GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2025 Volume 41 Issue 4 Pages 33–52

DOI: 10.24425/gsm.2025.155879

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Assessment of geological and technological parameters of the prospects of methane coal deposits for the extraction of methane from coal seams

Introduction

The study on methane extraction from coal seams is paramount in the rapidly developing energy landscape and the search for alternative energy sources. Methane from coal seams has great prospects as a renewable energy source, contributing to reducing greenhouse gas

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emissions and improving air cleanliness. Nevertheless, effective methane extraction from coal seams requires a deep understanding of the geological mechanisms and physico-chemical properties of coal formations and the development of modern technologies. Deepening the interaction between methane and coal, along with the development of production and use methodologies, not only contributes to the development of environmentally friendly energy sources but also reduces dependence on conventional energy sources, increases energy sustainability, and improves environmental conditions. This study is crucial not only among the ongoing efforts to combat climate change but also has the potential to profoundly impact the development of energy infrastructure and mitigate adverse environmental impacts.

Given the substantial methane potential of coal deposits and their crucial role in mitigating greenhouse gas emissions and expanding the energy spectrum, the examination of geological and technological aspects of methane production is becoming important to determine optimal use methods. Considering the distinctive geodynamic features of coal structures, analyzing the mechanisms of gas formation and reservoir permeability, and improving mining technologies, it becomes possible to increase the efficiency of the process and reduce its environmental consequences. Therefore, this study contributes to a comprehensive understanding of the processes of methane extraction from coal seams and stimulates the development of more sustainable and environmentally friendly approaches to the use of this natural resource.

In continental areas, there is a problem that requires a more thorough examination of the geological and technological aspects of methane extraction from coal seams. Liang et al. (2021) investigated the geological and technological aspects of methane extraction from coal seams, focusing on the influence of geodynamics on the efficiency of the process. Chandra et al. (2021) conducted an analysis of the global experience of industrial methane extraction from coal deposits, considering geological parameters and environmental aspects. Szlązak et al. (2021) examined the relationship between methane and coal based on theoretical and experimental data on the physical chemistry of artificial and natural sorbents. A chemical-geological analysis of the relationship between methane and coal was presented in Xu et al. (2021), emphasizing the role of the macrostructure of the coal seam in this process. Aspects of gas permeability and permeability of coal seams in the context of methane extraction were considered in a study by Salmachi et al. (2021).

Abanades et al. (2022) presented an analysis of international practice on methane extraction from coal seams with an emphasis on modern technologies. In the study by Kumar et al. (2022), technogenic methods of increasing reservoir permeability and intensification of gas recovery during methane extraction were considered. Zhao et al. (2024) examined geodynamic processes and their effect on the permeability of coal seams in the context of methane production. Guo et al. (2021) conducted an analysis of the environmental and energy aspects of methane extraction from coal seams, considering the requirements of sustainable development. Sharma et al. (2023) investigated the prospects for industrial extraction of methane from coal seams in various regions, considering geological and technological factors. Thus, it is necessary to continue the research, which covers all aspects of methane extraction from coal seams and integrates modern technologies and data on physical chemistry.

The purpose of this study is to assess the geological and technological characteristics that affect the potential for the development of methane deposits from coal seams to ensure the efficiency and economic feasibility of their extraction. Research objectives:

1. Analysis of the world experience of industrial methane extraction from coal seams and comparative examination of geological characteristics of deposits in accordance with international standards.
2. Investigation of geodynamic features of coal structures affecting the natural formation of cracks and permeability of formations, and assessment of the possibilities of using man-made methods to increase permeability and improve the gas production process.
3. Development of modern methods for extracting methane from coal seams, considering environmental and energy standards, and assessment of the prospects of the Karaganda basin for the implementation of methane extraction projects based on its geological characteristics.

1. Materials and methods

The study examined various important aspects necessary for the introduction of large-scale methane extraction from coal seams in Kazakhstan. First, it evaluated the industrial extraction of methane from coal seams in advanced coal mining countries such as the United States. This analysis included the technologies and methodologies applied to methane extraction, including hydraulic fracturing (fracking), horizontal drilling, and drainage wells. The study examined the economic structures and legal systems that contribute to the development of the coal methane industry. In addition, it explored the effects of technology adoption to mitigate environmental impacts and enhance safety measures.

An analytical assessment of the geological location of coal deposits and patterns of distribution of coal seams was conducted. Various sizes and types of cracks in coal seams were investigated, as their effect on the permeability of coal and the potential for methane release. An analysis was conducted on the impact of both natural and anthropogenic factors on the formation of fractures in coal seams. Moreover, an assessment was made of the rate and volume of methane emissions from coal seams, with a focus on identifying factors that contribute to increased emission intensity. The study examined theories related to the relationship between methane and coal, encompassing various theories regarding the mechanisms of methane formation and accumulation within coal seams. Detailed information on the physical chemistry of methane adsorption and desorption on coal adsorbents was thoroughly investigated. Both laboratory and field studies confirming different theories of methane interaction with coal matrices were considered. The conclusions drawn from experimental research aimed at identifying patterns in methane accumulation and release from coal were analyzed. The overall configuration of the coal seam and its impact on gas permeability were evaluated. The effect of natural moisture on pore saturation and the subsequent reduction in permeability within the coal seam was investigated. An assessment of the impact of the methane pressure gradient on its movement within the coal seam was conducted. Moreover, the characteristics of mining pressure manifestation and its effect on changes in the structure and permeability of the coal mass were examined.

The analysis starts with geological mapping, utilizing geographic information system software to create spatial representations of coal deposits obtained from field surveys and core sampling, which involves the systematic extraction of core samples for laboratory analysis through X-ray diffraction and scanning electron microscopy to determine mineral composition and pore structure. Fracture characterisation is conducted by imaging techniques such as photomicrography or computed tomography scanning to assess the size, orientation, and density of natural fractures, which are crucial for understanding gas flow dynamics. Permeability testing employs laboratory methods utilizing a gas permeameter to evaluate methane flow rates through coal samples under controlled conditions, whereas gas content measurement entails desorption tests to quantify methane release from sealed coal samples. Additionally, adsorption studies are performed using isotherm testing with pure methane gas at varying pressures to assess retention capacity, complemented by chemical analysis using elemental analyzers to determine the coal's carbon, hydrogen, nitrogen, and sulphur content.

This study put forward proposals for enhancing energy self-sufficiency, including strategies to ensure safety in coal mining and the implementation of modern, highly efficient technologies for industrial methane extraction from coal deposits. Strategies for improving safety in coal mining, including the introduction of methane concentration monitoring systems and ventilation, were also proposed. Recommendations for employing innovative technologies such as hydraulic fracturing and horizontal drilling to increase the efficiency of methane extraction were formulated. Suggestions for governmental support measures, such as preferential tax policies and investment incentives, have been made to stimulate growth in the coal and methane industries.

The geological characteristics of the Karaganda Basin, including the size, thickness, and depth of the coal seam, were evaluated. Substantial concentrations of methane were found within the coal seam of the Karaganda Basin, indicating considerable potential for industrial methane extraction. The existing infrastructure and logistical capabilities in the region were assessed for their suitability to support methane extraction projects. An analysis was conducted to assess the economic and environmental benefits arising from the implementation of methane extraction projects in the Karaganda Basin.

2. Results

The issue of degasification at mining enterprises remains pressing and requires immediate resolution. Despite targeted degasification efforts in the Karaganda coal basin, the level of gas emissions remains high, posing a substantial threat to miner safety and the efficiency of the coal industry. Over the past five years, over 90% of accidents in coal mines have been caused by unforeseen methane emissions, leading to both human casualties and material damage. Fatalities primarily result from methane explosions due to the high gas content in coal seams. In the Karaganda basin alone, such incidents have resulted in 138 fatalities (Matloob et al. 2024).

As a participant in the Kyoto Protocol, Kazakhstan has committed to reducing greenhouse gas emissions, particularly methane, which is released annually into the atmosphere through ventilation systems during coal extraction, amounting to approximately 1 billion cubic metres (Zhumabayev et al. 2022). Furthermore, by implementing methane extraction and utilisation programmes at the Oktau coal deposit in Kazakhstan, the country aims to reduce its reliance on coal-fired power stations. This will consequently reduce harmful emissions during coal combustion and decrease solid waste production. However, considering that nearly all hydrocarbon resources are concentrated in Western Kazakhstan (up to 98%), it is crucial for most industrial enterprises to strive for regional energy self-sufficiency by optimizing the use of regional resources, including non-traditional energy sources available in the central and eastern parts of the country.

Coal deposits containing methane have distinctive features: their methane reservoirs have physical and physicochemical properties that differ from those of conventional natural hydrocarbon gas (Table 1). The primary distinction within the considered reservoirs lies in the significant variability of gas occurrence and interaction methods within the "gas-natural porous medium" system.

The existing understanding of the relationship between methane and coal is based on theoretical principles from physical chemistry and experimental results using both synthetic and natural adsorbents. In a coal seam, a substantial portion of methane is present in a physicochemical state, predominantly dissolved in solid matter (absorption), condensed on pore surfaces (adsorption), and aggregated in supramolecular pores (Dutka and Godyń 2021). The process of methane absorption by coal involves the presence of micropores, which, despite their minuscule size comparable to methane molecules, are influenced by adsorption forces. These micropores, along with gas molecules located in the intermolecular spaces of the coal matrix, known as solid solutions of carbon gas, serve as the primary methane reservoir in coal seams. Interconnected micropores and fractures create a highly porous region within the coal, where complex physical and chemical phenomena occur (Golyshev et al. 2001).

Unlike oil and gas reservoirs, most coal seams typically have lower natural porosity and permeability, which limits filtration and diffusion processes (Deryaev 2023). The primary factors affecting the porous structure of coal include the original material from which the coal is derived, the conditions under which the plant residues formed, processes such as gel drying, and secondary phenomena such as metamorphism and folding. The volumetric porosity of coal usually exceeds 1%, mainly due to cleat space, whereas coal permeability, also related to cleat space, ranges from 0.001 to 100 mD (Mou et al. 2021). According to contemporary theories, a coal seam is characterized as a low-permeability structure with blocky-fractured features (Guo et al. 2021). It possesses primary porosity within the matrix, along with lesser secondary porosity in fractures. This fractured configuration

Table 1. Comparative characteristics of methane reservoirs in coalbeds and conventional gas

Tabela 1. Charakterystyka porównawcza złóż metanu w pokładach węgla i gazie konwencjonalnym

Characteristic	Conventional gas	Coalbed methane
Gas formation	Gas originates in the rock and subsequently migrates through the reservoir	Gas forms and is retained within the coal
Structure	Primarily large open pores. Fractures are randomly dispersed	A network consisting of macro-, meso-, and micropores. Pores are evenly distributed
Gas retention	Compression	Adsorption
Transport mechanism	Flow is characterized by layers under a pressure gradient (Darcy's Law)	Diffusive flow within the coal matrix, occurring under both concentration gradient (Fick's Law) and pressure gradient (Darcy's Law)
Reservoir performance	Initial formation rate is rapid, followed by a decline. Insufficient recovery requires water initiation	Gas rate initially increases, then decreases over time. Production primarily starts with water injection
Phase state of gases	Free and water-dissolved	Adsorbed
Gas storage	Gas retention in large pores according to the Ideal Gas Law	Gas retention via adsorption on microporous surfaces
Mechanical properties	Young's modulus $\sim 10^6$ Compressibility due to pores $\sim 10^{-6}$	Young's modulus $\sim 10^5$ Compressibility due to pores $\sim 10^{-4}$
Gas content	Gas content is determined based on well logging data	Gas content is determined from core samples
Gas-water ratio	The gas-to-water ratio decreases over time	The gas-to-water ratio gradually increases over time
Reservoir rock type	Inorganic reservoir rock	Organic origin reservoir rock
Pore size	Macropores from 1 μm to 1 mm	Micropores from 4 Å to 80 Å
Connection between reservoir and source rock	Reservoir and source rock are distinct entities	Reservoir and source rock are the same entity
Permeability dependence	Permeability is independent of stress	Permeability is highly stress-dependent
Filtration and storage properties	Porosity and permeability remain relatively stable throughout the gas extraction process	Porosity and permeability undergo considerable changes during the gas extraction process

Source: Bondarenko et al. 2014.

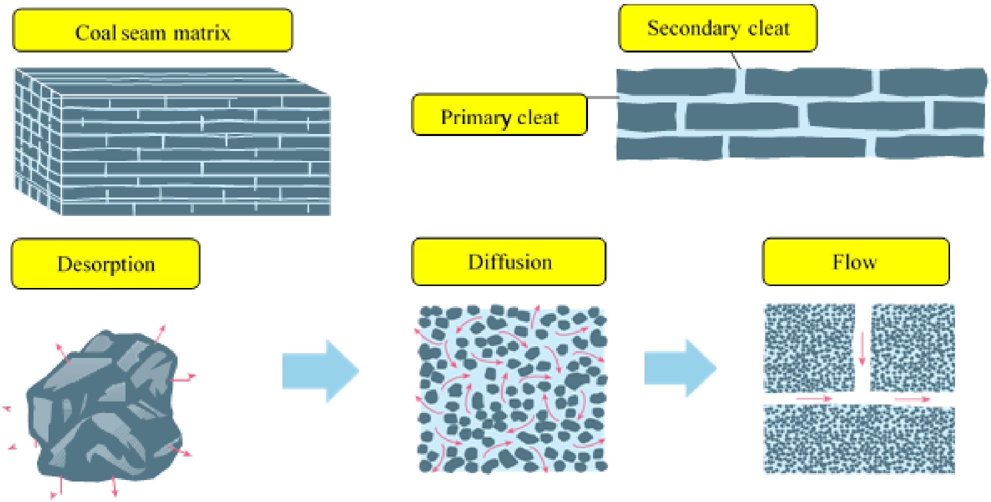

Fig. 1. The structure of coal and methane extraction mechanism from coal seams

Rys. 1. Struktura mechanizmu wydobycia węgla i metanu z pokładów węgla

of coal exhibits notable anisotropic properties. Fracturing is evidenced by the development of cleats, which divide the rock into various formations such as plates, fibres, lenses, and columns. The occurrence of these fractures depends on various internal and external factors, including processes associated with coal formation. Primary longitudinal fractures facilitate the movement of fluids to the surface, while secondary fractures, perpendicular to them and known as secondary cleats, contribute to additional permeability. Thus, fractures resulting from cleating are crucial in determining the permeability of the coal seam.

From the presented information, it can be concluded that various factors affect the permeability of coal seams in their natural state. These factors include the configuration of coal seams, the presence of water in the pores, the methane pressure gradient, and its impact on the pressure of adjacent rock formations. Coal seams are complex systems comprising fractures and matrices capable of retaining gas. Under unchanged conditions, they exhibit low permeability and porosity due to their structural characteristics. The filtering structure of coal is characterized by high resistance and relatively low permeability, which underscores the importance of maintaining the integrity of the coal mass for optimal gas permeability.

The interaction between methane and coal implies a specific binding energy that defines the difference between the energy expended on their interaction and the energy required for complete dissociation at an infinitely large distance. In real reservoir conditions, the gas release process from the coal structure and its transition to a free state takes more than six months (Prokopov et al. 1993). This indicates that even when pressure within the seam decreases, a “gas barrier” exists in the transition zone where methane adheres to the coal structure. Under the influence of external energy, the gas moves freely in microfractures, leading to a substantial reduction in binding energy. This suggests that the presence of the "gas barrier" is due to its energetic properties and can be mitigated through targeted intervention. For instance, using conventional hydraulic fracturing technology to stimulate a permeable coal seam from a surface well can enhance the extraction of up to 120% of the methane stored in the coal seam at a depth of 60 metres (Wang et al. 2021).

Modern understanding of the interaction between methane and coal is based on theoretical research in physical chemistry, supplemented by empirical data obtained from experimental studies. The presence of a solid solution of methane and carbon, containing up to 80% gas within the seam, indicates an equilibrium state with a single phase (Gaikwad et al. 2021). Thus, applying external energetic interventions makes it possible to induce changes in the equilibrium within the system. Consequently, most gases initially present in coal seams cannot be precisely classified as gases because they do not conform to the principles outlined in gas laws due to their bound state. Gas can only be considered a gas in a liberated state within the coal seam (Prokopov et al. 1989). Gases in a bound state cannot exhibit internal energy until they transition to a free phase. This transformation occurs with a decrease in gas pressure or the expansion of the gas-saturated coal seam. Consequently, gas release during mining operations is predominantly initiated through human intervention. The porosity in coal plays a crucial role, serving not only as a reservoir for methane but also as a medium for gas release from the reservoir while simultaneously acting as a natural adsorbent susceptible to stress and deformation (Telbayeva et al. 2024). Therefore, when evaluating coal reserves as a potential source for methane extraction via surface wells, the assessment should be based not only on the overall geological reserves of methane in the reservoir but also on the reserves that can be extracted through industrial methods.

The key factors influencing the composition of natural gas in coal seams and their suitability for commercial exploitation encompass several aspects. These factors include the degree of coal metamorphism, permeability levels, natural gas content, in-situ degassing processes, seam gas pressure, and the extent of the gas release zone extending from deep underground to the surface. Furthermore, it is important to consider the distinctive geodynamic characteristics of coal structures affecting natural permeability and fracture formation, alongside the potential use of technologies to enhance permeability and gas extraction. Experience from countries such as the USA, Canada, Australia, and China demonstrates that adopting effective technologies, including hydraulic fracturing methods and impulse pulsed hydrodynamics, can significantly increase methane production by up to 80% (Pavičić et al. 2022).

After a thorough examination of the Karaganda Basin geological and tectonic conditions, an assessment of coal quality and the degree of metamorphism, and a comparison with mining sites in coal basins such as San Juan in the USA and Kuznetsk in Russia, where successful methane extraction projects have been implemented, it was found that similar characteristics are evident in the Karaganda Basin. Considering geological and commercial performance factors, such as the presence and thickness of coal seams, methane content, and the abundance of methane sources, these deposits are comparable to those found in other regions. This highlights the opportunities the Karaganda Basin presents for implementing methane extraction initiatives from coal seams (Table 2).

Table 2. Comparative assessment of geological and technical indicators and their prospective potential

Tabela 2. Ocena porównawcza wskaźników geologicznych i technicznych oraz ich potencjału perspektywicznego

Evaluation criterion	Karaganda Basin	San Juan Basin	Kuznetsk Basin
Geological age	Carboniferous	Cretaceous-Paleogene	Carboniferous
Area	3,600 km^2	19,500 km^2	26,700 km^2
Tectonics	Coal seams have gently inclined slopes of 10 to 25 degrees with minimal development of faults. Overall, about two-thirds of the basin reserves are located in regions characterized by relatively simple tectonic structures.	Coal seams extend over extensive areas and generally exhibit calm, nearly horizontal bedding with an inclination of up to 1 degree.	Structural features of coal seams vary in different areas: the northern part of the basin shows folds disrupted by numerous faults, the extreme western part has compressed linear folds with steeply inclined strata complicated by thrusts and overthrusts, the central part features weakly disturbed brachyfolds, and the southern part of the basin exhibits gently inclined monoclines.
Coal bearing	Up to 80 coal seams Σ thickness up to 110 m	Up to 16 coal seams Σ thickness up to 34 m	Up to 135 coal seams Σ thickness up to 350 m
Rank composition	G, J, K, OS	D, G, J, K	D, G, J, K, OS, T, A
Petrographic composition	Vitrinite	Vitrinite	Vitrinite, fusinite
Vitrinite reflectance	0.77–1.3%	0.7–1.5%	0.6–3%
Permeability	Up to 15 mD	Up to 50 mD	Up to 80 mD
Methane content	Up to 35 m^3/t	Up to 20 m^3/t	Up to 30 m^3/t
Coal reserves	33.4 billion t	200 billion t	524.4 billion t
Methane resources	1 trillion m^3	2.4 trillion m^3	13.1 trillion m^3
Depth of resource assessment	Up to 1,800 m	Up to 1,980 m	Up to 1,800 m
Resource density	400–800 million m^3/km^2	300–1,000 million m^3/km^2	500–3,500 million m^3/km^2

Source: Portnov et al. 2014.

The Karaganda Basin stands out due to its exceptionally high methane content, placing it alongside regions globally renowned for their rich gas reservoirs. The genesis of hydrocarbon gases in this basin is attributed to the metamorphic processes occurring in its coal deposits on a regional scale. Extensive geological studies confirm the substantial natural methane content in the coal deposits, estimated at 25–35 m^3/t. The Ashlyarik and Karaganda formations exhibit the highest gas content, with depths exceeding 400 m, showing gas content ranging from 22 to 25 m^3/t in the primary layers of the Karaganda Formation. In contrast, areas such as Sherubainura and Tentek show figures rising to 25–27 m^3/t. The gas desorption zone in these areas extends from 120 to 175 m and from 130 to 160 m, respectively (Kopobayeva et al. 2024). Moreover, with increasing depth, the methane content of the coal seams also increases.

The research findings on methane extraction in the Karaganda Basin correspond with many United Nations Sustainable Development Goals (SDGs), highlighting their worldwide significance and contribution to energy sustainability and climate change mitigation (Take Action for… 2025). Methane extraction initiatives advance SDG 7: Affordable and Clean Energy by supplying a cleaner and more efficient alternative to coal, facilitating a transition to low-carbon energy systems. This transition meets regional energy requirements, diminishes dependence on coal-fired power stations, fosters energy self-sufficiency, and mitigates air pollution (Paramonov et al. 2024). The research additionally contributes to SDG 13: Climate Action by mitigating methane emissions, a powerful greenhouse gas, through the deployment of enhanced extraction technology and emissions monitoring systems. This initiative corresponds with international methane reduction objectives, including those established by the Global Methane Pledge, and underscores the significance of using methane as a resource instead of treating it as a waste product. The study illustrates a considerable possibility for mitigating the climatic effect of coal mining operations by minimizing venting and flaring.

The study prioritises sustainable techniques, like water recycling, land reclamation, and biodiversity protection, which closely align with SDG 12: Responsible Consumption and Production and SDG 15: Life on Land. The findings support the use of environmental protections and land restoration strategies in methane extraction projects to enhance resource efficiency and environmental sustainability, therefore reducing land degradation and fostering ecosystem health. Methane extraction projects, when executed properly, enhance socio-economic development by promoting energy security and economic diversity, therefore supporting SDG 8: Decent Work and Economic Growth. The results underscore the opportunity for job creation and infrastructure development in methane extraction, especially in areas like the Karaganda Basin, which may exemplify the integration of sustainable industrial practices within resource-dependent economies.

Kazakhstan possesses vast coal reserves, estimated to exceed 8 trillion cubic metres, making it one of the world's leading coal repositories. Therefore, the Karaganda Basin is important not only as a major coal mining region but also as a notable methane reservoir with unique distribution characteristics within the coal seams (Yessekina et al. 2024). Given the extensive territory with substantial methane reserves, it is prudent to continue the exploration and extraction of methane from coal seams. This initiative addresses energy issues in the Karaganda region and holds the potential to transform into an alternative energy reservoir for Central Kazakhstan by 2025. The development of coalbed methane resources in Kazakhstan promises numerous substantial benefits. It has the potential to significantly enhance mining safety, thereby reducing the number of accidents and injuries in mines. Furthermore, it may play a role in increasing coking coal production in the foreseeable future.

Future trends in energy transition are characterized by a transition from high-emission fossil fuels to cleaner, sustainable energy sources, driven by climate pledges and developments in low-carbon technology. Methane extraction, historically a byproduct of coal mining, is progressively acknowledged as a transitional energy source that can facilitate the shift from coal reliance to renewable energy implementation. Its comparatively low carbon emissions relative to coal and oil render it a significant resource for addressing short- to mid-term energy requirements while mitigating greenhouse gas emissions (Doroshenko 2023). The extraction of methane is consistent with overarching energy plans aimed at resource efficiency, energy security, and the reduction of emissions. The extraction of methane from coal seams, previously regarded as a supplementary step in coal mining, is now becoming an essential element of energy plans focused on reconciling resource efficiency with environmental objectives. This transition is driven by the understanding that methane, although a powerful greenhouse gas, may function as a transitional energy source with much reduced emissions relative to coal and oil. Worldwide methane abatement initiatives are intensifying, accompanied by notable technological advancements in methane capture and use (Jiang et al. 2024). Nonetheless, a discrepancy remains between these developments and the increasing methane emissions, underscoring the pressing necessity for scalable solutions that reconcile mitigation technology with emissions trends.

Innovative methods in methane extraction, including biomethanation and microbial enhanced oil recovery, are set to significantly impact the energy sector. Biomethanation uses biological processes to transform organic resources into methane, providing a sustainable approach for methane production that can augment conventional extraction techniques. This technology not only minimizes waste but also facilitates the incorporation of circular economy ideas into energy generation. Microbial improved oil recovery entails the utilisation of microorganisms to maximize hydrocarbon extraction while concurrently minimizing environmental repercussions (Wu et al. 2024). Such microbes may improve the permeability of reservoirs and promote the extraction of methane from coal seams and other unconventional sources. The integration of biologically driven technology may enhance methane extraction efficiency while minimizing geological disturbances and decreasing the carbon impact of operations.

The incorporation of these innovative approaches into methane extraction techniques significantly impacts the attainment of national and global climate objectives. The extraction of methane, when integrated with advanced technology and rigorous environmental protections, can function as a transitional fuel in the shift toward low-carbon energy systems. Countries such as Kazakhstan, endowed with extensive coal and methane deposits, might substantially decrease greenhouse gas emissions by appropriately using these resources to replace coal in electricity production and industrial processes. The implementation of methane-based energy systems may improve energy security, especially in areas reliant on imported hydrocarbons, while promoting economic growth through the establishment of sophisticated energy infrastructure and technology industries.

A thorough environmental impact framework for methane extraction in the Karaganda Basin must encompass essential indicators related to greenhouse gas emissions, water consumption, and land degradation. Greenhouse gas emissions may be tracked by real-time systems that analyze methane leakage, flaring, and venting, while life-cycle assessments offer a comprehensive review of the carbon footprint. Assessments of water usage and quality should quantify water consumption, recycling rates, and possible aquifer pollution, along with regular tests of chemical and metal concentrations. Metrics for land degradation should monitor the extent of disturbed land, soil erosion, and biodiversity loss, accompanied by reclamation strategies for habitat restoration. Air quality measurements must evaluate contaminants such as volatile organic compounds and particles, but the effects of noise and light pollution may be reduced by decibel monitoring and mitigation strategies. A cumulative environmental impact study consolidates these measures to assess long-term sustainability, with the active participation of local people and stakeholders guaranteeing openness and response to environmental and social issues. This paradigm facilitates sustainable energy generation while preserving environmental integrity.

Methane extraction could meet a substantial portion of the energy needs of Central Kazakhstan and the city of Astana for over 50 years. This will lay the foundation for the development of new fuel and energy sectors aimed at ensuring long-term energy stability. Moreover, methane extracted from coal seams has various applications across different sectors of the economy. This form of methane serves not only as a fuel source for mobile gas power plants and boiler houses for electricity generation but also facilitates the supply of gas necessary for domestic needs and transportation. Moreover, methane is used in the metallurgical and chemical industries for material synthesis. Ultimately, the exploitation of methane and coal reserves reduces environmental impact by decreasing gas emissions into the atmosphere, thereby contributing to clean and sustainable regional development.

3. Discussion

The assessment of geological and technological parameters for evaluating the potential of coalbed methane deposits is a critical step in exploring and developing such resources.

Emphasizing the importance of methane as a clean and efficient energy source is crucial. Methane, a ubiquitous hydrocarbon, is a cornerstone for electricity generation, heating, and various thermal processes (Marignetti et al. 2023). The growing importance of coalbed methane extraction is highlighted in reducing greenhouse gas emissions and transitioning to sustainable alternative energy sources. This perspective is supported by the findings of Stavert et al. (2022), who emphasized the pivotal role of coalbed methane extraction in the contemporary energy landscape and sustainable development initiatives. Undoubtedly, methane is a critical, clean, and efficient energy source. As one of the most prevalent hydrocarbons, it extends its utility to electricity generation, heating, and various thermal applications. Coalbed methane extraction is gaining prominence against increasing concerns about greenhouse gas emissions and the search for sustainable energy alternatives (Kucher et al. 2022). Furthermore, the study by Xu et al. (2023) underscores the critical importance of assessing geological and technological parameters when evaluating the potential of coalbed methane deposits for extraction. This involves considering numerous factors, including the degree of coal metamorphism, permeability, natural gas content, natural degassing processes, gas pressure within seams, and the extent of gas weathering zones. Moreover, accounting for the geodynamic complexities of coal structures, which may affect permeability and gas extraction, becomes essential, as confirmed by the results of this study.

In the effective utilisation of coalbed methane, careful consideration of environmental factors is of paramount importance (Kovach et al. 2024). The extraction process carries inherent environmental risks, including water contamination, greenhouse gas emissions, and even seismic activity induced by hydraulic fracturing (Kaldybaev et al. 2024). Thus, stringent environmental and safety protocols must be developed and implemented at all stages of coalbed methane development. This issue is corroborated by the findings of Wahab et al. (2021), whose research highlights that the realisation of the full potential of coalbed methane depends not only on technological and economic factors but also on mitigating potential environmental impacts. Their study highlights the range of environmental issues arising from coalbed methane extraction, including water contamination, greenhouse gas emissions, and seismic events resulting from hydraulic fracturing. Similarly, the study by Wang et al. (2022) underscores the necessity of minimizing the environmental risks associated with coalbed methane extraction. Central to this endeavour are measures aimed at reducing greenhouse gas emissions, preventing water contamination, and ensuring the safety of hydraulic fracturing operations. Achieving these goals requires adherence to strict regulations, implementation of advanced technologies, and systematic monitoring protocols. It is essential to emphasize that research and development aimed at mitigating the environmental risks of coalbed methane extraction are paramount alongside technological and economic considerations. Such an approach is vital for ensuring the sustainable and responsible use of this important energy resource under contemporary conditions.

The assessment of the potential of coalbed methane deposits largely depends on geological factors, highlighting their critical role in the evaluation process. These factors encompass various characteristics of coal seams, including thickness, permeability, porosity, gas content, structure, and deposit configuration, as well as the internal properties of the gas within the seam. Key considerations for geological evaluation include the adequacy of methane volume, its economic feasibility, and the potential for effective extraction. This aspect has garnered considerable attention from researchers, with researchers such as Kędzior and Dreger (2022) emphasizing the crucial role of geological factors in determining the presence, volume, and extractability of methane. Analysis of parameters such as seam thickness, permeability, and porosity aids in assessing the deposit potential and selecting optimal extraction methods.

Moreover, geological evaluation serves as a critical tool for risk reduction during extraction, allowing for the early identification of potential complications that may hinder methane extraction. The findings of Sinha and Gupta (2021) underscore the fundamental importance of geological aspects in determining the viability of methane extraction from coal seams. The assessment of a deposit involves a comprehensive examination of coal seam characteristics, including thickness, permeability, porosity, and geometric distribution. Parallel analysis of gas parameters at the deposit site, such as composition and pressure, enables decisions to be made regarding the economic viability of extraction. These findings align with previous research, confirming the indispensable role of geological factors in minimizing risks and strategic planning for field development. A nuanced understanding of geological features not only facilitates the development of effective extraction methods but also helps prevent adverse environmental impacts. Thus, given their critical importance, geological factors must be central to the planning and implementation stages of coalbed methane extraction initiatives.

Technological advancements are a key component in the extraction of methane from coalbeds, encompassing innovations and the implementation of new techniques and tools, such as hydraulic fracturing, degasification, and the regulation of reservoir pressure and temperature (Selvakumar et al. 2023). The effectiveness of extraction technologies is a primary factor determining the project's viability. Research conducted by Xu et al. (2022) underscores the importance of technological considerations in the successful execution of the project. Modern methods, such as hydraulic fracturing, demonstrate a remarkable ability to increase the permeability of coalbeds, thereby enhancing gas extraction efficiency. This method involves creating artificial fractures in the reservoir by injecting fluid under pressure, thereby facilitating the release of methane. In addition, studies by Fan et al. (2023) investigate degasification techniques aimed at reducing reservoir pressure, thereby ensuring a stable and sustainable methane extraction process. Effective management of reservoir pressure and temperature becomes a critically important aspect in optimizing the process, given their substantial impact on gas extraction rates and volumes. These concepts reinforce earlier discussions, highlighting the crucial role of efficient extraction technologies in the project's viability. They help to minimize costs and increase methane production, rendering coalbed methane extraction efforts both economically viable and environmentally sustainable.

Various methodologies are employed to assess the potential of coalbed methane deposits, encompassing geological surveys, reservoir modelling, geochemical data analysis, and the examination of contemporary extraction methods. These approaches assist engineers and geologists in understanding the reservoir capabilities and developing optimal extraction techniques. Research conducted by Qadri et al. (2022) highlights the importance of reservoir modelling in predicting gas behaviour in coalbeds under different operational conditions, such as variations in pressure and temperature. Such modelling efforts contribute to process optimisation, thereby reducing risks and enhancing operational efficiency. Furthermore, studies by Gajdzik et al. (2024) emphasize the importance of analysing geochemical markers in determining the composition and quality of methane, which is crucial for assessing its energy content and commercial viability. Modern extraction techniques, such as hydraulic fracturing and degasification, play a key role in methane extraction. By integrating these methodologies, engineers and geologists can comprehensively understand the reservoir's potential, which allows for the formulation of effective development strategies. This integrated approach ensures a balanced equilibrium between economic benefits and environmental preservation.

Overall, the evaluation of geological and technical characteristics of coalbed methane deposits for extraction is a complex and intricate task that requires a collaborative and interdisciplinary approach. Nonetheless, given the growing interest in alternative energy sources, this field of research remains valuable and holds potential for advancing progress in the energy sector.

Conclusions

Key geological factors influencing the potential of coalbed methane deposits encompass the thickness and gas content of the coal seam, its permeability and porosity, and the geometry of the deposit. A critical factor in assessing the potential of these deposits is the presence of a sufficient quantity of methane, evenly distributed across the region. In addition, the natural degassing process and the gas pressure within the formation particularly affect the feasibility of methane extraction.

Determining the geological and technical variables that impact the potential for methane extraction from coal seams is a multifaceted and complex task. This involves a detailed examination of geological, geochemical, and technical parameters to assess the deposit potential and develop effective extraction methods. Large-scale methane production from coal seams represents a modern, socially important, and environmentally sustainable initiative. It is crucial to formulate a national development plan for coalbed methane in Kazakhstan to transform methane extraction from coal seams into a rapidly growing sector in the country and attract foreign investment. This initiative should include government support in the form of tax incentives, investment stimulation, and other supporting measures.

This study delved into the practice of industrial methane extraction from coal seams under current coal mining conditions. It elucidated the geological and operational characteristics of methane deposits associated with coal seams. The study examined the geological features of coal formations, their fragmentation, permeability, and their gas desorption capacity. It thoroughly investigated the theory of methane interaction with coal. In natural conditions, it has been noted that the gas permeability of coal seams depends on various factors, such as the structure of the coal seam, the level of water saturation in the pores, the methane pressure gradient, and the impact of mining pressure.

To enhance energy self-sufficiency, safety measures have been integrated into coal mining operations alongside the implementation of advanced and efficient technologies for industrial methane extraction from coal seams. Considering geological and economic factors such as coal-bearing formations, seam thickness, and methane distribution, the Karaganda Basin emerges as a promising site for initiating coalbed methane extraction initiatives. One of the limitations of this study is the scarcity of data on contemporary technologies and methods employed abroad for methane extraction from coal seams. Further research is needed to adapt and implement modern methane extraction techniques, utilized internationally, to the specific conditions unique to the Karaganda Basin.

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP13268841).

The Authors have no conflict of interest to declare.

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ASSESSMENT OF GEOLOGICAL AND TECHNOLOGICAL PARAMETERS OF THE PROSPECTS OF METHANE COAL DEPOSITS FOR THE EXTRACTION OF METHANE FROM COAL SEAMS

Key words

Karaganda basin, permeability, gas content, fracturing, environmental requirements

Abstract

The study is conducted to assess the geological and technological parameters that affect the prospects for the development of methane-coal deposits and ensure efficient and economically feasible extraction of methane from coal seams. This study uses methods to analyze geological data and the physical and chemical properties of coal seams and to examine the technologies and economic aspects of methane extraction from coal seams. The study includes an assessment of industrial methane production from coal seams using international practice and a comparative analysis of the geological characteristics of deposits in accordance with international standards. Geodynamic features of coal structures affecting the formation of natural cracks and reservoir permeability were considered, as well as the potential use of artificial methods to increase permeability and improve gas production processes. In this study, modern views on the relationship between methane and coal are presented based on theoretical and experimental data from physical chemistry and studies on the properties of sorbents. It is identified that gas permeability through coal seams depends on their general structure, pressure fluctuations, and special pressure dynamics of rocks. Moreover, it was determined that intact coal seams exhibit permeability dependent on the integrity of the formation. The importance of developing modern methods of methane extraction in accordance with environmental and energy standards was emphasized. In particular, the Karaganda basin has become a promising region for methane extraction initiatives, given its geological characteristics. The results of the study provided valuable information for the development of effective strategies for extracting methane from coal deposits, which will contribute to improving the environment, increasing energy sustainability, and reducing dependence on traditional energy sources.

OCENA PARAMETRÓW GEOLOGICZNYCH I TECHNOLOGICZNYCH ZŁÓŻ WĘGLA METANOWEGO POD KĄTEM WYDOBYCIA METANU Z POKŁADÓW WĘGLA

Słowa kluczowe

Zagłębie Karagandyjskie, przepuszczalność, zawartość gazu, szczelinowanie, wymagania środowiskowe

Streszczenie

Badanie ma na celu ocenę parametrów geologicznych i technologicznych, które mają wpływ na perspektywy rozwoju złóż metanu węgla oraz zapewnienie wydajnego i ekonomicznie opłacalnego wydobycia metanu z pokładów węgla. W ramach badania wykorzystano metody analizy danych geologicznych oraz właściwości fizycznych i chemicznych pokładów węgla, a także zbadano technologie i aspekty ekonomiczne wydobycia metanu z pokładów węgla. Badanie obejmuje ocenę przemysłowej produkcji metanu z pokładów węgla z wykorzystaniem praktyk międzynarodowych oraz analizę porównawczą właściwości geologicznych złóż zgodnie z międzynarodowymi standardami. Uwzględniono cechy geodynamiczne struktur węglowych wpływające na powstawanie naturalnych pęknięć i przepuszczalność zbiorników, a także potencjalne wykorzystanie sztucznych metod zwiększania przepuszczalności i usprawniania procesów wydobycia gazu. W niniejszym badaniu przedstawiono współczesne poglądy na temat związku między metanem a węglem w oparciu o dane teoretyczne i eksperymentalne z zakresu chemii fizycznej oraz badania właściwości sorbentów. Stwierdzono, że przepuszczalność gazów przez pokłady węgla zależy od ich ogólnej struktury, wahań ciśnienia i szczególnej dynamiki ciśnienia skał. Ponadto ustalono, że nienaruszone pokłady węgla wykazują przepuszczalność zależną od integralności formacji. Podkreślono znaczenie opracowania nowoczesnych metod wydobycia metanu zgodnie z normami środowiskowymi i energetycznymi. W szczególności Zagłębie Karagandyjskie stało się obiecującym regionem dla inicjatyw związanych z wydobyciem metanu ze względu na cechy geologiczne obszaru. Wyniki badania dostarczyły cennych informacji do opracowania skutecznych strategii wydobycia metanu ze złóż węgla, które przyczynią się do poprawy stanu środowiska, bardziej zrównoważonego rozwoju energetycznego i zmniejszenia zależności od tradycyjnych źródeł energii.