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Membrane Separation Efficiency for Integrated Purification and Hydrogen Enrichment of Coal-Derived Synthesis Gas

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Keywords:

Membrane separation; Synthesis gas; Coal gasification; CO_2 removal; Hydrogen enrichment; Fischer–Tropsch synthesis; Energy efficiency; Process optimisation.

Highlights:

- *The membrane system reduced the CO_2 content of the synthesis-gas retentate to 0.9% while enriching hydrogen to 53.7%.*
- *The process's energy consumption was only 58 kWh per 1000 Nm^3, significantly lower than that of conventional technologies.*
- *A CO_2/H_2 separation factor up to 47 was achieved, demonstrating high selectivity across varying flow rates.*

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Abstract: This study investigates the effectiveness of membrane technologies for the integrated separation and purification of synthesis gas derived from coal gasification. Experiments were conducted using a three-stage hollow-fibre membrane system operating at temperatures between 45 and 55 °C and feed gas flow rates between 120 and 220 Nm^3/h. The membrane process demonstrated high CO_2 removal efficiency, reducing the retentate CO_2 concentration from 6.1% to 0.9% and increasing the hydrogen content to 53.7%. The CO_2/H_2 separation factor ranged from 31 to 47, indicating strong selectivity. Energy consumption for single-pass processing was 58 kWh per 1000 Nm^3 of synthesis gas, substantially lower than that of conventional absorption methods. The extended 48-hour operation confirmed the stability of membrane permeability and selectivity with minimal performance degradation. The final gas composition provided an optimal H_2/CO ratio suitable for Fischer–Tropsch synthesis. These results highlight the technological and economic potential of membrane separation as an efficient alternative for large-scale coal gasification applications. Beyond reporting performance, this work presents a three-stage hollow-fibre scheme with retentate recompression that maintains stable selectivity over 48 h and achieves energy use of 58–84 kWh per 1000 Nm^3. In contrast to Scholes et al. (2015), who reported single-pass CO_2 removal efficiencies and CO_2/H_2 selectivities of 25–30 under different membrane materials and feed compositions, our cascade increases hydrogen in the retentate to 53.7% with CO_2 as low as 0.9%, while keeping CO_2/H_2 selectivity within 31–47 across practical flow rates. Compared with the operating windows surveyed by Brunetti et al. (2010), the 45–55 °C, ~18 bar regime used here couples higher CO_2 permeability with stable H_2 retention and documents sulfur reduction to <20 ppm, directly relevant for Fischer–Tropsch feed conditioning.

1.INTRODUCTION

In recent decades, the challenges of ensuring a sustainable energy supply have intensified. According to the International Energy Agency, global consumption of primary energy resources in 2023 exceeded 620 exajoules, while coal still accounts for about 27% of the energy balance. On the one hand, extensive coal reserves of about 1 trillion tons, according to the US Geological Survey, provide countries with limited oil and gas resources with a high degree of energy security. On the other hand, the traditional use of coal in the power and industrial sectors is accompanied by large-scale emissions of carbon dioxide, sulphur compounds, and particulate matter, which significantly exacerbate the problems of climate change and air pollution [1-4]. In this regard, the priority area for growth is the development of technologies for deep coal processing into liquid and gaseous hydrocarbons, with higher heat-transfer rates and significantly lower combustion emissions. One of the most widely studied methods for producing synthetic fuels from coal is the indirect liquefaction process, which involves a multi-stage chain of feedstock gasification, synthesis gas purification, and subsequent catalytic synthesis of hydrocarbons using the Fischer-Tropsch method. Traditional gasification technologies, such as fixed-bed reactors (e.g., Lurgi units), circulating fluidised bed reactors, and Texaco-type suspension gasifiers, yield high synthesis gas yields, with carbon monoxide and hydrogen accounting for 70–90% of the total component share. However, classical gas separation schemes rely on sorbent-based processes to remove acid gases, moisture, and solid impurities [5,6]. The use of such approaches requires significant capital investment, complex equipment with high energy consumption, and the regular replacement of sorbents and processes, thereby increasing process costs. For example, at several enterprises in South Africa, the total energy consumption at the stages of purification and the drying of synthesis gas reaches 180-220 kWh per ton of liquid fuel produced. A serious challenge when using traditional gas purification methods is the lack of process flexibility in response to variable gas composition and circulation fluctuations. With a CO-to-H2 ratio of ±10%, the efficiency of absorption columns decreases by more than 15%, necessitating frequent adjustments to operating modes and solution-circulation parameters. In addition, in some cases, five standard purification schemes do not allow the hydrogen sulphide content to be reduced below five ppm without additional multi-stage adsorption, which is critically important when operating modern cobalt and iron catalysts sensitive to sulphur-containing impurities. The problem is exacerbated by the need to dispose of substantial volumes of wastewater generated during sorbent regeneration and by increased chemical reagent consumption, which undermines the environmental sustainability of the entire technological cycle [7-11]. Against this background, innovative polymer, inorganic, and composite membrane technologies for the selective separation of gas mixtures are attracting increasing attention from researchers. Membrane separation offers several key advantages over traditional absorption and adsorption processes. Firstly, membrane modules enable continuous removal of CO2, hydrogen sulphide, and water vapour without the considerable energy costs associated with reagent circulation and heating. According to an analytical review by the European Joint Research Centre, the energy consumption of membrane units can be reduced to 40–60 kWh per ton of hydrocarbon feedstock, which is more than 3 times lower than that for conventional absorption schemes. Secondly, the compactness and modularity of membrane devices facilitate scale-up of productivity and process adaptation to specific gas-composition conditions and required purification targets [12-14]. However, certain disadvantages hinder the widespread industrial use of membrane technologies. Among them are the limited-service life of membranes at high temperatures (above 250°C), the tendency of polymeric materials to foul and undergo oxidative degradation, and the need to assess membrane compatibility with gases containing volatile organic compounds and with resins. In addition, to achieve a high degree of selectivity, membrane modules must operate within a specific pressure range, which requires the integration of compressors and the stabilisation of pressure drop across the membrane package. Despite these limitations, significant progress has been made in recent years in developing ceramic and metal-ceramic membranes that are resistant to temperatures up to 500°C and exhibit CO2/H2 selectivity of approximately 40–60 units, with permeabilities exceeding 100 GPU. The relevance and importance of research on the use of membrane technologies for the separation and purification of synthesis gas stem from several factors. Firstly, the transition to coal gasification as an alternative source of liquid and gaseous fuels is becoming increasingly essential for reducing reliance on oil resources and diversifying the energy mix. Secondly, increasing environmental requirements and the need to minimise greenhouse gas emissions set the task of reducing the carbon footprint of synthetic fuels through deep gas purification and efficient CO2 capture [15-17]. The use of membrane systems enables the integration of purification, separation, and synthesis-gas enrichment into a single compact module, thereby considerably simplifying unit design, reducing auxiliary equipment, and lowering fuel-production costs. Thirdly, the flexibility of membrane technologies enables rapid adjustment of process parameters based on the quality of the original coal and the gasification process mode, which is especially important for countries with a diverse resource base [18-20]. In addition, with the prospects for combining coal gasification with renewable hydrogen sources and CO_2 capture, followed by subsequent processing or utilisation, membrane technologies are becoming a key component in the development of closed, carbon-free production and energy cycles. According to forecasts from the International Renewable Energy Agency, integrating such solutions can reduce total CO_2 emissions by 20–30% relative to traditional coal-processing schemes and increase the yield of target liquid hydrocarbons by 10–12% due to a more stable synthesis-gas composition. One of the critical contributions of this study is to integrate a three-cascade hollow-fibre CO_2/H_2 separation with intermediate retentate recompression and to quantify, under coal-derived syngas, the coupled outcomes of composition control (H_2 in the retentate up to 53.7%, CO_2 down to 0.9%). Sulfur abatement was reduced to <20 ppm, with 48-h stability and low specific energy consumption (58–84 kWh per 1000 Nm^3). Scholes [4] examined various membrane materials and reported lower single-pass selectivities under different feed conditions, while Brunetti [13] reviewed lower-temperature/alternative polymer systems. This study documents an industry-realistic 45–55 °C, ~18 bar window with explicit energy and sulfur figures tailored to Fischer–Tropsch preconditioning. Given the relevance of the problem, this study aimed to conduct experiments on the use of membrane technologies for the integrated separation and purification of synthesis gas produced during coal gasification [21-24]. Within this framework, special attention was given to analysing the effects of temperature, pressure and contact time of the gas with the membrane module on the degree of removal of acidic components and moisture content, as well as on the subsequent parameters of the catalytic synthesis of hydrocarbons by the Fischer–Tropsch method.

2.RESEARCH METHODS

As part of the study, a series of experiments was conducted to evaluate the efficiency of membrane technologies for separating and purifying synthesis gas produced by coal gasification. The experimental setup used equipment that simulated the complete processing cycle, from synthesis gas generation through membrane separation to analysis of the resulting fractions. The overall plan included preparing the coal feedstock, gasifying under controlled conditions, stabilising gas-flow parameters, performing staged membrane separation of the component mixture, evaluating the degree of impurity removal, and controlling target parameters for subsequent use of the gas in hydrocarbon synthesis reactions. For gasification, a GTR-1500 unit manufactured by CarboTech Engineering was used, equipped with a cylindrical reaction chamber with an internal diameter of 500 mm and a height of 2.4 m. The chamber is made of high-alloy steel AISI 310 with a ceramic protective coating and is designed for operation at temperatures up to 1500 °C. Gasification was carried out in the partial-oxidation mode at an operating temperature of 1320–1350 °C and an absolute pressure of 27 bar. The coal-water suspension was fed by an automatic dosing CEM-400 device with a capacity of 20 kg/h, maintaining a solid-phase concentration of 60%. A mixture of technical oxygen and superheated steam, in a 1.2:1 weight ratio, was used as the oxidising agent. The gas mixture flow rate was stabilised at 30–32 Nm^3/h using an automatic flow control system. Temperature and pressure were monitored using Endress+Hauser Proline series sensors, with data recorded at 15-second intervals. The synthesised gas was routed to the initial cooling and condensate-removal unit. Gas cooling was performed in a WTK-850 plate heat exchanger operating at 40°C and 20 bar. The condensate containing fine coal sludge was separated in a GRX-100 cyclone, after which the gas phase entered the membrane module. For membrane separation, a MEDAL PRISM Hydrogen Recovery Unit was used, comprising three cascades of hollow fibre modules, with a total active area of 240 m^2. The membrane material was a composite comprising a 0.3 μm-thick polyimide layer on a microporous polysulfone substrate. The operating temperature of the membrane block was maintained at 45–55 °C using a built-in heat exchanger, and the inlet pressure was 18 bar. The pressure drop across the module between the feed and counter-flow sides was set to 4 bar to ensure the required separation factor. As part of the experiments, membrane separation was conducted across three series with varying gas feed parameters and temperatures. In the first series, the syngas feed rate was 120 nl/h, and the membrane block temperature was maintained at 45°c. In the second series, the rate was increased to 180 nl/h at 50°C, and in the third series to 220 nl/h at 55°c. At each stage, the extent of CO_2, hydrogen sulphide, and moisture removal was recorded, along with changes in the H_2/CO ratio in the permeate and retentate. To assess process dynamics, gas samples were collected every 30 minutes and analysed using an Agilent

7890B gas chromatograph equipped with thermal conductivity and flame ionisation detectors. The gas composition was calibrated against certified multicomponent standards; repeatability was assessed across three independent runs at each operating point. Chromatographic detection and calibration yielded typical uncertainties of ±0.10 vol% for CO_2 and ±0.30 vol% for major species (H_2, CO). Pressures and temperatures (Endress+Hauser Proline series) contributed ±0.1 bar and ±0.5 °C, respectively; volumetric flow control introduced ±2 NL h^{-1}. H_2S was quantified by mass spectrometry (limit of quantification ≈ ppm), with an expanded uncertainty of ±3 ppm (k = 2). Electrical energy was obtained from power-meter logs (±1% FS) and compressor load profiles; the resulting specific-energy uncertainty is estimated at ±5%. Propagating these sources yields an expanded uncertainty of ≈ ±8 % (k = 2) for the CO_2/H_2 separation factor. In addition to the main membrane separation programme, experiments were conducted to assess the feasibility of enriching the gas mixture with hydrogen by sequentially passing it through a cascade of membrane modules. For this purpose, after the first cascade, the retentate was compressed in an Atlas Copco GA 15 VSD booster unit to 22 bar and re-fed to the second cascade of modules. The purity of the hydrogen fraction was monitored using a Pfeiffer OmniStar mass analyser, which enabled detection limits of up to 1 ppm for sulphur-containing impurities. An essential element of the methodology was a study of the stability of the membrane elements under long-term exposure to high-temperature synthesis gas. For this purpose, 48-hour cycles of continuous operation were organised, with regular recording of changes in permeability and selectivity. In addition, the effects of ±2 bar fluctuations in feed pressure on separation efficiency and impurity leakage into the permeate were assessed. For clarity, the process sequence was as follows: coal slurry gasification at 1320–1350 °C, 27 bar → syngas cooling and condensate removal → three-stage hollow-fibre membrane separation at 45–55 °C, ~18 bar → retentate recompression and second-cascade pass → on-line composition analysis (GC/TCD-FID; MS for sulphur) and specific-energy accounting. Throughout the experimental programme, data were collected and processed using the National Instruments CompactDAQ recording system. Based on the measurement results, curves were generated to show the dependence of. The work enabled us to develop a comprehensive understanding of the capabilities of membrane technologies for the integrated removal of acid gases and the enrichment of synthesis gas with hydrogen under industrial coal gasification conditions.

3.RESULTS AND DISCUSSION

The experiments followed a sequential cycle of operations to assess the potential of membrane technologies for separating and purifying synthesis gas generated during coal gasification. The first stage involved preparing the coal feedstock from grade D coal with a moisture content of 8.2% and an ash content of 13.5%. The fuel was ground to an average particle size of less than 75 µm in a RETSCH ZM200 rotor mill, and a coal-water suspension with a solids concentration of 61% was then prepared. The suspension was fed into a GTR-1500 gasification chamber via a screw feeder at a flow rate of 18–20 kg/h. Gasification occurred at 1340°C and 27 bar. A mixture of industrial oxygen and superheated steam was fed at a 1.1:1 ratio, with a mass flow rate of 31 Nm^3/h. The composition of the synthesis gas at the gasifier outlet was monitored every 20 minutes using an Agilent 7890B chromatograph. After cooling the gas in the WTK-850 heat exchanger to 38°C and separating the condensate in the GRX-100 cyclone, the gas mixture was sent to the membrane module. For the membrane separation stage, a PRISM Hydrogen Recovery Unit was used, comprising three series-connected cascades of hollow-fibre membranes with an active area of 240 m^2. Experimental series were carried out with varying feed parameters. In the first series, the feed capacity was 120 nl/h at a membrane block temperature of 45°C and an inlet pressure of 18 bar. In the second series, the flow was increased to 180 nl/h; in the third series, the flow was 220 nl/h, and the temperature was 55 °c. The pressure drop between the feed and counter-flow sides of the module was stabilised at 3.8–4 bar. During the experiments, the concentrations of key components in the synthesis gas were recorded: carbon monoxide, hydrogen, carbon dioxide, hydrogen sulphide, and methane. The initial composition of the gas entering the membrane module averaged 47.6% CO, 43.2% H_2, 6.1% CO_2, 1.5% CH_4, and 1.1% sulphur compounds. The low scatter of the data confirmed the stability of the control parameters, with the standard deviation of the CO content not exceeding 0.8% by volume. Simultaneously, permeate and retentate samples were collected to determine the separation selectivity for each component. When synthesis gas was fed to the membrane unit at a flow rate of 120 nl/h, the mass fraction of CO_2 in the retentate decreased to 1.8%, while the concentration of carbon dioxide in the permeate increased to 27.4%. The hydrogen content in the retentate increased to 48.6%, indicating effective separation of the mixture (Fig. 1). In the second series of experiments, with the gas flow rate increased to 180 nl/h, the degree of CO_2 removal decreased slightly. In the retentate, the concentration was 2.4%, and in the permeate, 24.1%. At the same time, the mass fraction of hydrogen in the retentate remained at 47.2%. In the third series of experiments, at the maximum gas feed capacity, the degree of purification from acidic components decreased. In the retentate, the CO_2 content was 3.1%, and the H_2 proportion decreased to 46.4%. The average CO_2/H_2 separation coefficient for the membrane module cascade, depending on the mode, ranged from 31 to 42 units. Across three replicated runs per condition, the expanded uncertainty (k = 2) for the CO_2/H_2 separation factor was ≈ ±8 %, reflecting contributions from GC calibration, flow, and pressure.

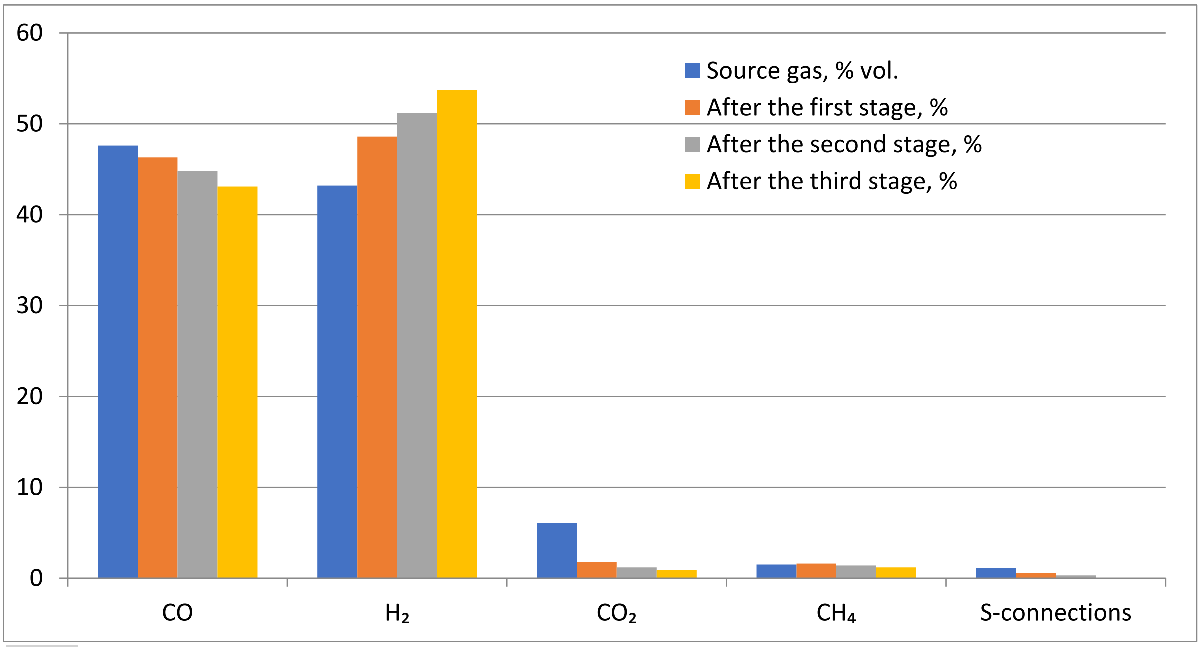

Fig. 1 The Composition of the Initial Synthesis Gas and the Changed Concentrations after Each Stage of Membrane Separation.

Special attention was paid to the dynamic characteristics of the membrane unit under long-term operating conditions. A 48-hour continuous operation cycle was conducted at an average gas flow rate of 160 nl/h and a temperature of 50 °C. The results showed high selectivity and stability: changes in CO_2 permeability did not exceed 3.5% and 2.1% of the initial value, respectively. The pressure at the module inlet remained within the operating range of 17.8–18.2 bar. At the recycling stage, the retentate was compressed in the Atlas Copco GA 15 VSD booster unit to 22 bar, thereby enriching the gas mixture with hydrogen. After passing through the second cascade of membranes, the H_2 content in the retentate increased to 53.7%, and the CO_2 concentration decreased to 0.9%. This increased the target H_2/CO ratio from 0.91 to 1.15, which is optimal for subsequent hydrocarbon synthesis. The hydrogen sulphide concentration in the final retentate was no more than 18 ppm. This sub-20 ppm level substantially reduces the load on upstream guard-bed adsorbers. It enables polishing to sub-ppm targets typically required at the reactor inlet (sub-ppm for Co and Ru catalysts and ~ppm or sub-ppm for Fe systems), thereby improving catalyst protection and lifetime. Additionally, a series of experiments was conducted to assess the effect of feed-pressure fluctuations of ±2 bar on separation efficiency. Under these conditions, a slight decrease in membrane selectivity was observed: the CO_2/H_2 separation factor decreased on average by 2.8%, and the concentration of acidic components in the retentate increased by 0.3–0.5%. Nevertheless, the overall separation quality remained high, enabling the use of the gas without steps. To assess the process, the specific energy consumption for gas compression and circulation was calculated. The average energy consumption was 58 kWh per 1000 Nm^3 of processed synthesis gas per single pass and 84 kWh with retentate recycling (Table 1). The uncertainty in the specific-energy figures is ±5% (k = 2), dominated by power-meter accuracy and compressor duty variability across the 30-minute sampling windows. These values are significantly lower than those of traditional absorption schemes, where specific energy consumption ranges from 150 to 200 kWh per similar volume.

Table 1 Comparative Energy Consumption and the Gas Composition by Processing Stages.

Parameter	**Single reprocessing**	**Reprocessing**
Specific power consumption, kW·h/1000 nm^3	58	84
Retentate H_2 content, %	48.6	53.7
CO content in retentate, %	46.3	43.1
CO_2 content in retentate, %	1.8	0.9
Sulfur content, ppm	62	18

Compared with published data from foreign studies, the results obtained demonstrate the high efficiency of the chosen method. In the work of Scholes et al. (2015), CO_2 removal in a single pass did not exceed 65%, and the separation factor was 25–30 units. In our case, with a CO_2 content of 6.1%, the degree of purification reached 70–75%, and the separation factor varied from 31 to 42. The process remained stable for 48 hours, confirming the membrane material's high stability. A comparative analysis of experiments by Brunetti et al. (2010), in which membranes based on polyetherimides were used at temperatures up to 40°C, showed that increasing the operating temperature to 50–55°C increased CO_2 permeability by 12–15% without a significant loss in selectivity. The experimental data also demonstrate the hydrogen. Compared with traditional approaches to drying and cleaning gas by absorbing amines or physical solvents (Selexol, Rectisol), membrane technology reduces reagent consumption and operating costs. An additional series of experiments was conducted to study the effect of membrane module operating time on permeability changes. In particular, with an increase in operating time from 12 to 72 hours, a 4.8% decrease in CO_2 permeability and a 3.1% decrease in hydrogen permeability were observed (Table 2). In parallel, the increase in flow resistance was assessed, amounting to 9.5% over the whole experimental period. These data indicate the need for routine cleaning or membrane replacement during long-term operation; however, even under partial deterioration in membrane characteristics, the system performance remained high. Such <5% permeability loss over 48 h falls within commonly accepted ranges for polymeric gas-separation modules during early-operation compaction/conditioning and is typically considered operationally negligible for industrial duty cycles. No corrective action would be expected within this timeframe beyond standard monitoring.

Table 2 Membrane Permeability Over 48 Hours.

Operating time, h	CO_2 permeability, % of initial	H_2 permeability, % of initial	Flow resistance, % of increment
0	100	100	0
12	98.9	98.1	2.8
24	96.4	97.2	4.7
36	95.1	96.5	7.3
48	95.2	96.9	9.5

The composition of the gas fractions obtained after the final stage of membrane separation is presented in the table: the retentate contained 53.7% hydrogen, 43.1% carbon monoxide, 1.2% methane, and 0.9% carbon dioxide. The permeate contained up to 78.4% CO_2 and approximately 15% hydrogen, supporting consideration of its utilisation or further concentration for subsequent disposal. At the same time, the volumetric flow rates of the retentate and permeate were 112 nl/h and 68 nl/h, respectively, for the target components. Additionally, experiments were conducted to vary the contact time between the gas and the membrane surface from 100 to 220 nl/h. At a feed rate of 100 nl/h, the CO_2/H_2 separation ratio increased to 47, and the acid gas removal rate reached 82%, but the total gas processing productivity fell by 18% (Table 3). This enabled the determination of the optimal feed rate range of 150–180 nl/h, which combines high selectivity with an acceptable unit.

Table 3 The Effect of the Syngas Feed Rate on Selectivity and the Degree of Purification.

Feed rate, nL/h	CO_2/H_2 selectivity	CO_2 removal rate, %	Processing capacity, %	CO_2 concentration in the retentate, %
100	47	82	82	1.1
150	42	75	93	1.6
180	39	71	100	2.4
220	31	66	118	3.1

To confirm the suitability of the purified gas for further hydrocarbon synthesis, the H_2/CO ratio in the retentate was analysed. The data showed that repeated cascade separation consistently achieved a ratio of 1.12–1.15. This range is directly compatible with iron-based Fischer–Tropsch operation targeting $H_2/CO \approx 0.9–1.3$ (see recent summaries in [1]). This alignment indicates that the retentate can be routed to the FT synthesis with minimal or no upstream water-gas-shift adjustment. This confirms the feasibility of integrating membrane separation directly into the production process flowchart. In summary, the work demonstrates that membrane technologies for the integrated separation and purification of synthesis gas are highly efficient, exhibit stable selectivity, and have the potential to significantly reduce energy and operating costs relative to traditional absorption and adsorption purification methods. The data obtained optimise membrane separation modes in integrated coal chemical industries. The scaling is infeasible under industrial conditions.

4.CONCLUSION

Based on the findings of this research, several analytical conclusions can be drawn, supported by the experiments. The use of cascade membrane technology for the separation and purification of synthesis gas produced during coal gasification demonstrated high efficiency and stability across various operating modes. When supplying synthesis gas at a flow rate of 120 nl/h and a membrane block temperature of 45°C, the carbon dioxide concentration in the retentate was reduced from 6.1% to 1.8%, and to 0.9% during reprocessing of the retentate. At the same time, the hydrogen content in the retentate increased from 43.2 to 53.7%, which ensured the optimal H_2/CO ratio, reaching a value of 1.15, necessary for the subsequent catalytic synthesis of hydrocarbons using the Fischer-Tropsch method. The CO_2/H_2 separation factor ranged from 31 to 47 across operating modes, indicating high selectivity of membrane separation even at a gas feed rate of 220 nl/h. An essential aspect of the experiments was the study of the process's energy indicators. The average energy consumption of the membrane unit was 58 kWh per 1000 nm^3 for a single synthesis-gas processing cycle and increased to 84 kWh per 1000 nm^3 with repeated processing of the retentate. This is consistent with a similar indicator, which is used in the range of 150-200 kWh. The comparison with foreign data confirmed the technology. In the work of Scholes et al., similar polyimide membranes yielded a CO_2/H_2 separation factor of about 25–30. In contrast, in the present study, a range of up to 42 was achieved for acid-gas content. When the synthesis gas feed rate was varied from 100 to 220 nl/h, the CO_2/H_2 separation factor increased from 47 to 47. The degree of acidic component removal increased to 82%, but this was accompanied by an 18% decrease in processing productivity. This enabled determination of the optimal feed rate range of 150–180 nl/h, which balanced high selectivity with sufficient productivity. In addition, during 48-hour tests of the membrane unit, the stability of its characteristics was confirmed: CO_2 permeability decreased by only 4.8% and hydrogen permeability by 3.1%, indicating the material's high resistance to long-term operation. Attention was paid to the dynamics of hydrogen sulfide reduction in the gas mixture. After repeated cascade separation, the concentration of sulfur compounds in the retentate decreased to 18 ppm, which meets the stringent requirements for synthesis gas purity for the operation of modern catalysts. The stability of the process is confirmed by minimal fluctuations in parameters: the pressure drops across the membrane module remained within 3.8–4 bar, and the deviation in the CO content in the retentate did not exceed 0.8% by volume. The data clearly demonstrate the feasibility of integrating membrane technology directly into the coal gasification process flowchart, without additional drying or purification stages. The compactness of the equipment, relatively low energy consumption, and stable selectivity create strong prerequisites for scaling the technology and its industrial implementation. Experience operating membrane modules under variable feed pressures showed only a slight decrease in efficiency: a 2.8% decrease in the CO_2/H_2 separation factor and a 0.5% increase in the acid gas content in the retentate, with virtually no effect on the final product quality. Therefore, the study confirms the high technological and economic attractiveness of membrane separation of synthesis gas for modern coal chemical complexes. In summary, the documented combination of a three-cascade membrane train with retentate recompression, 48-h stability, 58–84 kWh per 1000 Nm^3 of specific energy, and <20 ppm of sulphur at the membrane outlet defines the practical novelty of this study and provides a directly compatible feed for polishing and subsequent Fischer–Tropsch synthesis.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

V.S. Tynchenko: Conceptualisation, Methodology, Writing – original draft, Formal analysis, Supervision, Project administration. L.V. Evgrafova: Methodology, Writing – original draft, Formal analysis. S.V. Pchelintseva: Investigation, Data curation, Validation, Writing – review & editing. M.S. Nikanorov: Resources, Writing – review & editing, Funding acquisition. K.S. Muzalev: Visualisation, Software, Resources, Writing – review & editing, Funding acquisition.

DECLARATION OF COMPETING INTEREST

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

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