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Editorial

A Review of Exploration and Development Technologies for Coal, Oil, and Natural Gas

Gan Feng [1], Guifeng Wang [2], Hongqiang Xie [1,*], Yaoqing Hu [3], Tao Meng [3,4] and Gan Li [5]

1 State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource & Hydropower, Sichuan University, Chengdu 610065, China; fenggan@whu.edu.cn
2 State Key Laboratory of Coal Resources and Safe Mining, School of Mines, China University of Mining and Technology, Xuzhou 221116, China; wgfskl@163.com
3 Mining Technology Institute, Taiyuan University of Technology, Taiyuan 030024, China; huyaoqing@tyut.edu.cn (Y.H.); mengtao@tyust.edu.cn (T.M.)
4 School of Energy and Materials Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China
5 Department of Civil Engineering, Ningbo University, Ningbo 315211, China; ligan303@126.com
* Correspondence: alex_xhq@scu.edu.cn

Energy is the fundamental prerequisite for human survival and development, as well as the driving force behind the progress of human civilization. Fossil fuels, which primarily include coal, oil, and natural gas, are the dominant energy sources. Combustible ice, a novel type of fossil energy found on the seabed, represents a more recent addition to this category. These fossil fuels are all non-renewable energy sources [1]. The consumption of coal, oil, and natural gas is relatively balanced across major fossil fuel-consuming countries worldwide. The United States of America and European Union countries rely primarily on oil and natural gas as their main energy sources; China's energy mix, in comparison, is dominated by coal. Despite a brief decline in the proportion of fossil fuels in overall energy consumption during periods of global public health emergencies, the demand for fossil fuels in countries around the world is expected to continue to increase as the economy gradually recovers.

According to the distribution of coal seams, underground mining and open-pit mining are the primary methods employed for coal extraction. As the intensity of coal mining activities has increased, the depth of mining operations has gradually escalated in turn. The innovation of deep coal mining technology must consider issues related to safety, environmental protection, and economic viability [2]. From the perspective of coal mining safety, factors such as the instability of coal seam roof and floor, water inrush disasters, coal and gas outbursts, coal mine subsidence, and rockbursts pose significant threats to underground mining operations [3–6]. Conversely, in open-pit coal mining, water accumulation and slope instability are the primary safety concerns. Therefore, it is necessary to innovate and develop filling mining methods and water conservation mining techniques. For thick or gently inclined coal seams, the application of fully mechanized top coal caving technology can improve resource recovery rates, reduce dust pollution, and prevent fires [7,8]. In open-pit mining, the development of new technologies for grouting water blocking and slope reinforcement should be prioritized. From an environmental standpoint, issues such as underground rock damage, surface water pollution, groundwater leakage, and vegetation destruction in mining areas are becoming increasingly severe. Consequently, it is crucial to promote comprehensive green mining and management technologies, as well as explore methods for reducing and utilizing abandoned mine water, coal gangue, and waste material treatment. Simultaneously, it is necessary to study how to improve the ecological environment of mining areas, including the ecological restoration of surface subsidence areas caused by coal mining. From an economic perspective, the innovation of deep coal mining technology requires the development of more efficient, intelligent,

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and automated equipment and processes, as well as the creation of more advanced remote control and comprehensive management platforms. These advancements aim to enhance resource extraction efficiency, reduce production costs, minimize disasters and accidents, ensure personnel safety, and protect the ecological environment.

Petroleum is a widely utilized resource across diverse domains integral to human survival and development [9]. As oil extraction continues to evolve, recoverable oil reserves are becoming increasingly scarce, and the extraction of deep-seated petroleum deposits has emerged as a critical trend for future progress. However, the growing complexity of oil exploitation has rendered the efficiency of extraction processes highly dependent on the advancement of exploitation equipment. This issue therefore necessitates the development of state-of-the-art equipment adapted to deep-sea environments, capable of overcoming the myriad of challenges posed by high-temperature and high-pressure conditions. In the realm of oil extraction technology, water injection for oil production is a highly intricate process. Consequently, it is imperative to innovate and advance exploration and development technologies for deeper petroleum reserves, with the aim of enhancing oil production and recovery efficiency. This process entails the implementation of more accurate oil reservoir detection through cutting-edge digital, intelligent, and automated technologies. Simultaneously, it is essential to develop novel fracturing technologies to better control subterranean cracks. Furthermore, during the oil extraction process, paramount consideration must be given to safeguarding the ecological environment.

The role and prominence of unconventional oil and gas within the global energy landscape continue to steadily amplify. Shale oil, an unconventional petroleum resource with significant potential, has increasingly come to the forefront [10]. Similarly, the development of tight oil has been gradually progressing [11]. While the United States and Canada have indeed cultivated relatively mature technologies for unconventional gas exploration and development, the efficient extraction of unconventional natural gas in complex deep-sea environments continues to grapple with numerous challenges.

Coalbed methane represents a crucial frontier for the development of unconventional natural gas resources [12]. However, the exploration and development of coalbed methane face numerous challenges, such as the complex and variable geological structure of coal seams, which significantly impedes exploration efforts. Accurately assessing the coalbed methane content within coal seams is not only of paramount importance for coalbed methane extraction but also beneficial for evaluating the risk of coal and gas outbursts [13]. The assessment of coalbed methane resource reserves necessitates a comprehensive consideration of multiple fields, including geology, geochemistry, and physics, which poses significant challenges for accurate resource evaluation. Continuous innovation and research are indispensable in the development of coalbed methane mining equipment and processes that can effectively adapt to the diverse mining environments encountered.

Shale gas currently represents a critical domain for the development of unconventional natural gas resources [14,15]. Notably, the United States of America has emerged as the global leader in the mature application of shale gas exploration and development technology, with an estimated recoverable shale gas reserve of approximately 13.64×10^{12} m^3 [16]. Fayetteville stands out as a large-scale, commercially successful shale gas field, second only to the pioneering Barnett field. In addition to the traditional hydraulic fracturing techniques employed for shale gas extraction, the gradually evolving CO_2 fracturing technology is also being applied to shale gas recovery [17,18]. The utilization of CO_2 to enhance shale gas extraction efficiency holds substantial promise [19]; however, the large-scale commercial deployment of this technology remains in the exploratory stage [20].

It is generally recognized that industrial gas flows occurring within natural tight sandstones, which are challenging to extract without the application of hydraulic fracturing or CO_2 fracturing, are referred to as tight sandstone gas [21]. This definition is inherently relative in nature. The U.S. Department of Energy designates gas-bearing sandstone reservoirs with porosity less than 10%, original formation permeability less than 0.1×10^{-3} μm^2, and water saturation greater than 40% as tight gas sandstone reservoirs [22]. The degree of fracture development within the reservoir can significantly impact the physical and mechanical properties of the rock mass, leading to variations in tight sandstone gas production. Tight gas reservoirs are characterized by low porosity, low permeability, and a complex microstructure, with the presence of material migration, such as water and gas, within the pores. The United States of America has discovered over 900 tight gas fields across 23 basins, with estimated recoverable reserves of 5×10^{12} m^3 [23].

The potential global reserves of combustible ice are estimated to exceed 1.5×10^{16} m^3 [24–27]. Combustible ice contains substantial natural gas resources and possesses a high calorific value. In high-pressure environments on the seabed, combustible ice remains in a solid state; however, once extracted, it will decompose into gas. Common techniques employed for extracting combustible ice include depressurization, heat injection, displacement, and chemical inhibitor injection. More than 30 countries worldwide are conducting research on the extraction of combustible ice, with the United States of America, Canada, and Japan leading efforts and investing heavily in the development of extraction technologies. Despite ongoing innovation and advancements in mining technology, the extraction of combustible ice remains relatively costly. Moreover, current research on combustible ice extraction primarily focuses on indoor experiments and numerical simulations, with limited investigations on industrial-scale field experiments.

Research on the development of efficient and environmentally sustainable technologies for fossil fuel extraction encompasses multiple disciplines, including rock mechanics, seepage mechanics, physical chemistry, and fracture mechanics. We launched the research theme of "Advanced Coal, Petroleum and Nature Gas Exploration Technology, 2nd Edition" and have published five related studies on this topic. These studies hold significant promise in advancing technological innovation and exploration efforts in the development of fossil fuel resources.

Wu et al. [28] investigated the impact of high-temperature and high-pressure fracturing fluid immersion on shale reservoirs. They conducted immersion experiments on rock samples with varying mineral compositions, based on the reservoir's environmental conditions, temperature, and pressure settings, as well as triaxial compression mechanics experiments. The researchers analyzed the changes in fracture damage stress and peak deviatoric stress under shale mechanical loading with different viscous fracturing fluids over time. The results indicate that high-temperature and high-pressure hydration soaking has a significant softening effect on the stress characteristic values of shale gas reservoirs. Additionally, the soaking time and the use of fracturing fluids with different viscosities have a significant impact on the stress characteristics.

Wan et al. [29] analyzed the experimental data of natural gas hydrate reservoirs in a specific region of China and developed numerical simulations under different layout schemes. They conducted a simulation study to assess the natural gas production efficiency of these hydrate reservoirs. The results demonstrated that the production performance was optimal when the radial and transverse directions were arranged in a three-phase layer (TPL) configuration. Furthermore, various indicators were calculated to predict the percentage increase in natural gas production.

Li et al. [30] initiated a study focused on device development, leading to the creation of a novel type of conductor suction pile device. They then investigated the lateral stability performance of the conductor pile. This study involved theoretical analysis, mathematical equation derivation, and the development of a corresponding solution program using MATLAB. Lastly, a well in the South China Sea was used as an engineering case to verify the effectiveness of the method. Additionally, the researchers obtained the mechanical properties of the developed device.

Lin et al. [31] published a review article that provides a detailed analysis of the current research status and future development trends of gas injection to enhance oil recovery in gas reservoirs. The authors analyzed the gas injection and extraction situation of the gas reservoir from three aspects: experiments, numerical simulations, and field engineering. Some key conclusions were drawn, including the formation of an effective buffer gas in the bottom reservoir after gas injection, higher production efficiency and lower cost of N_2 injection, significant recovery effects in water-drive gas reservoirs and condensate gas reservoirs, and the potential to increase recovery rates by more than 10% through the injection of natural gas into water-drive and depleted reservoirs. Additionally, the authors put forward their own opinions, such as the need to study the gas penetration ability through experiments and the current lack of mixed-phase flow models.

Zeng et al. [32] mainly used indoor experimental methods to explore ways to improve oil recovery in tight reservoirs, specifically by conducting research on surfactants. The authors designed an experiment to investigate the mechanism of oil removal by in situ micro lotion. Through salinity scanning experiments, the researchers compared the relationship between different surfactants and crude oil from the Mahu reservoir. They then studied the adsorption and reflux characteristics of surfactant micelle solutions. Ultimately, the researchers concluded that by improving the channels between different media, the movement of the oil–water interface can be promoted, thereby increasing the permeability of the oil phase.

In summary, for the exploration and development of fossil fuels such as coal, oil, and natural gas, it is necessary to continue considering both mining efficiency and environmental protection in the future and to conduct further in-depth research. Fossil energy involves multiple fields, such as oil extraction, where the physical and mechanical properties of rocks affect drilling efficiency and wellbore stability, which is crucial for oil exploration and development. It is necessary to conduct research on the multi-field coupling effects of rock crack propagation involved in underground engineering. The authors of previous studies have examined the mechanical properties, fracture behavior, and fragmentation laws of rocks under the influence of certain environmental factors [33–36], providing a foundation for in-depth research on crack propagation. Moreover, in coal mining, the prominent stress environment characteristics of deep, high-stress conditions necessitate research on achieving efficient and safe coal mining. The transformation of unconventional natural gas reservoirs is another key technology [37] requiring extensive research from multiple perspectives.

Given this context, we released the theme of "Advanced Coal, Petroleum, and Natural Gas Exploration Technology, 3rd Edition" to attract high-quality research results. This topic includes, but is not limited to, research on unconventional oil and gas resource extraction, reservoir characteristics, improving oil and gas recovery, multiphase flow problems, numerical simulation, energy extraction efficiency, engineering testing, geomechanics, hydraulic fracturing, CO_2 fracturing, and rock mechanics. We invited papers on technology research and development, basic theories, reviews, indoor experiments, engineering experiments, engineering production, mining cases, and numerical simulations related to energy sources such as coal, oil, and natural gas.

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