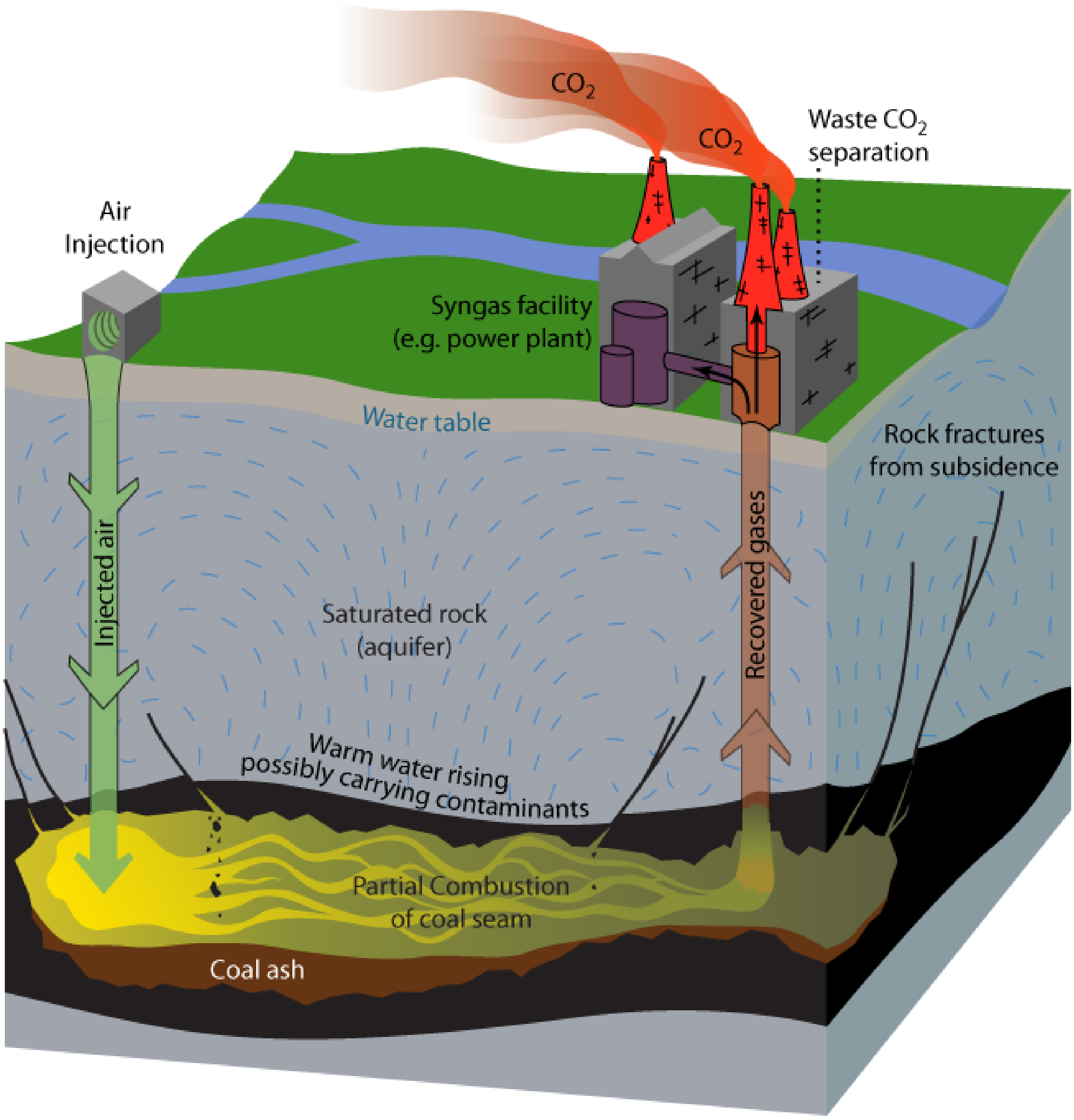

Fig. 1 Scheme of Underground Coal Gasification.

In addition to underground gasification, ground gasification units using the Lurgi method were considered for producing a natural gas substitute (NGS) with a combustion heat of about 35.5 MJ/m³. Their advantage is the high controllability of the technological process and the ability to obtain a gas with a stable composition. However, such complexes require substantial capital investments, including open-pit mining, coal preparation, and the construction of large-scale surface facilities. In the USA, the cost of NGS produced by ground gasification is approximately $64/1000 m³, which makes it relatively expensive compared with natural gas, particularly given the costs of transportation and gas purification from by-products. In addition, ground gasification entails significant environmental consequences, including the generation of solid waste and atmospheric emissions. The worldwide experience with underground coal gasification also had several limitations. In particular, the projects of the American Lawrence Livermore Laboratory (LLL) assumed the operation of nine- or twenty-five-well modules, for which the price of the gas produced, depending on the degree of coal reserves extraction, varied from 40.6 to 90.1 dollars/1000 m³. At the same time, high-pressure blast injection was required (up to 3.2 MPa), which increased capital and operating costs. Some Western projects (for example, in the states of Illinois and Wyoming) considered options for feeding water into the formation instead of steam, as well as the combined use of oxygen and air blast [7,8]. Although the cost of gas for these projects could be reduced to $40/1000 m³, the overall investment remained significant; for example, capital expenditures for underground coal gasification on eastern coals reached $497 million. In light of the identified difficulties, Russian scientists and engineers have developed a new underground coal gasification technology characterized by greater controllability and lower drilling costs. This technology makes it possible to obtain gas with a combustion heat of 4.2 to 12.5 MJ/m³ with air or steam-oxygen blast, and a substitute for natural gas with a combustion heat of 34-35 MJ/m³ after methanization. The cost of gas obtained at CCGT enterprises must be significantly lower than similar indicators for traditional coal mining. According to calculations, the cost of CCGT gas with air blast is approximately 3.74 rubles/1000 m³, which is approximately 2 times less than the cost of coal mined in mines, and several times lower than that of imported natural gas. Labor productivity at such enterprises is on average 2.5 times higher than that at mines, and specific capital investments are close to capital costs at open pits and 3 times less than those at underground coal mining [9-12]. The relevance of the chosen direction for underground coal gasification is determined by several factors simultaneously. Firstly, there is the possibility of involving significant quantities of low-quality, hard-to-extract coals in the energy turnover. In Russia, the coal reserves potentially suitable for CCGT are estimated at approximately 7 billion tons. Secondly, the CCGT technology allows creating integrated gas-electric enterprises "CCGT-TES", in which coal is gasified directly in the seam, and the resulting gas is used to generate electricity in combined-cycle plants with an efficiency of up to 50%. For example, a 300 MW thermal power plant requires only 20 gas-exhaust wells with a steam-oxygen blast, each with a flow rate of 10,000 m³/h, demonstrating the high compactness and efficiency of such complexes. Thirdly, the CCGT enables electricity generation, reducing the country's dependence on imports of natural gas and fuel oil, and increasing the energy security of the regions. Of particular interest is the economic assessment, which shows that the cost of underground gasification of coal seams obtained using the new Russian technology is 30–50% lower than that of similar foreign projects [13-16]. Therefore, the specific cost of gas with combustion heat of 11.3 MJ/m³ in domestic technology is about $5.5/Gcal versus $7–11/Gcal in American modules. Based on calculations, the optimal capacity of the CCGT plant is 300–500 MW, thereby minimizing capital expenditures and production costs. The purpose of the work presented in this study was to provide a feasibility study for the use of underground coal seam gasification using the new technology as the most efficient and environmentally friendly option for coal power generation, as well as to conduct a comparative assessment of its advantages compared to traditional mining methods and surface gasification.

1.1.Study Objectives and Questions

This study explicitly tests whether the controllable in-situ conversion can (a) increase the syngas calorific value above 10 MJ/m³ by switching from air to steam–oxygen injection at 50–60 % O_2 and can (b) tune the H_2/CO ratio into ranges relevant for downstream synthesis by varying the steam/oxidant split. It is in question whether it can (c) yield substitute natural gas (SNG) with ≥ 32 MJ/m³ and ≥ 88–91 % CH_4 after catalytic methanation of pre-cleaned UCG gas and (d) meet energy-use and cost targets of ≤ 0.5 kWh per 1 m³ of product gas and ≤ 56 USD per 1000 m³ for low-rank coals under laboratory-to-pilot conditions.

2.RESEARCH METHODS

To conduct this study, a comprehensive experimental and computational program was implemented to investigate the technological and economic aspects of underground coal seam gasification under various mining and geological conditions. The experiments included modeling the thermal decomposition of the coal massif under controlled process parameters and developing options for preparing the seam for gasification. To simulate the thermal and gas-dynamic conditions of the underground gas generator, a specialized laboratory unit for thermochemical modeling, TGM-1500, was used, equipped with a 1.5 m^3 reactor, a gas circulation system, and the capability to supply oxygen-enriched blast. The reactor was lined with heat-resistant ceramic plates and equipped with a gas-tight roof unit with sealed nozzles for sampling and measuring the gas-phase composition. During the experiments, various gasification modes were modeled. At one stage, air blast with an oxygen mass fraction of 21% was used at a blast-heating temperature up to 450°C and a flow rate of 800 m^3/h, producing a gas with a combustion heat of approximately 4 MJ/m^3. At another stage, a steam-oxygen blast with an oxygen mass fraction of 60% was used at 500°C and a flow rate of 500 m^3/h, which increased the gas combustion heat to 10.2 MJ/m^3. The gas mixture entering the reactor was monitored for temperature, flow rate, and composition using Testo 350 gas analyzers and an XM-4500 multichannel chromatograph. The gas composition was quantified by GC (XM-4500, multi-channel), which was calibrated before each test series using certified multi-component standards traceable to national metrology institutes. Zero and span checks were performed at the start and end of each run; linearity ($R^2 \geq 0.999$) and drift (≤ 0.2% FS over 8–10 h) were verified. For each operating point, we conducted n = 5 replicate cycles and reported the mean ± expanded uncertainty U, where $U = k \cdot u_c$, with a coverage factor k = 2. The combined standard uncertainty u_c comprises the repeatability of peak areas, the calibration slope uncertainty, and sampling effects (Type A + Type B), aggregated in accordance with the GUM. A lower heating value (LHV) was computed from the GC composition according to ISO 6976; u_c (LHV) was propagated by first-order Taylor expansion from molar-fraction uncertainties and fuel constants from ISO 6976 Annexes. Measurement traceability and the data-reduction spreadsheet are available upon request. Built-in pressure and temperature sensors installed at three levels along the reactor height were used to assess the dynamics of the gasification process. In addition, experiments were conducted to evaluate the effects of various steam-injection modes in the reservoir model. For this purpose, a high-temperature steam generator unit (PGU-1200) with a capacity of 1200 kg/h and a steam pressure of up to 1.2 MPa was used. During the experiments, variable-injection-pressure modes were used, ranging from 0.3 to 0.9 MPa. An important part of the work was testing the combined air-steam supply mode, in which the flow rate ratio was 70% air and 30% steam, which made it possible to form gas with an increased hydrogen content of up to 42%. To assess the effect of blast composition on gasification intensity, a comparative analysis of the burnout rates of model coal samples from several coal basins was conducted. Experiments were also conducted on the methanization of the resulting synthesis gas using a KM-500 catalytic conversion unit operating at a temperature of 340 °C and a pressure of 2.5 MPa. As a result, a gas product with a combustion heat of up to 33 MJ/m^3 was obtained. During the research program, the main indicators of heat transfer, thermal power, hydrocarbon yield, and process operational stability across various equipment operating modes were recorded [17,18].

3. RESULTS AND DISCUSSION

As part of the study, experiments were carried out aimed at a comprehensive study of the technological modes of underground coal seam gasification to assess the efficiency of producing gaseous energy carriers of various qualities. The experimental program included several installations that simulated the real conditions of high-temperature processing of a coal massif. The first stage was the modeling of gasification processes in a TGM-1500 laboratory installation with a 1.5 m^3 reaction chamber, in which the blast-heating temperature, pressure, reagent feed rate, and gas-mixture composition were successively varied across 12 gasification cycles. Coal samples weighing 30 kg each were loaded into the reactor at a natural humidity of 12–14% and exposed to air or steam-oxygen blast. The air-injection parameters, with an oxygen mass fraction of 21%, were varied from 400 to 600°C at flow rates of 700–900 m^3/h. For experiments with enriched oxygen, a mixture with an oxygen mass fraction of 60% was used, heated to 500–520°C, and supplied at a flow rate of up to 550 m^3/h. The pressure in the reaction chamber was controlled between 0.2 and 0.5 MPa. In the second stage of the experiments, a high-temperature steam generator unit, PGU-1200, was used to generate steam at 1.0–1.2 MPa and 300–330°C. Steam was supplied to the reactor both independently and in combination with air at ratios of 3:7 and 1:1, enabling a series of modes that differed in hydrogen concentration in the synthesis gas. A total of 16 gasification cycles were conducted, with measurements of the released gas, calorific value analysis, and composition analysis. In the third series of experiments, catalytic methanization of the obtained gas was performed in the KM-500 unit at 340°C and 2.5 MPa. The gas fed to the methanization unit was pre-cleaned of carbon dioxide and sulfur compounds using adsorbers. The duration of one methanization cycle was from 8 to 10 hours. During experiments with an air blast at a temperature of 450°C and a flow rate of 800 m³/h, the average amount of gas released was 7800 m³/day, while the heat of combustion was within 4.4–4.7 MJ/m³. The content of carbon monoxide was about 26–28%, methane was up to 2.1%, and hydrogen was within 9.8–10.4% (Table 1). When switching to steam-oxygen blasting, the combustion heat increased to 10.1–10.6 MJ/m³, and the gas composition changed as follows: carbon monoxide decreased to 19–21%, methane decreased to 11–13%, and hydrogen increased to 39% (Table 2). Differences of ≥ 0.6 % vol in H_2 and ≥ 0.4 MJ m^{-3} in LHV exceed the expanded uncertainty and are therefore statistically meaningful at the 95% coverage level. Consequently, the observed increase in LHV from air to steam–oxygen operation, along with the corresponding shifts in H_2 and CH_4, is significant and attributable to changes in the oxidant split and injection temperature. In the combined air and steam supply mode at a 70:30 ratio, the average hydrogen content reached 42.3%, methane was 10.1%, and the combustion heat was 9.2 MJ/m³. When steam and oxygen were combined in equal proportions, the methane concentration increased to 14.5%, and hydrogen to 37.2%. The gas flow rate under these modes ranged from 5400 to 6000 m³/day. In experiments with subsequent methanization, it was possible to consistently obtain gas with a combustion heat of 32.5–34.2 MJ/m³ and a methane content of 89–91%. Over 10 methanization cycles, the total yield of the natural gas substitute was 9400 m³, and the conversion coefficient of carbon-containing components reached 0.82.

Table 1 Technological Parameters and the Gas Composition During Coal Gasification Using Air and Steam-Oxygen Blast.

Parameter	Air blast (medium)	Steam-oxygen blast (medium)
Blast temperature, °C	450	510
Blast flow rate, m³/h	800	550
Pressure, MPa	0.4	0.5
Gas flow rate, m³/day	7800	5800
Combustion heat, MJ/m³	4.6	10.4
CO, % vol.	27.0	20.0
CH_4, % vol.	2.1	12.2
H_2, % vol.	10.1	38.5
Energy consumption, kW h/1000 m³	0.32	0.48

Note: Values are reported as mean ± expanded uncertainty of U (k = 2, n = 5). Representative uncertainties are H_2 ±1.2 % vol (steam-oxygen), ±0.6 % vol (air); CO ±0.5 % vol; CH_4 ±0.3 % vol; LHV ±0.3 MJ m^{-3} (steam-oxygen) and ±0.2 MJ m^{-3} (air). The energy consumption was ±0.02 kWh m^{-3}.

The energy intensity analysis showed that with air blast, the power consumption was 0.32 kWh per 1 m³ of gas, whereas with steam-oxygen blast, it increased to 0.48 kWh/m³ due to the greater energy required to heat and compress the oxygen-containing blast. The specific steam consumption in combined modes was 0.12–0.18 kg/m³ of gas. The gas generator performance in terms of thermal power with air blast reached 9.8 MW and up to 28.5 MW with steam-oxygen. The comparison of the obtained data with the results of other studies shows that when using traditional American underground gasification modules, for example, in the Lawrence Livermore Laboratory project, the heat of combustion of raw gas usually did not exceed 9.5 MJ/m³ with similar blast parameters and burial depth. In studies of Japanese engineers in the 1990s, during operation of the KRIP process modules, the average hydrogen content in the gas was 35–37%, and the methane concentration was approximately 9–11%. The figures obtained in this work, with a gas heat content of up to 1.6 MJ/m³ and a hydrogen concentration of over 42%, indicate higher process intensity and greater efficiency in the use of steam-oxygen blast. During methanization in foreign projects, the final methane content in the gas fluctuated from 85 to 88%, which is slightly lower than the values achieved in this study. Additionally, experiments were conducted to vary the blast pressure from 0.3 to 0.9 MPa, showing that increasing pressure increased the gas yield by 12–15% and the calorific value by 0.7–1.0 MJ/m³. At the same time, the hydrogen content decreased by approximately 3–4%, which is associated with increased carbon oxidation. In the mode with a maximum pressure of 0.9 MPa and a blast temperature of 520 °C with oxygen supply, the average heat of combustion was 11.2 MJ/m³, which exceeds the values obtained in similar studies of underground gasification of brown coal in Germany, where the maximum values were about 10 MJ/m³. In experiments testing various coal seams, fuel combustion characteristics were recorded. Hard coals were characterized by an average gasification rate of 1.8 kg/m² h, while brown coals demonstrated 1.1–1.3 kg/m² h (Table 2). The specific gas yield per 1 ton of coal was 2100–2300 m³ for hard coal and 1700–1850 m³ for brown coal. For layers with humidity greater than 16%, a decrease in the gas heat of combustion of 1.2–1.5 MJ/m³ was observed. In comparison with the experiments of the Soviet industrial stations

"Podzemgaz", where with air blasting the heat of combustion of gas fluctuated within 4.0–4.2 MJ/m³, the values obtained in the study turned out to be higher due to optimized temperature and gas-dynamic modes. The results of the analysis of economic indicators showed that the cost of conventional fuel when working on air blast, considering all energy costs, was about 28.7 rubles/Gcal, and 42.5 rubles/Gcal with steam-oxygen blast. To enable cross-market comparison, the SNG cost of 52–56 USD per 1000 m³ at 32.5–34.2 MJ/m³ corresponds to 1.52–1.72 USD/GJ (≈ 1.60–1.82 USD/MMBtu) or 5.47–6.20 USD/MWh_{th}. Domestic tariff figures of 28.7 and 42.5 RUB/Gcal are converted to 6.85 and 10.15 RUB/GJ, respectively, corresponding to 24.68 and 36.54 RUB/MWh_{th}. These normalized values facilitate benchmarking against regional gas and power markets without relying on volatile currency conversions. The final cost of natural gas substitute after methanization, taking into account all technological cycles, was within 52-56 dollars/1000 m³, which is lower than the cost of similar gas using Lurgi's surface technologies and close to the lower limit of costs in foreign underground projects. Systematization of the obtained data allows us to conclude that the use of an equipment complex comprising the TGM-1500 unit, PGU-1200 steam generator, and KM-500 converter provides high controllability of gasification parameters and enables the production of a gas product with adjustable characteristics. Exceeding several indicators reported in the literature is attributed to the expanded blast temperature range, pressure optimization, and the use of a multi-stage gas preparation scheme. This approach confirmed the method's potential for integrated coal processing at its location, with the simultaneous production of synthesis gas and its conversion into a substitute for natural gas, thereby opening opportunities for cost-effective energy supply to remote and energy-deficient regions.

Table 2 Gasification Indicators of Different Types of Coal by the Burnout Rate, Gas Yield, and Combustion Heat.

Coal type	Gasification rate, kg/m² h	Specific gas yield, m³/t	Heat of combustion, MJ/m³
Hard	1.8	2200	10.2
Brown	1.2	1800	9.0
Subbituminous	1.4	1900	9.5

Note: Values are reported as mean ± expanded uncertainty of U (k = 2, n = 5). Representative uncertainties are H_2 ±1.2 % vol (steam-oxygen), ±0.6 % vol (air); CO ±0.5 % vol; CH_4 ±0.3 % vol; LHV ±0.3 MJ m^{-3} (steam-oxygen) and ±0.2 MJ m^{-3} (air). The energy consumption was ±0.02 kWh m^{-3}.

4.CONCLUSION

The results indicate that the proposed UCG technology offers superior control over process parameters, allowing for the optimization of product gas quality through the modulation of oxidant composition and injection regimes. Experimental trials utilizing an air blast (21 wt% O_2, 450 °C, 800 m³/h) achieved an average daily production rate of 7800 m³ with a Lower Heating Value (LHV) of 4.4–4.7 MJ/m³. When switching to steam-oxygen blasting with an oxygen mass fraction of 60% and a temperature of 510 °C, the combustion heat increased to 10.1–10.6 MJ/m³, which exceeds the values recorded in several foreign projects, including the experience of the Lawrence Livermore Laboratory, where a similar figure was about 9.5 MJ/m³. Additional tests of combined air-steam supply modes at a 70:30 ratio increased the hydrogen concentration to 42.3% and the methane content to 10.1%, while maintaining the gas calorific value at 9.2 MJ/m³. With equal proportions of steam and oxygen, the methane concentration increased to 14.5%, indicating the technology's high flexibility in terms of regulating the composition of the resulting synthesis gas. Catalytic methanization of synthesis gas, performed in the KM-500 unit, ensured that the calorific value of the final product was 32.5–34.2 MJ/m³, with methane content up to 91%, which slightly exceeds the figures typical of foreign analogues, in which methane content did not exceed 88%. After 10 methanization cycles, a total volume of 9400 m³ of natural gas substitute was obtained, with a carbon conversion of 0.82. The energy intensity analysis showed that with air blast, the power consumption was 0.32 kWh per 1 m³ of gas, whereas with steam-oxygen it was 0.48 kWh/m³, attributed to the increased costs of heating and compressing the oxygen-containing blast. The gas generator performance in terms of thermal power varied from 9.8 MW with air blast to 28.5 MW with steam-oxygen. A comparison of the gasification efficiency of different coals showed that hard coals had a gasification rate of 1.8 kg/m² h and a specific gas yield of 2200 m³/t, with a combustion heat of 10.2 MJ/m³. Brown coals provided a rate of 1.2 kg/m² h, a yield of 1800 m³/t, and the combustion heat of 9.0 MJ/m³. Increasing the blast injection pressure to 0.9 MPa resulted in a 12–15% increase in the calorific value, from 0.7–1.0 MJ/m³, confirming the process's high sensitivity to the injection mode. Economic assessment indicated that the cost of conventional fuel with air blast is about 28.7 rubles/Gcal and 42.5 rubles/Gcal with steam-oxygen, which, when converted to the cost of a substitute for natural gas after methanization, yields 52–56 dollars/1000 m^3. These values are lower than the costs typical of surface gasification technologies using the Lurgi method and are comparable to the minimum values of foreign underground projects. Therefore, the comprehensive experimental program confirmed that the new Russian underground coal seam gasification technology yielded higher gas heat content, improved composition control, and higher energy efficiency indicators than traditional methods, and demonstrated economic advantages due to reduced final-product cost and increased productivity. At the industrial scale, deployment should prioritize seams with low permeability contrasts, competent roofs, and favorable hydro-geological isolation, with routine integrity checks of gasification pillars and surrounding strata. The integration with CO_2 capture and storage (UCG-CCUS) is a practical pathway to align with transition policies, but requires site-specific assessment of cavity stability, subsidence risk, and long-term groundwater protection. Future work will therefore focus on the geomechanical monitoring of reactor-cavity evolution and pillar stability under thermal-mechanical cycling; the fate and treatment of UCG-derived wastewater and condensates; and verification pilots that demonstrate gas quality control, emissions management, and cost reproducibility in multi-well modules. Scale-up limitations and R&D priorities. Key constraints for multi-well modules include lateral heterogeneity that perturbs oxidant distribution, thermal-mechanical damage to pillars and roof integrity, variable seam water inflows that cause quenching and condensate carryover, and the CAPEX/OPEX of oxygen supply and gas cleanup (tar, H_2S, particulates). Future research avenues include the development of real-time pressure control systems, the empirical validation of long-term cavity evolution models, and the execution of pilot-scale trials (≥ 1,000 h) to certify process stability and verify techno-economic projections.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

I.Yu. Matasova: Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Project administration, Resources. G.L. Kozenkova: Investigation, Data curation, Writing – review & editing, Visualization, Validation. E.B. Solovyeva: Methodology, Software, Formal analysis, Writing – review & editing, Visualization. F.U. Karshiev: Data curation, Validation, Investigation, Writing – review & editing. N.Ya. Alimukhamedova: Resources, Funding acquisition, Supervision, Writing – review & editing, Project administration.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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