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Research Progress on Fracturing Well Testing Models

Yongxiang Huang, Shaonan Wang, Chenjun Li, Chenhao Tian
College of Petroleum Engineering, Xi'an Shiyou University, Xi'an, Shaanxi, 710065, China

Abstract

With the advancement of industrialization, China's demand for various resources continues to grow, with the demand for oil and gas resources being particularly prominent. Conventional oil and gas resources can no longer meet the needs of social development; in the face of this situation, the efficient development of unconventional oil and gas has become an important solution to the current resource demand issue.The efficient development of unconventional resources usually requires fracturing stimulation of oil and gas wells. To evaluate fracturing effects and invert post-fracturing formation information, an accurate fractured seepage model is indispensable. This paper conducted a detailed investigation on the seepage models of fractured vertical wells and fractured horizontal wells, identified the existing problems of these current models, and proposed their potential development directions in the future, thereby providing research insights for relevant researchers.

Keywords

Oil and Gas Resources; Fractured Vertical Well; Fractured Horizontal Well; Seepage Model.

1. Introduction

Since the beginning of the 21st century, the process of industrialization and urbanization in China has accelerated, and the demand for various energy sources has been increasing, among which the demand for oil and gas resources is particularly prominent. Under such circumstances, conventional oil and gas resources can no longer meet the needs of current social development, while unconventional oil and gas resources have great potential in addressing the issue of energy demand.

Unconventional oil and gas resources include shale oil, shale gas, tight oil, tight gas, coalbed methane, heavy oil, and oil sands. Compared with conventional oil and gas resources, unconventional ones exhibit the "three lows and one wide" characteristics, namely low porosity, low permeability, low fluidity, low abundance, and wide distribution.It is precisely due to these characteristics that the development of unconventional oil and gas resources is more difficult than that of conventional ones, requiring artificial stimulation to achieve more efficient extraction.

Fracturing technology is one of the key technologies for achieving efficient development of unconventional oil and gas resources. This technology involves injecting high-pressure fluid into the reservoir to create artificial fractures, which greatly improves the reservoir's permeability and fluid flow capacity, thereby enabling the efficient development of oil and gas resources.

After fracturing the reservoir, well testing analysis is conducted on the fractured oil and gas wells to evaluate the fracturing effect. By monitoring the pressure and flow rate during the production or well shutdown processes after fracturing, an appropriate seepage flow model is selected to invert the fracture-related parameters. Fracturing well testing also provides a basis for the optimization of subsequent development plans.

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2. Research Status of Fractured Wells

2.1. Research on Well Testing Models for Fractured Vertical Wells

Liu Y W et al.[1-2], for dual-porosity reservoirs, established well testing models for vertical fractured wells with finite and infinite conductivity by combining the elliptical flow model with the mass conservation method, plotted the type curves of the models, and analyzed the curve characteristics under different conditions.Li F H et al[3]. obtained and analyzed the infinite conductivity solutions and equal-rate solutions for vertical fractured wells in heterogeneous reservoirs.Deng Y E et al[4]. established steady-state and transient nonlinear seepage mathematical models for vertical fractured wells in low-permeability reservoirs, and conducted mathematical derivation on the pressure distribution and influence radius of pressure disturbance of transient nonlinear seepage.Liu P C et al[5]., for vertical fractured wells with finite conductivity in three-zone composite reservoirs, derived the bottomhole pressure expressions and analyzed and discussed the bottomhole pressure dynamic characteristics and influencing factors of such wellbores.Yan T et al[6]. established a three-linear flow model for vertical fractured wells with finite conductivity that considers both the skin effect and wellbore storage effect, obtained the solution to the model, and analyzed the well testing curve characteristics of the model.Guo D L et al[7]., by combining the linear flow model with the effective wellbore radius model, established a new model for well testing analysis of vertical fractured wells, proposed a method for determining the effective wellbore radius of vertical fractured wells, and presented the variation relationship of the effective wellbore radius with fracture length, fracture conductivity, and fracture skin factor.Li A F et al[8]. developed a new solution algorithm for well testing models of vertical fractured wells with finite conductivity in dual-porosity media, and analyzed the influence of factors such as inter-porosity flow and storage ratio on pressure dynamics.Cai M J et al[9]. established an elliptical flow mathematical model for low-permeability dual-porosity reservoirs, obtained the bottomhole pressure expressions, and analyzed the main factors influencing bottomhole pressure dynamics.Tong D K et al[10]., considering the influence of quadratic gradient terms, established a bilinear model for dual-porosity media. They then eliminated the quadratic gradient terms through logarithmic transformation, established a finite difference scheme, and obtained the numerical solution of the model using the Thomas algorithm.Wang J H et al[11]. established a semi-analytical model for transient pressure analysis of vertical wells after volume fracturing stimulation and discussed and analyzed the relevant parameters.Du Z H et al[12]., by using the dynamic testing data after multi-layer fracturing of vertical wells, established a layered seepage mechanics model for vertical fractured wells and solved to obtain the bottomhole pressure during the production process.Guo J J et al[13]. established an analytical well testing model for volume-fractured vertical wells in stress-sensitive tight reservoirs, obtained analytical solutions for pressure responses at the bottomhole and any point in the formation, and conducted a sensitivity analysis on the relevant parameters.Gringarten et al[14]. derived the analytical solution of the finite element model for horizontal fractures by adopting the point source method. This achievement not only clarifies the mathematical expression of the horizontal fracture seepage process but also provides crucial theoretical support for in-depth research on the production dynamics of fractured oil wells, laying a solid foundation for subsequent studies on fractured reservoir development and well performance optimization.Cinco L et al[15]. established a mathematical model for finite-conductivity fractured vertical wells in infinite reservoirs. The model specifically targets the scenario of infinite reservoir boundaries and focuses on the finite conductivity feature of fractured vertical wells, providing a foundational theoretical tool for subsequent seepage analysis and well performance evaluation of such wells.Lee et al [16]. conducted in-depth research on the approximate three-linear flow model and successfully derived the analytical solution for finite-

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conductivity fractured vertical wells. This solution not only provides critical theoretical support for the dynamic analysis of fractured wells and the assessment of their operating conditions but also lays an important foundation for accurately evaluating formation physical parameters and optimizing fracturing operation plans.Azari M et al[17]. considered two scenarios-with and without reservoir boundaries-as well as constant pressure and constant production conditions. Based on this comprehensive consideration, they derived the analytical solution for oil reservoirs with vertically fractured wells of finite conductivity, offering a solid theoretical basis for subsequent seepage analysis and well performance assessment of such reservoirs.The Cossio Santizo[18] team successfully derived a new semi-analytical solution for finite-conductivity fractured vertical wells by innovatively integrating the fractal diffusion equation with the three-linear flow model, and this solution is clearly defined as the "fractal fracture solution". This solution is not a universal model but has a clear applicable boundary: it is only effective for scenarios where the dimensionless fracture conductivity is greater than 3. It provides accurate theoretical support that fits specific working conditions for subsequent research on seepage laws of such fractured wells, prediction of dynamic characteristics, and optimization of development parameters.Wei C et al[19]. focused on overcoming the problems in the finite-conductivity fracture well testing model. They first established an influence function for fracture conductivity, and on this basis, derived an approximate analytical model that boasts fast calculation speed and accurate results. This model not only addresses the limitations of the original testing model but also provides reliable theoretical support for the development of finite-conductivity fractured vertical wells.Xia B et al[20]. addressed the issue that traditional fracture characterization methods and seepage mathematical models fail to accurately describe the actual reservoir conditions, leading to errors in dynamic analysis results. They proposed an oil-gas two-phase seepage model for fractured carbonate reservoirs considering stress sensitivity, and further analyzed the impact of relevant parameters on production dynamics, providing theoretical support for accurate dynamic analysis and development decisions of such reservoirs.

2.2. Research on Well Testing of Fractured Horizontal Wells

Li S S et al[21]., aiming at the complex boundary conditions of reservoirs, introduced the fracture discretization mechanism, established well testing models and interpretation methods for the multi-well fracture system of fractured horizontal wells, and analyzed their pressure dynamic characteristics. This provides more field-consistent technical support for the well testing interpretation of fractured wells in complex reservoirs.Li S S et al[22]., through their research on well testing models for fractured horizontal wells, established a well testing model for the multi-fracture system of fractured horizontal wells under the condition of 2D fractures.Yao J et al[23]., considering the existence of threshold pressure gradient in low-permeability reservoirs, established a three-linear transient seepage mathematical model for fractured horizontal wells.Xu M Y et al[24]. coupled the reservoir stress sensitivity effect into the seepage model for multi-stage fractured horizontal wells in tight sandstone gas reservoirs and established a new well testing analysis method for horizontal wells.Wang B C et al[25]., through research on the influencing factors of well testing models for multi-stage fractured horizontal wells, established a transient seepage model for multi-stage fractured horizontal wells.Gao J et al[26]., considering the adsorption and desorption of shale gas and diffusion mechanism, established a three-linear seepage model for fractured horizontal wells in shale gas reservoirs, which provides theoretical support for the development of shale gas reservoirs.Zhao C et al[27]., targeting the variable conductivity of artificial fractures in fractured horizontal wells, established a new well testing model for multi-stage fractured horizontal wells in tight gas reservoirs and analyzed the influence of relevant factors on well testing curves.Qin J Z et al[28]., through researching the influence of irregular oil production on bottomhole pressure response, established a well testing model for irregular oil production in

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fracturing fractures and horizontal wellbores of multi-stage fractured horizontal wells.Chen H S et al[29]., through conducting research on the shape of pressure difference derivative curves in actual well testing data, established a well testing model for volume fracturing stimulation that considers both main fractures and secondary fracture networks.Ye Y P et al[30]. established a well testing model for multi-stage fractured horizontal wells in fractured hydrocarbon reservoirs that considers both the reservoir stress sensitivity effect and fracture variable conductivity.Wang H Q et al[31]., to address the issue that there are certain discrepancies between the measured curves and theoretical curves of multi-stage fractured horizontal wells in tight sandstone gas reservoirs in terms of flow regime characteristics and curve shapes, established a seepage model for multi-stage fractured horizontal wells and analyzed the influence of fracture parameters on well testing curves.Brown M L[32] team aimed to simulate the pressure transients and production dynamics of fractured horizontal wells in unconventional shale reservoirs. To this end, they proposed a new three-linear flow analytical solution. Beyond meeting the simulation needs, this solution also provides a suitable algorithm for the regression analysis of pressure transient tests in shale reservoirs, laying a theoretical foundation for related reservoir dynamic research.Wang X et al[33]., by studying the influence function of fracture conductivity, proposed a new analytical solution for fluid transient flow for vertical fractured wells with finite conductivity. This solution has thus provided a new theoretical tool for the seepage dynamic analysis of such wells.Guo J et al[34]. fully considered two critical factors in tight oil reservoir development: the finite conductivity of hydraulic fractures and the stress-dependent permeability of reservoirs. On this basis, they proposed a coupled model tailored for multi-stage fractured horizontal wells in tight oil reservoirs. The model effectively integrates the above two key influencing factors, which not only reflects the actual reservoir and fracture characteristics more accurately but also provides strong theoretical support for the subsequent optimization of fracture parameters.Jiaming Z et al[35]. established a seepage model for naturally fractured carbonate reservoirs, taking full account of the reservoir's stress-sensitive characteristics and dual-porosity properties. Meanwhile, they also put forward a semi-analytical solution for this model, laying a foundation for subsequent seepage analysis of such reservoirs.Yin D et al[36]. addressed the problem of complex fluid flow among three media—matrix, microfractures, and main fractures-in tight oil reservoirs. Aiming at the fracturing development scenario of such reservoirs, they developed a nonlinear mathematical model with triple-medium coupling (matrix/microfractures/main fractures). This model lays a theoretical foundation for subsequent analysis of fluid seepage laws in the reservoirs and optimization of fracturing development parameters.Fan J et al[37]. aimed to refine the well testing model's accuracy, innovatively coupling two critical elements-the interference effect of water injection wells and finite conductivity-into the well testing model. They further derived the model's analytical solution based on this integration. This work offers robust support for the accurate modeling of oil well production dynamics, particularly in scenarios where the influence of water injection wells needs to be taken into account.Wang K et al[38]. established a new fractal model for reservoir seepage, which specifically takes into account the non-Darcy flow of gas in nanopores, effectively addressing this key flow issue in reservoir research.

After a long period of development, the research on fracturing well testing models has evolved significantly: starting from the early models that assumed a single fracture and an ideal reservoir, it has progressed to incorporating heterogeneous reservoir characteristics and multi-medium coupling into model construction. Currently, with the popularization of volume fracturing technology (commonly used in the development of unconventional oil and gas resources), the development of fracturing models has entered a stage characterized by "multi-scale, multi-field coupling, and digitalization". Thanks to the efforts of researchers, seepage

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models are becoming increasingly closer to the actual seepage conditions of reservoirs after fracturing.

3. Conclusion and Outlook

Researchers have developed mature theoretical methods for the seepage theoretical models of fractured vertical wells and fractured horizontal wells, covering the entire process from model construction and model solution to the accurate characterization of parameters.However, as the models become more consistent with actual seepage scenarios, their complexity continues to increase. This leads to a rise in the difficulty of model solution, requiring reliance on more efficient numerical methods and intelligent algorithms to achieve model solution.

In the subsequent development of well testing seepage models, they will move toward the direction of "precision, intelligence, and integration". Specifically, in terms of model construction, efforts will be made to more accurately characterize the seepage of fluids in oil reservoirs; in terms of model solution and parameter inversion, intelligent algorithms will be incorporated to improve researchers' work efficiency; and in daily work, an integrated "well testing-monitoring-development" platform will be established to realize the real-time optimization of reservoir development plans.

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