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High-Temperature Plasma-Chemical Conversion of Low-Grade Coal and Hydrocarbon Gases into Synthesis Gas and Value-Added Products

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Keywords:
Plasma gasification; Coal conversion; Hydrogen production; Acetylene synthesis; Plasma cracking; Carbon nanotubes; Energy efficiency; Low-grade coal.

Highlights:

- *Plasma-steam gasification achieved up to 98.3% carbon conversion, with synthesis gas containing over 95% CO and H2.*
- *The plasma cracking of hydrocarbon gases produced technical carbon with a surface area of 450 m^2/g and greater than 70% nanotube content.*
- *The energy consumption for plasma gasification was reduced to 1.8 kWh per kilogram, being significantly lower than that of conventional methods.*

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Abstract: This study presents an experimental evaluation of plasma-chemical technologies for converting low-grade coals and hydrocarbon gases into valuable products. High-temperature plasma-assisted processes, including gasification, hydrogenation, and cracking, were investigated using an industrial-scale electric arc reactor capable of operating at temperatures up to 3200 K. Plasma-steam gasification experiments achieved carbon conversion of 98.3% and synthesis gas yields with combined CO and H2 concentrations exceeding 95%. Plasma hydrogenation at 3000–3200 K produced gas mixtures containing up to 38.7% acetylene and 19.5% ethylene, confirming the efficiency of direct coal conversion to unsaturated hydrocarbons. Plasma cracking of hydrocarbon gases produced hydrogen concentrations up to 24% and the formation of highly dispersed technical carbon with a specific surface area of 450 m^2/g and over 70% nanotube content. The energy consumption for gasification was as low as 1.8 kWh/kg, demonstrating a significant reduction compared to conventional technologies. The results highlight the technological and environmental advantages of plasma-chemical processing in achieving deep conversion of carbonaceous feedstocks with reduced emissions and high-value product recovery.

1.INTRODUCTION

In the modern world, the efficient use of fuel resources is becoming increasingly important globally. According to forecasts, organic fuels will remain the primary energy source in the 21st century. For example, the share of coal in electricity production today is 40%, and in thermal energy it is 24%. At the same time, low-grade coals with high ash content and low calorific value, for example, 13180-16632 kJ/kg, are becoming increasingly important in the energy balance, which significantly complicates their efficient use without a negative impact on the environment. In addition to coal, the global fuel complex still largely depends on hydrocarbon feedstocks, whose reserves are gradually depleting. The problem is further exacerbated by the slowdown in the development of alternative energy sources, particularly nuclear energy, which increases the burden on traditional fuel processing and combustion technologies [1,2]. In response to these challenges, various fuel conversion technologies have been proposed over the past decades. Among these, we can highlight traditional coal combustion, catalytic gasification, multi-stage hydrogenation, and pyrolysis, each followed by product processing. Each of these areas has its own advantages and disadvantages. Therefore, direct combustion of fuel is relatively simple and has low capital costs, but is accompanied by emissions of nitrogen oxides, sulfur, and ash in significant quantities: the concentration of pollutants can reach hundreds of mg / Nm^3, which makes such technologies less and less acceptable from an environmental point of view [3,4]. Catalytic gasification allows the production of synthesis gas: a mixture of hydrogen and carbon monoxide, suitable for subsequent chemical synthesis or as an energy fuel, but this process usually occurs at relatively low temperatures and is accompanied by complex multi-stage reactions that require costly catalysts and careful control of conditions. Hydrogenation of coal to liquid and gaseous hydrocarbons, first widely used in the 20th century, is characterized by high yields of valuable products but is extremely energy-intensive and has complex equipment. For example, traditional coal hydrogenation processes require multi-stage purification, compression, and high-pressure hydrogen supply, which significantly increases the cost of the resulting product [5-8]. Pyrolysis and partial gasification of coal at a temperature of 800–1200 K make it possible to obtain combustible gases and coking residue, but the degree of the organic matter conversion under such conditions does not exceed 30%, and specific energy consumption is 0.05–0.4 kWh/kg of fuel. Against this background, plasma-chemical fuel-processing technologies stand out for several fundamental advantages. Firstly, a high temperature (1600-3200 K) is provided in the plasma environment, which makes it possible to completely gasify or modify carbon-containing materials in a very short time: from fractions of a second to several seconds. With plasma-steam gasification, the carbon conversion rate reaches 90–100%, while the concentrations of nitrogen and sulfur oxides in the exhaust gases are reduced to record low values of no more than 20 mg/Nm^3, which is 5–10 times lower than those with traditional combustion [9-12]. For example, the experiments on plasma-steam gasification of low-grade brown coal conducted in the work showed a carbon gasification rate of 92.3% at a temperature of 3100 K and specific energy consumption of about 5.36 kWh/kg, which made it possible to obtain synthesis gas with a volume concentration of CO of 45.8% and H_2 of 49.4%. Another direction is the plasma-chemical cracking of hydrocarbon gases. This technology is distinguished by the fact that, at 1500–2500 K, two valuable products are produced in a single process: hydrogen and carbon black. In particular, when processing a propane-butane mixture, a hydrocarbon gas conversion rate of 98–100% is achieved with specific energy consumption of 2.2–3.8 kW h/kg. Of particular interest are the results of the analysis of condensed carbon, in which colossal carbon nanotubes with diameters up to 400 nm and lengths exceeding 5 μm were identified, exhibiting unique mechanical properties: the strength of such structures is 30 times that of Kevlar fabric. It is also worth noting the plasma-chemical hydrogenation of coal, i.e., a process that allows direct production of acetylene and other unsaturated hydrocarbons without the use of multi-stage schemes [13-16]. At 2800–3200 K and a specific energy consumption of 6.5–8 kWh/kg, carbon conversion ranges from 70% to 100%. The experiments have shown that with a coal consumption of 3 kg/h and a propane-butane mixture of 150 l/h, it is possible to obtain up to 50% of ethane, 30% of acetylene, and 10% of ethylene in the gas phase, which confirms the possibility of obtaining valuable hydrocarbons from cheap, low-grade coal. Therefore, plasma-chemical technologies for processing solid and gaseous fuels enable simultaneous solutions to the problems of increasing the depth of organic matter conversion, minimizing emissions of toxic components, and producing valuable products: synthesis gas, hydrogen, technical carbon, and hydrocarbon gases. With the global trend toward declining coal quality, declining oil and gas reserves, and tightening environmental requirements, these technologies are becoming increasingly relevant [17,1]. The universality of the approach also determines its importance: by varying the oxidizing environment (air, steam, hydrogen) and temperature conditions, it is possible to purposefully regulate the composition and properties of the processed products, adapting the processes to specific tasks of the energy, chemical industry, or metallurgy [19,20]. Despite decades of development, most reported plasma gasification systems still face scale-up constraints (limited torch life and refractory wear under high specific powers), non-uniform temperature fields, and short residence times that penalize carbon conversion, as well as energy inefficiencies at low enthalpy densities and instability when processing heterogeneous, ash-rich feeds. Microwave and RF plasma reactors are effective for low-temperature activation, but at industrial throughput, they typically exhibit lower gas throughput and more sensitive power coupling than transferred-arc systems. These limitations motivate the present experimental approach, which employs a high-enthalpy, steam-assisted arc plasma and an industrial-type reactor geometry [21,22, 23]. This research evaluates plasma-chemical pathways—specifically pyrolysis, gasification, hydrogenation, and cracking—for the valorization of low-grade coal and hydrocarbon gases. Key objectives include the optimization of operational parameters, the quantification of product yields, and a comparative assessment of environmental and resource efficiency against conventional processing techniques.

2.RESEARCH METHODS

During this study, a comprehensive program for studying plasma-chemical processes for the conversion of low-grade coal and hydrocarbon gases was implemented. The main objective of the work was to compare the characteristics of plasma gasification, hydrogenation, and cracking in a wide range of temperatures and specific energy consumption with the production of target products in the form of synthesis gas, hydrogen, and carbon black. For the experiments, a high-temperature plasma installation of the industrial PGI-300 type (Fig. 1) was used, equipped with a vertical electric-arc reactor with water-cooled walls made of alloyed stainless steel (12X18N10T). We selected the PGI-300 transferred-arc reactor because it combined high specific enthalpy with stable, long-duration operation at 50–150 kW, accommodated dust-laden feeds, and offered straightforward scale-up via torch multiplexing and higher gas throughput (up to 35 $Nm^3 \cdot h^{-1}$ in our setup). At the same time, microwave and RF plasma systems, while useful for activation, generally provide lower throughputs and are more sensitive to load-impedance changes during the coal/biomass conversion. The reactor design provided for the presence of an oxidation chamber, a gas-slag separation zone, and a slag collector with graphite lining elements, ensuring stable operation at temperatures of up to 3500 K.

2.1.Gas Composition Analysis

Gas compositions were quantified by gas chromatography with thermal conductivity detection (GC-TCD) using two parallel packed columns: a molecular sieve 5A channel (2 m × 3 mm) for H_2, O_2, N_2, and CO, and a Porapak Q channel (2 m × 3 mm) for CO_2, CH_4, and C_2–C_3 hydrocarbons. Samples were withdrawn downstream of the quench and particle trap through a 1.0 mL stainless-steel sampling loop. Argon was used as the carrier gas (≈ 30 mL min^{-1}). The MS5A channel was operated isothermally at 50 °C and the Porapak Q channel at 70 °C, with timed back-flush to protect the MS5A from higher hydrocarbons. Calibration employed traceable multicomponent syngas standards covering 1–60 vol% for CO and H_2, 0.1–10 vol% for CH_4 and CO_2, and 100–5000 ppm for C_2 hydrocarbons. Repeatability ($n = 10$) was better than 1.0% RSD for CO and H_2; method detection limits were ≤ 0.02 vol% for C_2 hydrocarbons. Unless otherwise stated, volume fractions are reported on a dry basis; H_2/CO ratios are given on an N_2-free basis for comparability with literature.

2.2.Carbon Morphology and Surface Area

The condensed carbon was examined by field-emission scanning electron microscopy (FE-SEM; accelerating voltage, 5–10 kV; working distance, 5–8 mm) using secondary-electron imaging at 10–50k×. Powders were ultrasonically dispersed in ethanol, drop-cast on Si substrates, and sputter-coated with ~5 nm Au/Pd. Nanotube diameters and lengths were extracted from ≥ 300 objects per sample using ImageJ; distributions were reported as medians with interquartile ranges. The areal fraction of tubular nanostructures was estimated by segmentation across ≥ 10 random fields (> 1000 objects in total). The specific surface area was measured by N_2 adsorption at 77 K (BET, $P/P_0 = 0.05$–0.30) after degassing at 300 °C for 4 h. A mixture of water vapor and nitrogen with a steam mass fraction of 60% was used as the plasma-forming gas, fed to an APG-75 plasma torch operating at 50–150 kW. The plasma torch operated in the stabilized arc mode with a plasma-forming gas flow rate of up to 35 nm^3/h and a rated arc current of 350 A. The experimental series included the sequential processing of coal dust at 8% humidity, with a supplied fuel concentration of 25–40 g/m^3 in the gas flow. During plasma-steam gasification, the reaction zone temperature was maintained in the range 1800–2600 K, which ensured a synthesis-gas yield with carbon monoxide up to 52% and hydrogen up to 44% at a carbon gasification degree of 94–98%. To carry out plasma-chemical hydrogenation of coal, the reactor was switched to a mode of feeding hydrogen-forming plasma at 99.9% purity. The operating parameters of the plasma torch were 120 kW, and the arc temperature was about 3100 K. The experiments were conducted using DG (long-flame gas) coal with an ash content of 27%. As a result, a gas product was obtained that included up to 38% of acetylene, 15% of ethylene, and 25% of methane. A separate series of experiments was devoted to the plasma-chemical cracking of natural gas in an installation with an additional section for the rapid cooling of the decomposition products. At 2300–2800 K, complete conversion of hydrocarbons was achieved, yielding highly dispersed technical carbon and hydrogen, with mass fractions of up to 22%. Additionally, as part of the study, experiments were conducted on the plasma reduction of coal mineral oxides to form silicon carbide, ferrosilicon, and metallic aluminum. These experiments were conducted at approximately 2900–3200 K, thereby confirming the feasibility of synchronous production of synthesis gas and rare earth components within a single technological cycle.

Fig. 1 The High-Temperature Plasma Installation of the Industrial PGI-300 Type.

3.RESULTS AND DISCUSSION

As part of the study, a wide range of experiments was conducted to elucidate the plasma-chemical conversion processes of various carbon-containing materials, including low-grade hard and brown coal, as well as hydrocarbon gases. The studies were conducted on a high-temperature electric arc unit that allows variation of the plasma torch and the composition of the plasma-forming gas over a wide range. During plasma-steam gasification of coals, gaseous fuel was obtained with a total concentration of CO and H2 from 86 to 94%, which is comparable with the indicators previously reported in the world literature. The average degree of the carbon conversion into synthesis gas reached 93.7%, while the carbon content in the condensed phase decreased more than four times relative to the initial value (Table 1). At a temperature of 2700 K, the yield of gaseous products was up to 98% of the mass of the loaded coal. For comparison, similar experiments conducted on other installations with less intense plasma heating reported gasification levels of 70–85%, confirming the high efficiency of the selected heating scheme. In a series of experiments on plasma-chemical hydrogenation of solid fuel at a temperature of 3000–3200 K and a hydrogen plasma-forming gas flow rate of 48 nm^3/h, a high yield of unsaturated hydrocarbons was achieved. In particular, the gas contained up to 36% acetylene, 18% ethylene, 9% propylene, and 12% methane. The degree of conversion of organic matter into gas products was 88%. At the same time, energy costs for processing 1 ton of coal were 7.0–7.5 kW·h, which is 10–12% lower than previously reported values for conventional plasma installations for a similar purpose. The use of the preheated coal feed mode further increased thermal efficiency and reduced the proportion of the residual carbon phase. The experiments on the plasma-chemical cracking of hydrocarbon gases included the processing of propane-butane and ethane-propane mixtures at a temperature of 2400–3100 K. In one experiment, the plasma torch delivered a total power of 150 kW, and the gas flow rate was 38 nm^3/h. Under these conditions, up to 24% of the mass fraction of hydrogen, as well as a significant amount of methane and ethylene, was recorded in the gas phase. Condensed carbon black was collected from a water-cooled chamber and characterized as a highly dispersed material with a specific surface area of over 450 m^2/g. Electron microscopy analysis showed that approximately 70% of the carbon structure consisted of nanotubes with diameters of 60-180 nm and lengths up to 7 μm (Table 2). Individual fractions exhibited unique branched forms, such as "octopuses" and elbow tubes with partitions. An experimental series on the mixed processing of coal and biomass was carried out at 2000–2500 K and a component ratio of 3:1. A high proportion of hydrogen was observed in the gas phase (up to 40%) and carbon monoxide of about 50%. The degree of gasification of the organic mass was 91%, and the specific energy consumption averaged 1.6 kW · h/kg. This demonstrates the promise of the approach for the utilization of biogenic waste and low-grade coals to produce high-calorific fuel. A series of experiments on the plasma-chemical reduction of the mineral component of coal to obtain valuable products was conducted separately. At temperatures in the range of 2800–3400 K, silicon carbide formations with a concentration of up to 15% of the mass of solid products, ferrosilicon (up to 7%), and metallic aluminum (up to 2%) were recorded in the condensed residue. The overall degree of oxide reduction averaged 42%, which was significantly higher than values reported in previous studies, which did not exceed 30–35%. The results of similar studies of plasma-chemical processing performed on lower-power installations were used to compare the obtained data. With an arc power of 80–100 kW and a steam consumption of no more than 20 nm³/h, the synthesis gas yield rarely exceeded 85%, and the gasification degree remained at 70–75% (Table 3). Beyond low-power arc systems, it is instructive to position these results relative to catalytic and hybrid plasma-catalysis routes. Non-thermal plasma combined with heterogeneous catalysts can reduce apparent temperatures and tune selectivity. But for solid fuels, overall syngas yields and carbon conversion are often constrained by mass-transfer limitations, catalyst deactivation, and relatively low throughputs. Hybrid thermal plasma plus catalyst configurations improve tar cracking and CO/H2 adjustment, yet introduce additional material complexity and catalyst management. In contrast, the present high-enthalpy arc approach achieves >90% carbon conversion with intrinsically low NO_x/SO_x without requiring catalysts, while remaining compatible with downstream catalytic polishing if required.

Table 1 The Chemical Composition of the Gas Phase During Plasma-Chemical Gasification of Coal and Coal with Biomass.

Temperature, K	Ratio coal/biomass	CO, % vol.	H_2, % vol.	CH_4, % vol.	C_2H_2, % vol.	N_2, % vol.	Total gas content, % of fuel mass
1800	100/0	42.3	38.1	8.4	1.2	9.0	89.6
2200	100/0	46.5	42.0	5.6	2.1	3.8	94.2
2500	75/25	49.2	44.0	4.2	2.6	2.8	96.7
2700	75/25	50.5	44.9	2.8	3.3	1.9	98.3
2900	50/50	51.8	45.5	2.1	4.0	1.3	99.0

Table 2 Morphological Characteristics of Condensed Carbon Black.

Parameter	Value at 2400 K	Value at 2800 K	Value at 3100 K
Average diameter of nanotubes, nm	85	120	150
Length of nanotubes, µm	3.2	4.5	6.8
Wall thickness, nm	35	50	80
Specific surface area, m²/g	220	360	450
Mass fraction of nanostructures, %	55	63	72

In contrast to these findings, the present experiments demonstrated that operating in a more intensive mode consistently achieved organic matter conversion above 90%, while maintaining low nitrogen and sulfur oxide emissions (below 15 mg/nm³). The measured NO_x levels of 12–15 mg·Nm⁻³ and very low SO_x are well below typical international emission limit values (e.g., EU Industrial Emissions Directive ranges for combustion/incineration units and U.S. EPA standards for municipal/commercial waste combustors), indicating that the technology can be engineered to meet stringent regulatory targets.

Table 3 The Comparison of Plasma-Chemical Gasification Indicators with Data from Similar Studies.

Parameter	Data from this study	Range in literature (mean)	Deviation, %
Carbon gasification degree, %	93.7	78–85 (81.5)	+15.0
Total CO+H2 yield, % vol.	89.5	75–82 (78.5)	+14.0
Specific energy consumption, kWh/kg	1.8	2.4–3.0 (2.7)	−33.0
NOx concentration, mg/nm³	12	40–80 (60)	−80.0

To make the energy- and conversion-comparison explicit without adding new figures, we summarize the relative gains as follows. Under our conditions, the specific energy consumption for plasma gasification is 1.8 kWh kg⁻¹, i.e., ≈ 33% lower than the literature mean collated in Table 3, while the carbon conversion remains above 90% across the operating window. The combined CO+H2 yield is elevated by ≈ 14 percentage points relative to the reported ranges. These quantitative deltas, already presented numerically in Table 3, convey the same message: a bar chart would provide the same information while avoiding redundancy in the main text. The analysis of the results shows a significant advantage of plasma-chemical methods compared to traditional gasification and pyrolysis in shaft and drum units. In the classical scheme of gasification in a boiling bed, the temperature rarely exceeds 1400–1500 K, which prevents complete transfer of carbon to the gas phase and results in a significant amount of ash and sulfides in the residue. In the experiments presented, at temperatures of 2500–3100 K, the organic mass was almost completely converted to gas, and the condensed residues had a simplified mineral composition suitable for subsequent processing or disposal (Table 4).

Table 4 Parameters of Plasma-Chemical Hydrogenation of Coals.

Temperature, K	H_2 consumption, nm³/h	Acetylene, % of gas mass	Ethylene, % of gas mass	Propylene, % of gas mass	Methane, % of gas mass	Conversion rate, %
2800	35	28.0	12.0	7.0	10.5	82.5
3000	42	33.5	15.4	8.3	11.8	86.4
3200	48	36.2	18.1	9.0	12.1	88.0
3400	50	38.7	19.5	10.2	12.8	89.3

In addition, data on the morphology of condensed carbon demonstrate a high degree of structural order and the prevalence of nanostructures, suggesting the potential use of such products as raw materials for composite materials or catalysts. A comparison of the specific surface areas of samples obtained at different temperatures showed that, with an increase in temperature from 2400 to 3100 K, the specific surface area increased from 220 to 450 m²/g. Analysis of energy costs showed that the average energy consumption during plasma-chemical gasification was about 1.8 kWh/kg, 7.2 kWh/kg during hydrogenation, and about 3.0 kWh/kg during the cracking of hydrocarbon gases. At the same time, the high yield of target products made it possible to reduce the conventional energy consumption per unit of produced hydrogen and hydrocarbon gases by 10-15% compared to the data of world analogues. Summarizing the results, it can be concluded that the implemented experimental program demonstrated the possibility of deep conversion of low-grade coals, biomass, and hydrocarbon gases with simultaneous production of a wide range of products. The high degree of gasification, significant reduction in emissions, and formation of carbon nanostructures confirm the high technological and environmental efficiency of the plasma-chemical approach.

4.CONCLUSION

The study experimentally confirmed that plasma-chemical technologies for processing low-grade coals and hydrocarbon gases achieve significantly higher organic matter conversion and energy efficiency than traditional methods. In plasma-steam gasification of coal, the total yield of carbon monoxide and hydrogen was up to 96.7% at 2500K and up to 99.0% at 2900K, and the gasification degree was 98.3% in some experiments. This is 15% higher than the average values reported in the literature for installations with less intensive heating, in which the degree of gasification typically does not exceed 81.5%. At the same time, the specific energy consumption was only 1.8 kWh/kg, approximately one-third lower than that of known analogues. A significant achievement can also be considered the minimization of nitrogen and sulfur oxide emissions: their concentration in the exhaust gases did not exceed 12-15 mg/Nm³, while in classic gas generators these figures vary from 40 to 80 mg/Nm³. Separately, the high efficiency of plasma-chemical coal hydrogenation was confirmed. In the experiments at temperatures of 3000-3200 K and a hydrogen flow rate of 48 Nm³ / h, a conversion rate of up to 89.3% was achieved with the formation of a gas fraction containing up to 38.7% of acetylene and up to 19.5% of ethylene. These figures are among the highest reported in the literature, where the mass content of acetylene rarely exceeds 30%. At the same time, specific energy consumption was in the range of 7.0-7.5 kWh / kg, which is 10-12% lower than the values for the previous generation of units. Analysis of the condensed residue composition showed significant formation of silicon carbide (up to 15% by weight) and ferrosilicon (up to 7%), further confirming the versatility of the proposed processing scheme. No less significant are the results of the plasma-chemical cracking of hydrocarbon gases. At a temperature of 3100 K, a gas phase with a hydrogen mass fraction of up to 24% and condensed technical carbon with a high degree of dispersion and unique morphology. The specific surface area of the obtained carbon was 450 m²/g, and the nanotube content was up to 72%, which significantly exceeds comparable parameters of materials synthesized at lower temperatures. Such characteristics demonstrate the potential for using such products in composite materials and catalysts. Additionally, experiments on the processing of a coal-biomass mixture at a 3:1 ratio and 2500 K showed a gasification degree of 91% with very low specific energy consumption (1.6 kWh/kg). This clearly illustrates the resource-saving potential of the joint processing of organic raw materials of various origins. A comparative analysis of the literature showed that all three directions (gasification, hydrogenation, and cracking) under plasma-chemical conditions yield higher target-product yield and lower energy costs, while simultaneously reducing pollutant emissions. Therefore, the study confirmed the high technological and environmental efficiency of plasma-chemical processes, enabling the deep conversion of low-grade carbon raw materials and producing valuable gaseous and condensed products at optimal energy costs.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

M.Sh. Isakulova: Conceptualization, Methodology, Writing – original draft, Investigation, Formal analysis, Data curation, Visualization. **Q.N. Nazarov:** Investigation, Validation, Writing – review & editing, Resources, Supervision. **I.V. Gordienko:** Writing – review & editing, Project administration, Technical support, Supervision, Funding acquisition.

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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