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Research on Fractures in Hydraulic Fracturing Reservoirs

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Abstract: Hydraulic fracturing is an important technology for unconventional natural gas extraction. It generates volume opening in the reservoir by injecting a fluid volume exceeding the reservoir's pore elasticity, thus opening up migration channels for free gas. The fracturing effect is significantly influenced by the distribution of natural fractures and fissures in the reservoir. Natural fractures are crack systems formed in rocks under natural conditions and are widely present in unconventional reservoirs such as shale, tight sandstone, and coal seams. During the hydraulic fracturing process, they communicate with hydraulic fractures to form complex fracture networks. Moreover, natural fissures can alter the stress field distribution in the reservoir, affecting the initiation and propagation behavior of fractures. Therefore, this paper focuses on the impact of fractured reservoirs on fracturing effects, providing theoretical references for optimizing fracturing designs.

Keywords: Hydraulic fracture; cleat reservoirs; fracture networks.

1. Research Background and Significance

In recent years, advancements in oil and gas exploration and development technologies have facilitated the large-scale exploitation of tight gas, coalbed methane and shale gas. Unconventional oil and gas resources have gradually become an important area for oil and gas exploration and production increase in China. In 2023, China's oil and gas production equivalent exceeded 390 million tons, with crude oil production reaching 208 million tons and natural gas production reaching 230 billion cubic meters, maintaining a growth of over 10 billion cubic meters for seven consecutive years. The output of unconventional natural gas exceeded 96 billion cubic meters, accounting for 43% of the total natural gas production, becoming the main driving force for natural gas production increase. The construction of shale oil and gas demonstration zones has been continuously advanced, and significant breakthroughs have been made in deep coalbed methane exploration. The output of unconventional oil and gas has continued to grow, providing important support for the increase in national oil and gas production.

Hydraulic fracturing technology is a key yield-increasing measure in the development of oil and gas fields, especially playing an important role in the development of unconventional oil and gas resources such as shale gas, tight sandstone gas and coalbed methane. By injecting fluids that exceed the pore elasticity of the reservoir, the pores of the reservoir undergo elastic expansion, and the matrix framework undergoes chain fractures, forming hydraulic fractures. Eventually, a fracture network is constructed in the reservoir, creating artificial permeability, providing channels for the seepage, desorption and diffusion of natural gas, and achieving effective oil and gas extraction. However, the natural fractures and fracture distribution within the reservoir have a significant impact on the effect of hydraulic fracturing, which makes the study of the characteristics of natural fractures and their role in the fracturing process the key to engineering design and optimization.

Natural cutting is a system of fractures or fissures formed in rocks under natural conditions, and its formation is mainly influenced by various geological processes. Firstly, tectonic stress is one of the main causes of cutting formation. When the Earth's crust is subjected to tectonic stresses such as compression, tension or shear, rocks will rupture, forming a regular network of fractures. Secondly, during the cooling process of igneous rocks, internal stress is generated due to volume contraction, which leads to rock rupture and the formation of cooling shrinkage cracks. In addition, weathering is also an important factor in the formation of cuts. Physical weathering, chemical weathering and biological weathering can all cause rocks to gradually break. Finally, unloading can also lead to the formation of cuts. When the overlying rock layer is eroded or spiced, the rock expands and ruptures due to the reduction of pressure. These geological processes jointly shape the natural cutting systems in rocks, which are widely present in unconventional reservoirs such as shale, tight sandstone and coal seams, providing important channels for the storage and migration of unconventional natural gas.

These natural fissures usually have complex spatial distribution and geometric morphology, and their characteristics such as direction, density, opening and filling materials vary. During the fracturing process, the propagation path and morphology of artificial fractures are often strongly influenced by natural fractures. When cracks encounter natural cracks, phenomena such as crack turning, bifurcation or expansion along natural cracks may occur, thereby forming a complex crack network. The formation of this fracture network can significantly increase the volume opening degree of the reservoir, but at the same time, it may also lead to the ineffective loss of fracturing fluid and proppant, affecting the fracturing effect.

In addition, the existence of natural fractures can also change the stress field distribution of the reservoir, thereby affecting the initiation and propagation behavior of artificial fractures. For example, in high-density natural fracture areas, stress concentration may lead to the non-uniform expansion of fractures and even induce microseismic events. Therefore, analyzing its influence on the hydraulic fracturing process is of great significance for optimizing the fracturing design and improving the fracturing effect. In recent years, with the development of geomechanics, numerical simulation and microseismic monitoring technologies, researchers have been able to depict the characteristics of natural fractures more accurately and predict their impact on the fracturing effect, providing a scientific basis for the efficient implementation of hydraulic fracturing engineering.

2. Research Status of Hydraulic Fracturing

Hydraulic fracturing technology was first put into practical use in the field of oil and gas extraction in the 1930s. By the middle of the 20th century, scholars had constructed the theoretical framework of this technology for the first time. With the vigorous development of the oil and gas industry, researchers have continuously and deeply explored the mechanical principles and theoretical modeling of the hydraulic fracturing process, and successively established systematic fracturing mechanical analysis models and fracture propagation theoretical systems. These important research achievements have laid a solid theoretical foundation for the subsequent development of various modeling methods and have become an important basis for verifying the accuracy of new models.

The classic models of hydraulic fracturing opening degree, such as PKN, KGD and Radial models[1-5], are all rooted in the fertile soil of linear elastic fracture mechanics theory. These models provide global analytical solutions for crack length, width and fluid pressure distribution. To depict the influence of stratum stratification on fracture morphology, the study further discretized the parallel plate model into basic fracture units and constructed numerical models such as P3D, PL3D and Full3D based on the discontinuous displacement method (DDM), which were used to simulate the hydraulic fracturing process. Adachi[6] systematically expounded on the application of these numerical models in the petroleum industry. This type of model is based on the idealized fracture morphology, assuming that the fracture surface is flat and the propagation path is preset. It mainly focuses on the evolution of parameters such as fluid pressure, fracture width and length, without considering the changes in the external stress field of the fracture and the pore structure.

Another classic type of crack numerical simulation method is the Cohesive finite element method (Cohesive FEM) [7-8]. This method simulates the crack opening process by embedding cohesive units on the preset fracture path, mainly characterizing the changes of internal parameters of the crack, without considering the responses of the surrounding pore structure, thereby achieving the idealized characterization of cracks in infinitely large elastomers.

At the microscopic scale, the hydraulic fracturing mechanism model mainly studies the initiation, propagation and interpenetration processes of micro-fractures. Due to the relatively simplified characteristics of mesomechanical behavior and the need to consider the macroscopic constitutive relationship of rocks and the dynamic propagation law of faults, it is suitable for the analysis and application of various numerical simulation methods. Such as Extended Finite Element (XFEM) [9-11], seepage - stress - Damage finite element model [12], Discrete element model [13], boundary element model [14], and continuous and discontinuous element model [15], etc. Although these models can visually display the details of crack propagation, the uncertainties caused by structural discretization (such as microstructure modeling and parameter assignment) make it difficult to be directly extended to large-scale engineering applications.

Huang Liuke [16] et al. established a three-dimensional fully coupled stochastic fractured shale reservoir three-cluster fracturing numerical model based on the discrete lattice method, with a focus on analyzing the influence law of natural fractures on the competitive propagation of multiple clusters of hydraulic fractures. Studies show that when hydraulic fractures meet natural fractures, they exhibit various patterns such as penetration, turning, and bifurcation. The natural fracture network intensifies the stress shadow effect, providing important guidance for the optimization of shale gas fracturing parameters.

Zhu Haiyan [17] et al. simulated the random propagation behavior of hydraulic fractures in fractured shale reservoirs by establishing a seepage-stress-damage coupled finite element - discrete fracture network (FFEM -DFN) model, and explored the effects of natural fracture approach Angle, cluster spacing, horizontal stress difference and pump injection displacement on the propagation of multi-cluster fractures. The research finds that the interaction between hydraulic fractures and natural fractures mainly manifests in three mechanisms: penetration, opening or being prevented. As the approach Angle of natural fractures increases, the propagation direction of hydraulic fractures is more likely to deflect or even be prevented.

Li Quangui [18] et al. adopted the discrete element numerical method to establish the flux-structure coupling model of hydraulic fracturing and analyzed the influences of fracturing displacement, Poisson's ratio and natural fracture density on stress evolution and fracture propagation. The results show that the fracturing displacement has a significant influence on the direction of stress evolution and the shape of the path curve. Under a low displacement, the stress ratio near the fracture gradually increases, while under a high displacement, it first increases and then decreases. The natural fracture density plays a key role in the propagation of hydraulic fractures. In coal seams with highly developed fractures, the direction of hydraulic fracture propagation is difficult to predict, and the direction of stress evolution may reverse.

Wasantha[19] et al. used the discrete element software UDEC to study the influence of natural fractures in reservoirs on the geometry of hydraulic fracture propagation and found that natural fractures had a significant impact on the symmetry of fracture propagation. Zhang et al. explored the mechanism of hydraulic fracture propagation and the influence of natural fractures on hydraulic fracture propagation using the continuous-discontinuous element method. The results showed that when hydraulic fractures were close to natural fractures, the natural fractures preferentially suffered shear failure, making the fracture morphology more tortuous.

3. Research Status of Reservoir Cutting Fractures

Coalbed methane, as an important unconventional natural gas resource, its development efficiency is closely related to the cutting, porosity and fracture characteristics of coal reservoirs. In recent years, with the development of coalbed methane gradually expanding into deep reservoirs, researchers have conducted extensive and in-depth studies on the development characteristics of coal seam cuts, pores and fractures and their influences on the migration and production of coalbed methane [20-29]

Wang Wenwen, Liang Yunan [30] et al. found that there are significant differences between coal reservoirs and conventional reservoirs in terms of properties, components and gas occurrence states, and coal seams have complex cutting systems. The degree of cut development is closely related to the change of permeability. Therefore, effectively evaluating the development of cuts is of great significance for the efficient development of coalbed methane. The researchers introduced the influence of cutting on the elastic properties of the medium and the local flow effect between pores and cutting into the equation, increasing the two key parameters of cutting density and cutting aspect ratio. Combined with the CT analysis data of coal and rock, the development degree of coal seam cutting in a certain block in the southern part of the Qinshui Basin was evaluated, revealing the influence law of cutting characteristic parameters on the productivity of single coal seam Wells.

Wang Zhenzhi, Fu Xuehai [31] et al. systematically analyzed the four stages of deep coalbed methane production: rapid increase in production, relatively stable production, slow decrease in production, and low production stage. Studies show that during the rapid production increase and relatively stable production stages, the reservoir pressure is relatively high, the gas source is mainly free gas, and the methane migration is dominated by seepage. The main influencing factors include the structure of the coal body, the development degree of pores and fractures, reservoir temperature, in-situ in-situ stress, etc.

Shi Leiteng, Zhao Qiming [32] et al. established a two-dimensional fracture network model of coal and rock using COMSOL Multiphysics software and studied the influence of factors such as fracture length, density, opening and Angle on seepage capacity. The results show that the larger the fracture length, density and opening, the smaller the Angle with the flow direction, and the stronger the seepage capacity of coal and rock. However, with the increase of these factors, the growth rate of flow gradually slows down. The further increase of a single factor has no significant effect on improving coalbed methane exploitation and the cost is relatively high. The research also suggests that by using directional boreholes and hydraulic slots to communicate the natural fracture system, combined with the high-pressure hydraulic cutting method, the development efficiency of coalbed methane can be effectively improved.

Liu Shiqi, Wang He [33] et al. discovered that the genesis types of coal seam pores and fractures are complex, the scale distribution range is wide, and the heterogeneity is strong. Their development characteristics are the result of the combined action of multiple factors such as coalification, metamorphism, tectonic evolution, the composition of coal and rock materials, and underground fluids. Coalification is the internal cause and tectonic stress is the external cause. The combined action of the internal and external causes has formed the development characteristics of coal seam pores and fractures in different coal grades, different coal-bearing basins and different tectonic positions. The research also emphasizes that in the future, coal seam pores and fractures should be recognized as an overall desorption - diffusion - seepage network, and further explore the sources and effectiveness of permeability controlled by the pore-fracture connectivity network, as well as the development characteristics and structural relationships of pore-fractures at the nanoscale.

Hou Lianlang, Liu Xiangjun [34] et al. conducted uniaxial compression numerical simulation experiments on two-dimensional numerical models with different cutting numbers, densities and angles using RFPA software. Studies show that the loading process of coal and rock can be divided into three stages: energy accumulation, energy dissipation and energy release. With the increase in the number of cuts, the rising speed of the total energy and elastic energy curves of coal and rock slows down, and the dissipated energy changes little, indicating that the external force only needs to do less work on the specimen to destroy it. The cutting Angle has the greatest impact on energy storage. The energy storage efficiency is the highest at cutting angles of 0° and 90°, while it is the lowest at 60°. The research also found that an increase in the complexity of the cutting structure would lead to a decrease in the total energy and elastic energy, but had no significant impact on the dissipated energy.

Ma Geng et al. [35] conducted physical simulations of hydraulic fracturing on similar material specimens with artificially preset fractures through an indoor test system, and analyzed the influence of natural fractures on the propagation of hydraulic fractures in combination with three-dimensional scanning technology. The results show that the existence of natural cracks significantly reduces the crack initiation pressure and generates secondary pressure peaks during the pumping process. The morphology of natural fractures has an important influence on the extension path of hydraulic fractures. When the main fracture encounters a natural fracture, the extension path changes, often penetrating and expanding with the natural fracture, forming a complex fracture network system, providing an efficient migration channel for coalbed methane. This research reveals the key role of natural fractures in the formation of fracture networks.

Jiang Changbao et al. [36] utilized a true triaxial fluid-structure coupling test system to explore the influence law of natural fractures on the initiation and propagation of coal in hydraulic fracturing. The research finds that natural fractures can significantly reduce the fracture initiation pressure of coal and rock, and induce the expansion of hydraulic fractures along the direction of natural fractures. From a mesoscopic perspective combined with fracture mechanics analysis, the complex mechanism of the interaction between natural fractures and hydraulic fractures has been revealed. The results show that the existence of natural fractures leads to the diversity of hydraulic fracture propagation forms and has an important impact on the permeability enhancement effect of coal seams.

Zhou et al. [37] conducted true triaxial tests to observe the geometric shape and propagation behavior of fractures. The results showed that the higher the shear strength of natural fractures, the more easily hydraulic fractures were "captured" by natural fractures. Zhang et al. designed a triaxial fracturing experiment of a closed cemented fracture network to explore the influence of natural fractures on the propagation behavior of hydraulic fractures. The study found that there were four interaction behaviors between natural fractures and hydraulic fractures. However, most of the experiments can only study the fracture propagation characteristics after fracturing and cannot visually display the fracture propagation evolution process.

4. Conclusions and Prospects

The classical fracture model and its propagation mechanism provide a fundamental theory for hydraulic fracture propagation and are applicable to idealized simple fractures. Although the fracture mechanism model reveals the complexity of the fracture network at the micro level, its overly discretization feature makes it difficult to reflect the macro characteristics of the reservoir, and the production of oil and gas mainly depends on the macro effect. Therefore, the existing hydraulic fracturing and stress disturbance models are mostly concentrated on the analytical solutions, semi-analytical solutions or numerical solutions of the overall fracture scale, and the unified modeling of the volume opening degree of hydraulic fracturing, fracture propagation mechanism and stress disturbance has not yet been achieved.

In modern horizontal well volume fracturing technology, with the increase of process complexity and scale, mechanical problems such as the interaction between fluid and reservoir under multi-field coupling, the development mechanism of fracture networks in the three-dimensional stress field, the long-term diversion capacity of fractures, and fracture propagation and control in the well factory mode have become increasingly prominent. The core of these problems lies in the effect of stress disturbance, and its evaluation method has become a key issue in the exploitation of unconventional natural gas.

The development characteristics of coal seam cutting, pores and fractures have significant influences on the occurrence, migration and output of coalbed methane. The research on the influence of coal and rock fracture morphology on seepage capacity shows that optimizing the geometric characteristics of the fracture network can increase the production of coalbed methane. The development of coal seam pores and fractures is diverse, and the research focuses on the characterization of multi-scale pore-fracture structures and their influence on permeability. Furthermore, the research on the influence of cutting on the energy evolution characteristics of coal and rock provides a new perspective for the mechanical problems in the development of coalbed methane.

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