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Research on Post-fracture Production Forecasting Models for Horizontal Wells

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Abstract

The prediction of post-fracturing production in horizontal wells is crucial for designing effective hydraulic fracturing parameters in tight shale reservoirs. However, conventional production prediction methods face significant challenges in utilizing conventional well logging data due to the substantial heterogeneity and variation in reservoir lithology and properties in both vertical and horizontal directions. To overcome these challenges, researchers have primarily used analytical and numerical simulation methods to study the production capacity of horizontal wells in tight shale formations. Additionally, some scholars have attempted to study the fracturing production of tight shale horizontal wells using methods such as hydraulic simulation and linear regression. However, the application scope of physical simulation methods based on hydroelectric similarity theory is limited and not suitable for low-permeability and ultra-low-permeability oil and gas reservoirs. Furthermore, research on regression empirical models, numerical models, and analytical models regarding the impact of strong heterogeneity and complex reservoir spatial types in tight fractured sandstone and tight conglomerate formations under the existence of natural fractures is still relatively limited.

Keywords

Tight Shale; Post-fracturing Production; Prediction Model; Analytical Method; Numerical Simulation; Physical Simulation.

1. Introduction

With the gradual depletion of conventional oil and gas resources, tight shale reservoirs have received extensive attention as an important unconventional energy resource. However, due to the unique characteristics of tight shale reservoirs, especially the large variations and heterogeneity in reservoir lithology and properties in both vertical and horizontal directions, the prediction of production capacity in horizontal wells in tight shale formations faces significant challenges. Traditional production prediction methods often yield unsatisfactory results in such cases, highlighting the urgent need to develop reliable and effective models for predicting post-fracturing production in horizontal wells.

Currently, the prediction of production capacity in tight shale horizontal wells relies mainly on analytical methods and numerical simulation. Analytical methods establish various analytical models based on reservoir and fluid characteristic parameters to predict production, offering the advantage of fast computation. However, due to the complexity and heterogeneity of tight shale reservoirs, traditional analytical models have certain limitations in terms of accuracy and applicability. Therefore, researchers have started adopting numerical simulation methods to model reservoirs and fractures, simulating the production and flow behavior in horizontal wells. Numerical simulation methods overcome the limitations of analytical methods, which can only study single-phase, two-dimensional homogeneous reservoir flow, and have significant advantages in evaluating the production capacity and predicting the production dynamics of horizontal wells with high reservoir heterogeneity and complex oil-water relationships.

Therefore, this paper aims to review the current research status of prediction models for post-fracturing production in horizontal wells. It summarizes the application of analytical methods, numerical simulation methods, and other approaches in predicting production capacity in tight shale horizontal wells, and identifies the current shortcomings. By reviewing and analyzing existing research, this paper will provide references and guidance for further improvement and development of prediction models for post-fracturing production in horizontal wells.

2. Analytical Methods

GIGER was the first to establish a mathematical model to study the production capacity of fractured horizontal wells. However, this model did not effectively couple the fluid flow process. Building upon this work, SOLIMAN et al. considered the fluid flow in the fractures as radial flow and obtained the production capacity of a single-fracture horizontal well. They then superimposed the production capacities to estimate the production of multi-fracture horizontal wells. OZKAN et al. studied the analytical method for a single fracture and used the superposition principle to calculate the production capacity of horizontally fractured wells. However, this method idealized the fractures by assuming vertical hydraulic fractures in the horizontal wellbore with equal fracture spacing and ignored the interaction between fractures.

2.1 Analytical Models Considering the Start-up Pressure Gradient for Production Prediction

Tight shale gas reservoirs exhibit characteristics such as low permeability, non-Darcy flow, and start-up pressure gradient. In recent years, researchers have derived new formulas for the production capacity of fractured horizontal wells by considering the influence of the start-up pressure gradient. They have also developed mathematical models to describe the flow behavior, taking into account factors such as gas slippage and fracture interference to improve the accuracy of production prediction in tight gas reservoirs. These studies have provided important theoretical foundations and practical guidance for the development of tight shale gas reservoirs. For instance, in 2012, based on previous research, LIANG Bin derived a new formula for the production capacity of fractured horizontal wells by considering the impact of the start-up pressure gradient. LIANG Bin, ZHANG Liehui, and others followed a similar approach and considered the influence of the start-up pressure gradient on flow behavior in low-permeability gas reservoirs, establishing a trinomial non-Darcy flow equation.

2.2 Multi-factor Coupled Production Prediction Models

YUAN Lin et al. established a production capacity model for gas-water co-production in low-permeability reservoirs with fractured horizontal wells and obtained accurate predictions through coupled numerical solutions. ZHANG Deliang et al. developed a coupled model for the equivalent wellbore diameter of horizontally fractured wells with multistage fracturing, considering the differences in fracture properties. This model better reflects the production behavior of tight shale gas reservoirs. SHI Xian considered the fluid flow behavior in tight gas reservoirs and proposed production calculation methods under post-fracturing pseudo-steady-state and transient conditions. YANG Zhaozhong et al. established a non-steady-state production capacity prediction model for fractured horizontal wells in low-permeability tight sandstone gas reservoirs based on the equivalent flow theory and the coupling of reservoir and fracture flow. LI Yongming et al. derived a dynamic production prediction formula for homogeneous circular closed boundary gas reservoirs with fractured horizontal wells and solved it through programming. ZENG Fanhui et al. considered the heterogeneous distribution characteristics of reservoir permeability bands in tight gas reservoirs with fractured horizontal wells and established a production capacity calculation model considering reservoir heterogeneity and start-up pressure gradient. LI et al. optimized the production rate of horizontal wells in the Yuanba high-sulfur gas reservoir and proposed a more accurate evaluation method. TIAN Gang et al. selected and compared different analytical models for multi-stage fractured horizontal wells, evaluating their applicability and accuracy through numerical simulation.

3. Numerical Simulation Methods

Numerical simulation methods have advantages in well productivity evaluation and dynamic production prediction, particularly in cases of heterogeneous reservoirs and complex oil-water-gas relationships. For fractured horizontal wells, numerical simulation needs to focus on describing the fractures, with commonly used methods being finite difference and finite element methods, with the latter offering greater flexibility. In recent years, numerical simulation methods have been widely applied to accurately describe horizontal wells and establish production prediction models. Researchers have developed various models and methods that consider gas compressibility, non-Darcy flow, and simulate the production and flow characteristics of horizontal wells. These studies also take into account factors such as stress sensitivity of the reservoir, fracture closure, and use seismic inversion and lithology distribution data to establish reservoir models. For ultra-deep and ultra-high-pressure fractured sandstone gas reservoirs and shale gas reservoirs, adsorption, desorption, diffusion mechanisms, and stress sensitivity effects of natural fractures are also considered. In summary, numerical simulation methods provide powerful tools for well productivity prediction and production optimization.

4. Physical Simulation Methods

Fluid flow in reservoirs follows Darcy's law and the Laplace equation, while electric current flows in conductive media according to Ohm's law and the Laplace equation. Due to the similarity of these equations, the electric current field can be used to simulate the flow field.

Physical simulation methods are based on the principle of hydraulic analogy, using an electric field to simulate the flow field of a horizontal well and applying similarity criteria for transition and unification.

In 2009, WU Xiaodong et al. conducted electrical simulation experiments on fractured horizontal wells, studying the influence of fracture parameters on production capacity under single-well and well-network conditions. In 2013, QU Zhanqing et al. used a hydraulic analog device to investigate the effects of fracture position, distribution, number, and length on the production capacity of horizontally fractured wells. In 2017, YIN Jiawei conducted hydraulic simulation experiments to study the post-fracturing production capacity of horizontal wells, resolving the unclear relationship between fractures and production capacity. In 2016, MA Jing et al. conducted electrical simulation experiments based on the principles of hydraulic analogy, analyzing the effects of fracture parameters on production capacity and addressing the complex wellbore design and flow mechanisms of horizontal wells . In 2019, LI Linlin proposed a new formula for correcting the production capacity of horizontal wells through experimental measurements and formula calibration. This formula eliminates the influence of boundary distance on fracture capacity and extracts the effects of boundary distance and fracture spacing on production.

5. Other Methods

In 1994, Ouyang Jian et al. proposed the use of rock permeability and water saturation as indicators for evaluating reservoir productivity. Cheng et al. predicted the productivity index of reservoirs using formation resistivity and flushed zone resistivity. In 2004, Zhang Yun et al. analyzed the elastic characteristics, fracture parameters, and fracturing parameters of reservoirs based on reservoir identification, and predicted the productivity index. Zhang Lingyun proposed the intersection area method using oil and gas indicator parameters and the intersection index to rapidly predict the initial production of gas reservoirs. Subsequently, based on reservoir characteristics and production influencing factors, Zhang Lingyun established the relationship equation between reservoir production and parameter using regression analysis. Direct regression method and analytic hierarchy

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process were proposed to calculate comprehensive evaluation index parameters of reservoirs, and the relationship equation between reservoir production and effective thickness was obtained. In 2013, Yang Feng et al. established a model for predicting the productivity of fractured sandstone using linear regression methods based on the description of low-porosity fractured sandstone in the Kuqa foreland basin. In 2015, Zhang Sidun et al. obtained fracture parameters of fractured sandstone reservoirs through imaging logging data and studied the relationship between fracture parameters and productivity, establishing a formula for predicting fractured sandstone productivity. In 2021, Pan Yuan et al. used a two-stage hybrid algorithm of grey correlation projection and random forest, introducing weighted grey correlation to select appropriate training sets and improve the prediction accuracy of the model.

Table 1. Comparison of production capacity prediction models

Researchers	Research approaches
GIGER	Establish mathematical models
SOLIMAN	Apply radial flow and superposition principle
OZKAN	Superposition of potentials
Guo Huiling, et al.	Consider initiation pressure gradient
Yan Wende, et al.	Establish a trinomial productivity equation considering initiation pressure gradient
Liang Bin, et al.	Combine the three-line flow model with initiation pressure gradient
Zhang Ruihan, et al.	Consider initiation pressure gradient and slip effect
Zhu Weiyao, et al.	Consider gas slippage and coupled flow between fractures
Wang Jing, et al.	Consider initiation pressure gradient, slip factor, and stress sensitivity
Qiu Xianqiang	Consider two-phase gas-water flow, reservoir stress sensitivity, and high-speed non-Darcy flow
Yuan Lin, et al.	Consider differences in fracture properties for multistage fractured horizontal wells
Zhang Deliang, et al.	Design using a two-dimensional extended model combined with fracture geometry parameters
Shi Xian	Consider initiation pressure gradient, inter-fracture interference, and coupled flow between reservoir and fractures
Yang Zhaozhong, et al.	Use basic flow theory, Newton iteration, and LU algorithm for solving
Li Yongming, et al.	Consider fracture heterogeneity, discrete technology, and inter-fracture interference
Zeng Fanhui, et al.	Incorporate gas compressibility and non-Darcy flow effects using semi-analytical models and BOSIM software
Roberts	Use a three-dimensional single-phase flow model
Goktas	Perform numerical simulations using Eclipse-300
Hashemi	Develop software for three-dimensional two-phase gas-water flow with initiation pressure gradient
Zhang Liehui, et al.	Employ a three-dimensional two-phase black oil model for modeling and history matching using Eclipse
Mu Lin, et al.	Use numerical simulation and orthogonal experimental design
Ma Jing, et al.	Extend the Eclipse black oil simulator and establish an attribute model using stochastic simulation methods

<table>
<tr><td>Zhu Wenjuan</td><td>Develop a productivity model based on imaging logging fracture characterization technology</td></tr>
<tr><td>Li Xiangtong, et al.</td><td>Construct a Cartesian grid model using Eclipse</td></tr>
<tr><td>He Xiuling, et al.</td><td>Independently designed water-electricity simulation device based on the principle of hydraulic-electric similarity</td></tr>
<tr><td>Li Tingli</td><td rowspan="6">Modify fracture productivity equation based on electrical simulation
Consider factors such as permeability and water saturation
Analyze reservoir elasticity characteristics and fracture parameters
Apply the intersection area method and analytic hierarchy process
Utilize support vector machine and multiple-factor regression analysis</td></tr>
<tr><td>Wu Xiaodong, et al.</td></tr>
<tr><td>Qu Zhanqing, et al.</td></tr>
<tr><td>Yin Jiawei</td></tr>
<tr><td>Ma Jing, et al.</td></tr>
<tr><td>Li Linlin</td><td>Establish a predictive model for fracture-porous sandstone productivity using linear regression method</td></tr>
<tr><td>Ouyang Jian, et al.</td><td>Establish mathematical models</td></tr>
<tr><td>Zhang Jun, et al.</td><td>Apply radial flow and superposition principle</td></tr>
<tr><td>Zhang Lingyun, et al.</td><td>Superposition of potentials</td></tr>
<tr><td>Huang Jianhong, et al.</td><td rowspan="2">Consider initiation pressure gradient
Establish a trinomial productivity equation considering initiation pressure gradient</td></tr>
<tr><td>Shi Lei, et al.</td></tr>
<tr><td>Yang Feng, et al.</td><td rowspan="2">Combine the three-line flow model with initiation pressure gradient</td></tr>
<tr><td>Zhang Sidun, et al.</td></tr>
</table>

6. Issues and Outlook

The existing formulas for tight shale horizontal well productivity are mostly derived from formulas for horizontal oil wells. Although modifications have been made by incorporating factors such as pressure gradient, inter-fracture interference, gas slippage effect, and unstable flow, there is still a certain degree of error when using the analytical solution derived from gas parameters introduced in horizontal oil well productivity formulas as the productivity formula for tight shale gas reservoirs. This is due to the differences in fluid flow conditions between gas reservoirs and oil reservoirs.

Numerical simulation for horizontal wells relies heavily on mature reservoir simulation software combined with accurate descriptions of the flow behavior in horizontal wells. However, it lacks a reasonable geological model, requires numerous evaluation parameters, has a large computational workload, slow calculation speed, and the physical interpretation of the terms in the differential equations is lacking.

Linear regression formulas and empirical formulas based on well logging data have limited applicability in certain gas fields.

Physical modeling methods based on the principles of similarity between water and electricity fields are applied to simulate the flow field in horizontal wells. However, they are not suitable for low-permeability and ultra-low-permeability oil and gas reservoirs.

The impact of fracture network development characteristics cannot be ignored in predicting productivity, especially in tight fractured shale gas reservoirs where gas production is minimal before hydraulic fracturing. There are already many models available for predicting productivity in tight sandstone reservoirs, but there is limited research on regression empirical models, numerical models, and analytical models for tight fractured sandstone reservoirs with natural fractures and under the influence of strong heterogeneity and complex storage space in tight sand and gravel. To improve

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prediction accuracy, it is necessary to emphasize the combination of field experiments, physical modeling, and numerical simulation based on the improvement of flow mechanisms.

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