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ENHANCING APPROACHES FOR THE EFFECTIVE DEVELOPMENT OF COMPLEX MULTILAYER NATURAL GAS FIELDS: A COMPARATIVE STUDY

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Abstract
Multilayered natural gas fields represent a significant portion of global hydrocarbon reserves, yet their development is hindered by complex geological structures, reservoir heterogeneity, and high extraction costs. This study provides a comparative analysis of four major multilayered gas fields: Urengoy (Russia), Galkynysh (Turkmenistan), Haynesville (USA), and East Berdakh (Uzbekistan). The research evaluates the effectiveness of current extraction methods, including hydraulic fracturing (HF), horizontal drilling, and reservoir pressure maintenance strategies. Using a comparative methodology, this study identifies key challenges and proposes optimized approaches to enhance gas recovery factors (GRF). The findings suggest that a hybrid HF approach, AI-assisted digital modeling, and improved well placement strategies can significantly enhance the efficiency of multilayered gas field development.

Keywords: Multilayer gas fields, hydraulic fracturing, gas recovery factor, reservoir pressure management, digital modeling.

Introduction
Multilayered natural gas reservoirs account for a significant share of global hydrocarbon reserves, playing a crucial role in meeting the growing energy demand. However, their development is associated with significant technical and economic challenges due to their complex geological structure, heterogeneity of reservoir properties, and varying permeability across different strata [1, p. 52-53]. These factors lead to uneven depletion, inefficient gas drainage, and rapid pressure decline, ultimately reducing the gas recovery factor (GRF) and increasing operational costs.

Traditional development strategies, including primary depletion and basic pressure maintenance techniques, often prove inadequate for ensuring sustainable and efficient extraction from multilayered reservoirs [3, p. 121-124]. Given the increasing demand for natural gas and the depletion of conventional fields, optimizing recovery techniques for multilayered deposits is essential. The implementation of advanced reservoir modeling, enhanced gas recovery (EGR) methods, and digital twin technologies can contribute to the effective exploitation of these complex resources [2, p. 112-116]. Developing a systematic approach that integrates geophysical, petrophysical, and engineering data is critical to improving reservoir performance and maximizing hydrocarbon recovery from multilayered gas formations.

Methods

The selected gas fields—Urengoy (Russia), Galkynysh (Turkmenistan), Haynesville (USA), and East Berdakh (Uzbekistan)—serve as case studies for evaluating the geological and physical properties of multilayered reservoirs and the technological parameters employed in their development. These fields represent a diverse range of geological settings and extraction challenges, making them suitable for comparative analysis.

To assess the effectiveness of existing development approaches and identify potential optimization strategies, the study employs the following methods:

comparative analysis of the geological characteristics of multilayered reservoirs to determine the impact of structural complexity and heterogeneity on production efficiency;

evaluation of the effectiveness of applied technologies, including hydraulic fracturing (HF), horizontal drilling, and digital reservoir modeling, to identify their advantages and limitations under different geological conditions;

analysis of gas recovery factor (GRF) across different fields to assess the success of various extraction techniques and pressure maintenance strategies.

The study evaluates the selected fields based on the following key parameters:

reservoir type to determine the impact of geological properties on gas extraction.

applied extraction technologies to assess their suitability for multilayered formations.

Results

Among the complex multilayered natural gas fields, four significant case studies illustrate the diverse geological, technological, and operational challenges in gas extraction: Urengoy (Russia), Galkynysh (Turkmenistan), Haynesville (USA), and East Berdakh (Uzbekistan). These fields represent different geological formations, extraction methodologies, and efficiency factors, making them ideal for comparative analysis in optimizing gas recovery approaches.

The Urengoy gas field is one of the largest conventional gas fields, covering 2876 km² in Russia's Yamalo-Nenets Autonomous Region. It consists of Cenomanian, Valanginian, and Achimov formations, with high porosity (28–35%) and permeability (500–1500 mD) [14]. While natural depletion is sufficient in early stages, deeper formations require gas lift and compressor-assisted extraction. The Achimov formation, characterized by low permeability, necessitates hydraulic fracturing to sustain production. However, challenges such as reservoir pressure decline and water encroachment reduce efficiency, necessitating advanced pressure maintenance and water management technologies [7, p. 13-14].

In contrast, Galkynysh, Turkmenistan's largest gas field, represents a deep carbonate reservoir system with proven gas reserves of 27.4 trillion cubic meters. The Mesozoic carbonate formations (Upper Jurassic, Lower Cretaceous) lie at depths between 3900 and 5100 meters, with low porosity (10–20%) and extremely low permeability (0.1–50 mD) [11]. Gas extraction is technically challenging, requiring hydraulic fracturing, horizontal drilling, and gas re-injection to maintain pressure. However, high reservoir pressures (500–600 kg/cm²), elevated temperatures (80–120°C), and the presence of hydrogen sulfide (H_2S) introduce operational difficulties, requiring advanced purification technologies and specialized drilling fluids [12].

Moving from conventional to unconventional reservoirs, the Haynesville Shale in the USA exemplifies deep shale gas extraction. Discovered in 2008, this Jurassic-age shale reservoir covers 23,000 km² and is characterized by ultra-low permeability. The depth of 3200–4000 meters, combined with high formation pressures, demands horizontal drilling and multi-stage hydraulic fracturing (HF) as primary extraction techniques [15]. Despite its high potential, reservoir depletion, economic constraints, and price fluctuations have led to varying production levels. However, recent advances in artificial intelligence-driven well optimization and refracturing techniques have improved efficiency and sustainability.

Table 1. Geological Characteristics of Selected Gas Fields

Parameter	Urengoy (Russia)	Galkynysh (Turkmenistan)	Haynesville (USA)	East Berdakh (Uzbekistan)
Reservoir Type	Sandstone	Carbonate	Shale	Multilayer Gas-Condensate
Depth (m)	900–3500	3900–5100	3000–4500	1400–2750
Permeability (mD)	1–1000	0.1–50	<0.01	0.5–200
Porosity (%)	15–25	5–15	3–10	10–20
Main Challenges	Water breakthrough	High temperature, H_2S	Low permeability	Reservoir heterogeneity

The East Berdakh gas field in Uzbekistan presents a multizonal gas-condensate system, with 27 identified productive layers spanning Upper and Middle Jurassic formations at depths of 1400 to 2750 meters. While reservoir pressure reaches 200 kg/cm², permeability remains low, necessitating stimulation methods such as hydraulic fracturing and multi-zone completion [5, p. 11]. The field faces reservoir compartmentalization, water encroachment, and heterogeneous permeability, making real-time reservoir monitoring and adaptive extraction strategies essential for optimizing production [9, p. 17-19].

These four fields collectively highlight the complexities in developing multilayered gas reservoirs. While conventional fields (Urengoy, Galkynysh) require enhanced pressure support and reservoir management, unconventional formations (Haynesville, East Berdakh) rely on advanced stimulation techniques for economic production. By integrating digital reservoir modeling, AI-driven well optimization, and advanced hydraulic fracturing technologies, the efficiency of multilayered gas extraction can be significantly improved, ensuring sustainable production across diverse geological settings.

Table 2.
Comparative Analysis of Development Methods and Challenges

Parameter	Urengoy (Russia)	Galkynysh (Turkmenistan)	Haynesville (USA)	East Berdakh (Uzbekistan)
Primary Extraction Method	Natural depletion, gas lift, compressor-assisted extraction	Natural depletion, gas lift, compressor-assisted extraction	Horizontal drilling, multi-stage hydraulic fracturing	Natural depletion, gas lift, compressor-assisted extraction
Enhanced Recovery Techniques	Hydraulic fracturing, multilateral drilling	Hydraulic fracturing, horizontal drilling, gas re-injection	AI-driven well optimization, refracturing techniques	Hydraulic fracturing, multi-zone completion, gas re-injection
Reservoir Complexity	Multilayered, moderate permeability, pressure decline	Deep carbonate formations, extremely low permeability	Shale formation, ultra-low permeability	Compartmentalized, low to moderate permeability
Challenges	Water breakthrough,	High pressure and temperature, H_2S	High production costs, price	Reservoir compartmentalization,

	declining pressure, heterogeneous permeability	contamination, reservoir heterogeneity	fluctuations, rapid decline rates	water encroachment, selective stimulation
Applied Digital Technologies	Limited use of digital monitoring, gradual implementation	Emerging digital solutions for real-time monitoring	Advanced AI-driven predictive models, real-time optimization	Limited digital integration, early adoption of AI-driven monitoring
Overall Efficiency	Moderate to high, but decreasing due to aging reservoirs	Moderate, requires advanced stimulation and processing	High but heavily dependent on continuous technological upgrades	Moderate, but constrained by geological complexity

The analysis of Urengoy, Galkynysh, Haynesville, and East Berdakh highlights several key challenges in the development of complex and multilayered gas fields (table 2). Addressing these issues requires advanced technologies and optimized extraction strategies.

Discussion

Limited real-time monitoring and predictive modeling reduce production efficiency in Urengoy and East Berdakh. Uncertainty in fluid movement across reservoir layers leads to uneven depletion and suboptimal well placement. Implementing AI-driven reservoir simulations can improve pressure and flow predictions, while digital twin models allow for real-time monitoring and production adjustments. The use of big data analytics enhances decision-making, reducing operational downtime and improving reservoir performance [8, p. 24-25].

Inconsistent fracturing efficiency in Galkynysh and East Berdakh results from permeability variations across different layers. In Haynesville, declining well productivity in tight formations remains a key issue [15]. The adoption of hybrid fracturing techniques, combining proppant-based and acid fracturing, can improve permeability. Nanoparticle-enhanced fracturing fluids further enhance fracture conductivity, optimizing gas extraction from low-permeability formations. Refracturing of older wells can help restore productivity and extend field life.

Reservoir pressure depletion limits gas production in Urengoy and Haynesville, while high reservoir pressures in Galkynysh complicate extraction and require specialized well designs. In East Berdakh, compartmentalized reservoirs make pressure maintenance difficult, leading to uneven depletion [5, p. 53-54].

Gas re-injection techniques can help sustain reservoir pressure in deep and complex formations. Foam-based and CO_2 injection methods provide alternative pressure

maintenance solutions. The integration of real-time pressure monitoring systems ensures better reservoir control and optimization of gas extraction rates [4, p. 39].
Ultra-low permeability in Haynesville significantly restricts gas flow, while fracture closure in Galkynysh reduces production efficiency over time [12]. In some reservoirs, traditional proppants prove ineffective in maintaining permeability. Smart proppants with shape-memory polymers help keep fractures open longer, while high-strength ceramic proppants improve fracture conductivity under high-pressure conditions. The application of nano-engineered surfactants enhances gas mobility and prevents blockages, improving overall well performance.
Developing complex and multilayered gas reservoirs requires a combination of digital technologies, hybrid stimulation techniques, pressure optimization strategies, and innovative materials. The integration of AI-driven reservoir management, smart fracturing technologies, and real-time monitoring will significantly enhance gas recovery efficiency, reduce costs, and ensure long-term sustainability of these challenging fields [6, p. 11-13].

Conclusion

Multilayered gas fields require customized development strategies due to their geological complexity. Standard extraction methods are often insufficient, making advanced fracturing, optimized well placement, and adaptive pressure management essential.
East Berdakh and Haynesville demand significant fracturing improvements and well placement optimization to enhance gas flow and sustain production. Their low permeability and compartmentalized reservoirs require hybrid fracturing and multi-zone completions for efficient recovery.
AI-driven reservoir management and digital twin technologies provide real-time monitoring and predictive analytics, improving well performance and operational efficiency. These tools enable dynamic pressure control and optimized extraction strategies.
Future research should focus on pilot testing AI-driven solutions, validating their impact on efficiency, cost reduction, and long-term field sustainability.

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