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Research Progress of Three-dimensional Geological Modeling and Multi-field Coupling of Fractured Oil and Gas Reservoirs

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Abstract: Fractured oil and gas reservoirs play an important role in oil and gas exploration and development due to their complex fracture network structure. As the main fluid channel in the reservoir, fractures have a significant impact on the migration, accumulation and exploitation efficiency of oil and gas. This paper summarizes the key geological characteristics of fractured reservoirs, including fracture types, distribution rules and main controlling factors of fracture development, and discusses the influence of fractures on reservoir physical properties. Furthermore, the deterministic and stochastic modeling methods of three-dimensional geological modeling of fractured reservoirs and the latest progress of discrete fracture network modeling technology are introduced in detail. In addition, this paper also discusses in detail the application of multi-field coupling model in the numerical simulation of fluid flow in fractured reservoirs, including continuous medium model and discrete medium model, and their advantages and disadvantages in simulating fluid flow in fractured reservoirs. Finally, this paper summarizes the research progress of multi-physics coupling model of fractured reservoirs, and points out the direction and challenges of future research. Through these studies, it can provide theoretical support and technical guidance for oil and gas exploration and development, in order to achieve more effective development and management of fractured reservoirs.

Keywords: Fractured reservoir; geological characteristics; three-dimensional geological modeling; multi-field coupling model; numerical simulation; oil and gas exploration.

1. Introduction

As an important object in oil and gas exploration and development, the complex fracture network structure of fractured reservoirs has a decisive influence on fluid migration, aggregation and extraction efficiency. With the development of oil and gas resources gradually expanding to deep and complex rock formations, the in-depth study of fractured reservoirs is particularly urgent. The purpose of this paper is to review the geological characteristics of fractured reservoirs, 3D geological modeling methods, and the research progress of multi-field coupling models, in order to provide theoretical support and technical guidance for hydrocarbon exploration and development.

In the study of fractured reservoirs, the types of fractures, their distribution patterns, and the main controlling factors of their development are basic and key scientific issues. In addition, the effect of fractures on reservoir physical properties, such as permeability and porosity, is directly related to the potential for oil and gas recovery. Therefore, accurate simulation of fracture networks and prediction of their effects on reservoir properties are key to achieving effective development. In recent years, with the development of computer technology and numerical simulation methods, significant progress has been made in 3D geological modeling and multi-field coupled modeling of fractured reservoirs. In this paper, we will detail the latest research results in these fields and discuss their potential and challenges in practical applications.

2. Geologic Characterization of Fractured Reservoirs

2.1. Crack type and distribution pattern

Fracture types and distribution patterns in fractured reservoirs are key research elements in the fields of petroleum geology and hydrocarbon exploration. Fractures, as the main fluid pathways in reservoirs, have an important impact on the migration, aggregation and extraction of hydrocarbons. Fracture types usually include interlayer fractures, level fractures and intralayer fractures, which can be further subdivided into tension fractures, shear fractures and composite fractures, etc. The formation of these fractures is controlled by a variety of geological factors. As for the distribution law, the development of cracks is subject to the joint effect of regional tectonic stress field, depositional environment, rock type and lithology combination and other factors. For example, in tectonically active regions, the distribution of cracks is often closely related to faults, folds and other tectonic features, while in sedimentary environments, the distribution of cracks may be controlled by sedimentary phase zones, layer thickness variations and lithologic differences. The distribution pattern of fractures can be studied by geologic mapping, geophysical exploration, logging analysis and numerical simulation.

Ghosh et al [1] studied fracture orientation, strength and connectivity in the Teton backslope region of Montana, revealing how tectonic stresses control fracture development and distribution, providing important insights into understanding the behavior of fracture networks in complex geologic structures. Liu et al [2] simulated a paleotectonic stress field, which quantitatively predicted the multi-phase fracture distribution, which provides a scientific basis for identifying and assessing the stage of fracture development in shale gas exploration. Li et al[3] analyzed the effect of random discrete fracture network (DFN) in shale gas reservoirs on the recovery of the reservoir, and explored how the geometric properties and connectivity of the fracture network affect the extraction efficiency of the shale gas. Xu et al[4] proposed a method of calculating the fracture porosity of a dense fractured reservoir, which is useful to assessing the degree of fracture development and hydrocarbon exploration potential of reservoirs. Wu et al[5] investigated the effect of multi-phase paleotectonic stress field on fracture distribution in Lower Cambrian shale reservoirs in southern China by numerical simulation methods, which provided a new perspective for predicting fracture development.

2.2. Analysis of the main controlling factors of crack development

The primary controlling factors of fracture development are an important research topic in the field of geology and oil and gas exploration because fractures have a significant impact on reservoir permeability, fluid flow, and the development of oil and gas reservoirs. The formation and distribution of fractures are controlled by a variety of geologic factors including, but not limited to, tectonic stress field, rock type, depositional environment, geologic history, and surface and subsurface stress state.

The tectonic stress field is the main driving force for crack development, which determines the morphology, direction and distribution of cracks in rocks. In high stress regions, rocks are more prone to rupture and crack formation. The brittleness and strength of the rock also affects the crack development, and rocks with higher brittleness are more likely to form cracks under stress. Sedimentary environments, such as depositional rates, sedimentary phases, and the degree of compaction of sediments, affect the physical properties of rocks, which in turn affect the formation of cracks. Periods of tectonic activity, magmatism and metamorphism in the geological history also have an impact on the development of cracks.

In addition, the thickness, lithology and interlayer combination of the strata may also affect the development of cracks. For example, thinly bedded rocks may be more susceptible to crack formation under stress, whereas thickly bedded rocks may have a higher stress-carrying capacity due to their larger volume. Unevenness of interlayer combinations, such as alternating soft and hard rocks, can also affect the distribution of cracks.

2.3. Effect of fracturing on reservoir physical properties

Fractures, as the main fluid pathways in reservoirs, have a significant impact on the migration, aggregation and production of hydrocarbons. The presence of fractures can significantly increase the permeability and porosity of the reservoir, thus affecting the fluid transportation capacity of the reservoir and the recovery efficiency of the reservoir.

First, the presence of fractures breaks the continuity of the rock and provides additional flow paths for fluids, thereby increasing the effective permeability of the reservoir. This increased permeability is critical to the recovery of hydrocarbons, as it allows for faster flow of hydrocarbons to the wellbore and increased production. However, the permeability of fractures is not uniform, and they are often concentrated along certain paths in the fracture network, forming so-called “dominant flow paths”.

Second, fractures can increase the porosity of a reservoir because they provide additional storage space for fluids. This increased porosity contributes to the reserve estimation and development potential of the reservoir. However, the connectivity and openness of fractures can vary with time and stress changes during exploitation, which may affect the physical properties of the reservoir and the mobility of hydrocarbons.

In addition, the degree of development, distribution, and orientation of fractures can affect the physical properties of the reservoir. The density and spacing of fractures affects the nonhomogeneity of the reservoir, while the orientation and inclination angle of fractures affects the direction and path of fluid flow. In fractured reservoirs, these characteristics of fractures need to be characterized by detailed geological modeling and geophysical analysis.

Finally, the physical properties of the fracture, such as roughness, fill, and openness, are also important factors that affect reservoir performance. The roughness of the fracture surface affects the resistance to fluid flow, while the fill in the fracture may reduce its permeability. The openness of fractures, on the other hand, determines their effectiveness in the reservoir, i.e., whether they are able to provide access for fluid flow.

Bisdom et al [6] explored the effects of in-situ stress and outcrop-based fracture geometry on hydraulic fracture opening and up-scale permeability in fractured reservoirs, providing a new perspective for understanding the role of fractures in controlling the physical properties of reservoirs.

3. Three-dimensional Geologic Modeling Method for Fractured Reservoirs

3.1. Deterministic versus stochastic modeling approaches

Deterministic and stochastic modeling approaches for fractured reservoirs are two complementary geologic modeling techniques that play a crucial role in oil and gas exploration and development. Deterministic modeling is usually based on detailed geologic data and geophysical information, and aims to construct an accurate reservoir model reflecting characteristics such as distribution, strike, dip, and width of fractures. This approach relies on explicit geologic assumptions and data-driven reasoning, and is suitable for reservoirs that are rich in geologic information and have a more regular distribution of fractures. Deterministic models can provide engineers with a clear picture of the fracture network structure, which can help optimize drilling locations and development strategies.

In contrast, stochastic modeling methods focus on dealing with the uncertainty and variability of geological data. In fractured reservoirs, it is difficult to obtain complete fracture distribution data due to the irregularity and complexity of the fractures. Stochastic modeling generates multiple possible reservoir models through geostatistical techniques such as kriging interpolation and stochastic simulation, each reflecting the probability distribution of the data. This approach captures the randomness and spatial heterogeneity of fracture distributions and provides an effective means of assessing the uncertainty and risk of fractured reservoirs.

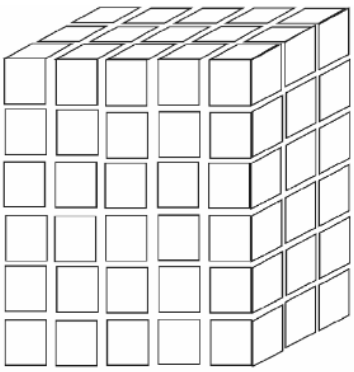
Caine et al [7] analyzed fault zone structure and fluid flow through field data and models, which provided a reference for stochastic modeling of fractured reservoirs. Long et al [8] proposed porous media equivalents for discrete fracture networks, which had a significant impact on the development of stochastic modeling methods.

Dong et al [9] proposed a three-dimensional geological modeling method for multi-scale fractures in tight sandstone reservoirs. By combining deterministic modeling and stochastic modeling techniques, the method firstly uses seismic data interpretation to obtain large-scale fracture networks, and then realizes the coupling of multi-scale fracture information through the distribution function matching method to determine the parameters required for modeling small- and medium-scale fracture networks. Then, the improved density-constrained discrete fracture network modeling method is used to generate the small- and medium-scale fracture networks, and finally the fracture networks of different scales are superimposed to form a complete multi-scale fracture system model. The effectiveness and accuracy of the modeling method is verified by comparing it with the actual geological data, taking the Ordos Basin H oilfield as an example.

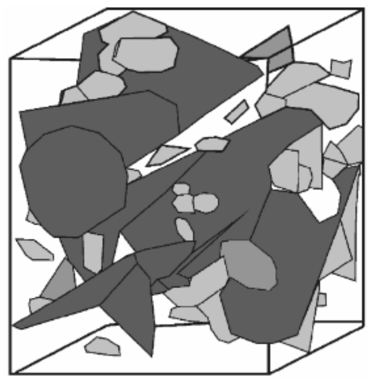
Zhang et al [10] established a post-fracturing reservoir physical property prediction model by combining the 3D seismic data before and after fracturing and the 5D seismic fracture prediction results, using the geological modeling method based on artificial fracture seismic prediction for a tight reservoir in the long 81 section of the Xifeng well zone in the Xifeng field of the Ordos Basin. The results show that the modeling method can accurately describe the physical changes of the formation after fracturing and provide an effective geological model for predicting the distribution of residual oil in low-permeability reservoirs, and the accuracy of the model is verified by the simulated trial calculations of the field dynamic data.

3.2. Discrete fracture network modeling techniques

Currently, numerical simulation studies for fractured oil and gas reservoirs mainly use the equivalent continuous sugar-cube type model (Fig. 1(a)) and the discrete fracture network DFN model (Fig. 1(b)). The discrete fracture network (DFN) modeling technique is a method used to simulate and analyze the distribution, connectivity, and geometric properties of fractures in fractured reservoirs. This technique has important applications in oil and gas exploration, water resource assessment, and geoengineering. By treating the fracture network as a series of discrete fracture entities, the DFN model is able to capture the spatial distribution and interactions of fractures, thus providing detailed insights into the fluid flow and stress field of the reservoir.



(a) Equivalent continuous model (ECM)



(b) Discrete fracture network model (DFN)

Figure 1. Schematic diagram of fractured reservoir modeling [11]

In DFN modeling, cracks are usually considered as linear or faceted features in 2D or 3D space with attributes such as length, width, orientation, dip, and roughness. These fractures can be constructed based on geologic data, geophysical surveys, or direct observations. With the development of computational techniques, DFN models have evolved from simple static representations to the ability to perform dynamic simulations, including crack generation, extension, and interaction.

Key steps in DFN modeling include data integration, statistical analysis of fracture properties, network construction, and model validation. Modern DFN models usually incorporate geostatistical methods to deal with spatial data uncertainties and numerical simulation techniques to predict the effects of fracture networks on fluid flow. In addition, the application of machine learning and artificial intelligence techniques further improves the predictive capability and automation of DFN models.

Lang et al [11] pointed out that the degree of fracture development has a direct impact on the efficiency of oil and gas exploration and final recovery, so fracture prediction is crucial.The DFN model describes the fracture system by constructing a fracture network consisting of fracture fragments with different scales and morphologies, and this method can realistically and meticulously characterize the geometry of the fracture system and seepage behavior. The study verified the effectiveness of the DFN model in simulating the subsurface porosity and permeability distribution by testing the data from the actual work area, and pointed out that although the DFN model is an advanced method, the method still needs to be further improved due to the non-homogeneous nature of the fracture properties.

Liu et al [12] compared and analyzed reservoir fracture modeling methods at different scales, including pre-stack seismic attribute prediction for large-scale fractures, discrete fracture network (DFN) stochastic modeling for mesoscale fractures, and computed tomography for small-scale fractures. The study points out that pre-stack seismic attributes contain richer geological information than post-stack attributes, and are more suitable for predicting the development direction, intensity and density of large-scale fractures; microseismic event information combined with DFN modeling can be closer to the actual oil and gas production, and improve the detection rate of small- and medium-scaled fractures; and computed tomography can quantitatively characterize micrometer-sized micro-scale fractures, and obtain more accurate information about the small-scaled fractures.

Tang et al [13] established a numerical model of thermal recovery based on a two-dimensional fracture network numerical simulation method for the evaluation of thermal recovery efficiency in dry-heat rock reservoirs, taking into account the complex fracture network, hydraulic fracture, wellbore effect and other factors. The model was solved by the finite element method, and the accuracy of the model was verified by comparing with the analytical solution of single-fracture thermal mining. The effects of hydraulic fracture opening, natural fracture opening, orientation, length, density, and fracture network connecting leaky faults on the thermal recovery efficiency of enhanced geothermal system (EGS) were studied and analyzed.

Zhang [14], for the Lower Cambrian Niushutang Formation shale reservoir in Changde area, Hunan Province, used the particle flow discrete element method combined with the discrete fracture network to investigate the effects of the number of natural fractures, dip angle and other factors on the shale mechanical properties and damage morphology, as well as the interactions between hydraulic fractures and natural fractures under the joint influence of the geopathological stresses and the nature of the natural fractures.

4. Advances in Multi-field Coupled Modeling of Fractured Reservoirs

Numerical simulation of fluid flow is a key issue in fractured reservoirs. Existing mathematical-physical models can be roughly divided into two categories: continuous medium models and discrete medium models. Continuous medium models, such as the dual medium model (DPM) and the equivalent continuous medium model, are relatively easy to compute, but they may not accurately capture the local flow field characteristics near the cracks. On the other hand, discrete medium models, such as the discrete fracture network model (DFNM) and the discrete fracture-matrix model (DFMM), are able to simulate the fracture and the flow field more accurately, but are more computationally intensive and require higher computational resources.

The multiphysics field coupling model further considers the effects of physical processes other than fluid flow, such as geostress field, temperature field, and chemical reactions, on fluid flow. For example, changes in the ground stress may affect the opening and closing states of the fractures, which in turn change the fluid flow path and the permeability of the reservoir. Changes in the temperature field may affect the viscosity and density of the fluid, which in turn affects the flow characteristics. Accurate modeling of these coupled effects is crucial for the development strategy of fractured reservoirs.

Xia et al [15] discussed the current research status of numerical simulation of fluid flow in fractured reservoirs from the perspectives of both mathematical-physical models and numerical solution methods. The continuous medium model and discrete medium model are discussed, and their advantages and disadvantages in simulating fluid flow in fractured reservoirs. The continuous medium model is computationally simple but the local flow field is poorly delineated, while the discrete medium model has more accurate crack and flow field delineation but is more computationally intensive. Some emerging numerical methods are also proposed, and the problem of how to balance the accuracy and efficiency of complex fracture calculations on the engineering scale is discussed.

Jiang [16] investigated fluid flow and fluid-solid coupling in fractured reservoirs based on the extended finite element method (XFEM). XFEM can better handle the geometrical complexity of fractures and provides an efficient method to simulate fluid flow and rock deformation in fractured reservoirs.

Wang et al [17] proposed an embedded discrete fracture method (EDFM) for modeling fracture-dominated fluid flow and heat transfer in geothermal reservoirs. This method allows 3D discrete fractures to be discretized independently of the surrounding rock volume and explicitly inserted into the main fracture/matrix grid, which did not previously contain 3D discrete fractures.

Wang et al [18] performed numerical simulations by means of a coupled hydraulic-mechanical-damage model to reveal the multi-modal fluid flow mechanism in fractured-cave reservoirs and predicted the hydrocarbon accumulation areas. The results show that secondary fractures have a significant effect on hydrocarbon migration efficiency and initial production in different fracture-cave bodies.

Aliyu et al [19] presented a numerical model of a three-dimensional multi-fractured hot dry rock (HDR) system through a coupled thermo-hydraulic-force (THM) modeling process. The study analyzed the effect of fracture spacing and number on reservoir productivity and considered the effect of fracture porosity, permeability and stiffness variations on each individual fracture during long-term development (30 years).

Ren et al [20] developed a hybrid discretization approach that approximates fracture mechanics by the extended finite element method (XFEM) and treats the multiphase flow equations using an embedded discrete fracture model (EDFM) to accurately simulate the fluid-solid coupling of fractured media in unconventional oil and gas resources. The methodology considers an efficient representation of small fracture networks and is demonstrated with several validations and computational results.

5. Summary

In this paper, we comprehensively analyze the geological characteristics of fractured oil and gas reservoirs, three-dimensional geological modeling methods and the research progress of multi-field coupling models. Through the discussion of fracture types, distribution laws and their main controlling factors, we recognize the important influence of fracture networks on the physical properties of reservoirs. In addition, three-dimensional geological modeling techniques for fractured reservoirs, especially discrete fracture network (DFN) modeling, provide effective tools for accurately describing the geometry and seepage behavior of fracture systems. The development of multi-field coupled modeling further considers the effects of physical processes other than fluid flow, such as geostress field, temperature field, and chemical reactions, on fluid flow, which is crucial for the development strategy of fractured reservoirs.

Although significant progress has been made in the study of fractured reservoirs, many challenges remain. For example, how to more accurately model the dynamic development process of fractures, improve the computational efficiency of numerical simulations, and how to better integrate multi-source geologic data need to be addressed in future research. In addition, the application of machine learning and artificial intelligence technologies provides new possibilities for fractured reservoir modeling and multi-field coupling models, which are expected to further improve the prediction accuracy and modeling efficiency. In conclusion, the study of fractured reservoirs is a multidisciplinary field, which requires not only an in-depth understanding of the physical processes, but also the development of efficient numerical methods and computational tools to realize the efficient development and utilization of hydrocarbon resources.

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