Research Progress of Productivity Prediction Method for Horizontal Wells Fracturing

Lin Wu[1, a], Liqiang Zhao [1], band Zhifeng Luo [1, c]

[1]Petroleum Engineering School, SouthWest Petroleum University, Chengdu 610500, China

[a] sgywlin@163.com, [b] zhaolq@vip.163.com, [c]125987394@qq.com

Abstract

Horizontal wells fracturing is an effective method to develop low permeability oil and gas fields. Accurate prediction of horizontal well productivity is the basis of horizontal well fracturing design. This paper systematically analyses and summarizes the analytical method, semi-analytical method and numerical simulation method commonly used in productivity prediction of fractured horizontal wells, which provides a basis for accurate prediction of productivity of fractured horizontal wells.

Keywords

Horizontal well fracturing, Productivity prediction, Analytical solution, Semi-analytical solution, Numerical simulation.

1. Introduction

Horizontal well fracturing is an effective method to develop low permeability oil and gas fields [1-3]. In the early stage, people usually used simple analytical models to quickly predict the steady productivity of fractured horizontal wells under ideal conditions. With the wide application of advanced mathematical theory in petroleum engineering, semi-analytical models that can predict more accurately complex well patterns and reservoir conditions have begun to emerge. Compared with the analytical model, the semi-analytical model needs fewer assumptions, and can consider the heterogeneity of the reservoir, which is closer to the real production situation. In order to solve the problem of three-phase flow of oil, gas and water in reservoir, reservoir numerical simulation technology came into being. This paper systematically summarizes and analyses the different methods of productivity prediction of fractured horizontal wells, compares the advantages and disadvantages of each method, and provides a basis for accurately predicting the productivity of fractured horizontal wells.

2. Research progress of productivity equation for horizontal well fracturing

2.1 Domestic research progress of productivity equation

Because of the high fracturing cost of horizontal wells, comprehensive economic evaluation is needed before fracturing operation of horizontal wells, besides reservoir conditions and technical problems. In this case, productivity prediction of fractured horizontal wells is very important. Accurate productivity prediction can not only improve the scientificity of fracturing horizontal well decision-making, but also provide reliable basis for parameter design of horizontal well fracturing technology.

Fan Zifei [4] put forward a formula for the steady-state solution of vertical fractures in rectangular reservoirs. On the basis of this formula, the influence of non-Darcy effect on the productivity of horizontal wells was considered. In the derivation process, factors such as top and bottom boundary, bilateral boundary, completion mode, anisotropy of matrix and penetration of vertical fracture through reservoir were considered.

Lang Zhaoxin and others [5]assumed that the output of each fracture was the same in many fractures. Using potential theory and superposition principle, the method of determining the output of horizontal wells with multiple fractures after fracturing was studied, and the relationship between the output and production pressure drop and the length of fractures and the number of fractures was obtained.

Guo Jianchun [6], based on the two-dimensional dual-medium oil-water two-phase seepage model, simulated the productivity of fractured horizontal wells by taking into account the factors such as wellbore pollution, fracture wall pollution, fracture conductivity varying with position and time, formation heterogeneity, anisotropy and fluid expansion. Combining with the economic evaluation of fracturing construction, the optimization method of fracturing strip number in horizontal wells was put forward.

Ning Zhengfu et al. [7] revised the productivity prediction formula of fractured horizontal wells by applying the reset potential theory, superposition principle and the numerical analysis method of matrix equation, and considering the seepage resistance and pressure loss in the fracture, so that the calculation results were more realistic.

According to the seepage resistance method, Li Hujun et al. [8] put forward the production performance prediction formula of horizontal wells with multiple vertical fractures. The total pressure drop was composed of three parts: the pressure drop produced by the oil drainage boundary flowing into the fracture, the pressure drop produced by the crude oil flowing in the fracture and the pressure drop produced by the confluence of crude oil in the formation near the wellbore.

Li Xiaoping [9] established a seepage model for horizontal fractured wells with multiple vertical fractures in homogeneous reservoirs, and gave a formula for calculating bottom hole pressure.

Liu Pengcheng [10] studied the seepage characteristics of fractured horizontal wells in rectangular low permeability reservoirs based on the principle of hydropower similarity and the method of equivalent seepage resistance, and established the productivity formula of fractured horizontal wells considering start-up pressure gradient and stress sensitivity.

Guo Genliang [11] deduced the productivity formula of horizontal wells in natural fractured reservoirs, which comprehensively considered the factors such as permeability anisotropy, partial penetration of horizontal wells, partial penetration of fractures and arbitrary angle between fractures and wellbore.

Yue Jianwei and Duan Yonggang et al. [12] analyzed the seepage process of fractured horizontal gas wells, divided the pressure drop of gas flowing from bottom to bottom of horizontal wells into three parts, solved the productivity prediction model of fractured horizontal gas wells by programming considering the connection conditions, and put forward that there was an optimum value for the number of fractures and the half-length of fractures. Fracture production at the front end of horizontal wellbore would be higher than that at the end of horizontal wellbore.

Jiang Tingxue [13] used conformal transformation method to study the finite element method for dynamic prediction of fractured wells in low permeability reservoirs. Taking wells as internal boundary conditions, their productivity formula was deduced. Jiang Tingxue and Shanwen [14] also used conformal transformation method to deduce a simple productivity formula for vertical fractured wells with good consistency with existing typical curves.

Ding Yiping and Wang Xiaodong [15] deduced the productivity formula of fractured horizontal wells by using the concept of equivalent diameter, and analyzed the influence of fracture number and spacing on bottom hole pressure and fracture flow distribution of fractured horizontal wells.

According to the plane radial unstable seepage equation and the continuous condition of the two-zone interface, Zhang Gongshe and Tang Guangcai [16] established the mathematical model of pressure drop under the condition that the fluid flowed into the wellbore at a constant flow rate. Dimensionless bottom hole pressure curve was solved by Laplace transformation and Stehfest numerical inversion, and the production rate and oil recovery index were calculated when the bottom hole pressure was saturated pressure.

Wang Xiaoquan and Zhang Shouliang [17] studied eight factors affecting the output of horizontal wells after multi-stage fracture fracturing.

The unsteady productivity model of multi-fractured horizontal wells in gas reservoirs is deduced by Shining Congxin and Li Xiaoping [18], taking into account the pressure drop discontinuity caused by the existence of fractures and the influence of the upper and lower surface of fractures on seepage flow.

Lian Peiqing and Tong Dengke [19] applied Green's function and Newman product principle to deduce the formula of unsteady seepage pressure drop in horizontal wells with vertical fracture fracturing, and put forward that friction and horizontal length of horizontal wells had certain influence on the production performance of fractured horizontal wells. The output of each fracture was different, and the length of horizontal section and the number of fractures exist the most optimal range.

Mou Zhenbao and Yuan Xiangchun [20] deduced the productivity formulas of fractured horizontal wells under the condition of filling and non-filling according to the principle of hydroelectric similarity and the method of equivalent seepage resistance, and compared them with the productivity formulas and numerical simulation results studied by predecessors, and proposed that Mou Zhenbao formula should be adopted in the case of filling after fracturing horizontal wells, Lang Zhaoxin's formula was recommended in the case of no hole filling after well fracturing.

Sun Liangtian and Sun Yijian [21] discussed the optimization of fracture number, fracture length, fracture conductivity, and the effect of fracture layout and fracture location on productivity of fractured horizontal wells.

Ma Hui [22] combined Guo Genliang’s horizontal well fracturing productivity prediction method, through the establishment of horizontal well fracturing physical model with different fracture morphology, the productivity formula was revised and improved, and the field application accuracy was higher.

In summary, the analytical method for productivity prediction of fractured horizontal wells is simple in form and easy to use, but limited by the assumptions of the model, it is very difficult to deal with complex reservoir boundary, reservoir heterogeneity, productivity change with time, and fractured incomplete penetration of reservoirs, so its application scope is relatively narrow.

Semi-analytical productivity prediction model is a new productivity prediction method for fractured horizontal wells. This method can overcome many limitations of analytical method, and is faster and more effective than numerical simulation method in calculation. The semi-analytical productivity prediction model of fractured horizontal wells firstly uses Laplace transform to obtain the change of productivity and pressure of fractured horizontal wells with time in massive reservoirs, and then couples the contribution of fractures to productivity in the form of skin factor into the semi-analytical productivity prediction model of horizontal wells, so as to simulate massive oil by semi-analytical method. Among them, the analytical model can deal with any number of fractures in massive reservoirs crossing a horizontal well at any angle with the wellbore, while the semi-analytical model of horizontal wells can fully consider the influence of different boundary types and skin factors on the productivity of fractured wells. And the semi-analytical method is the main research method in foreign countries.

2.2 Abroad research progress of productivity equation

Karcher [23] studyed the productivity characteristics of fractured horizontal wells with infinite conductivity fracture and horizontal wells with several transverse fractures, and gave a calculation model of production ratio with vertical wells. Giger [24] deduced the productivity equation of fractured horizontal wells with infinite conductivity fracture in low permeability reservoir, studied the distribution law of seepage field and pressure field of fractured horizontal wells, and theoretically calculated the variation law of production index ratio of fractured horizontal wells and fractured vertical wells with the degree of fracture extension.

EIRafie [25] studied the production performance of 8 horizontal fractured wells with transverse fractures. It was believed that after a period of production, the flow between fractures would interfere. The closer the fracture was to the inside, the greater the interference would be, the lower the production would be, and the distance between the two lateral fractures would have a greater impact on the oil recovery index. It was pointed out that it was beneficial to increase productivity of fractured horizontal wells by using unequal spacing fracture spacing, especially increasing the spacing of lateral fractures. Soliman [26] studied the early production model of a fractured horizontal well with multiple limited conductivity fractures in an infinite thick reservoir, and proposed that high conductivity fractures can overcome the additional pressure drop caused by streamline convergence around horizontal wells.

J. E. Brown [27] compared the production of fractured horizontal wells and fractured vertical wells under steady seepage, and calculated the optimal number of fractures under actual conditions by economic evaluation method. Norris [28] gave the production chart of horizontal wells with multiple limited conductivity fractures.

Herge [29] put forward the conversion formula between effective wellbore radius and fracture conductivity, fracture number and size, wellbore radius and fracture spacing. The converted productivity formula can be used to calculate the productivity of horizontal and vertical fractured wells. Aboaba and Cheng [30] analyzed the early linear flow characteristics of multi-stage skillfully fractured horizontal wells in shale gas reservoirs. On this basis, the fracturing parameters were determined by using the chemical production data of the early linear flow stage.

3. Research progress of numerical simulation for horizontal well fracturing

Generally, analytical methods can only be used to calculate single-phase and simple two-phase fluids, and the analytical methods can only reflect the capacity characteristics of quasi-steady state, but can not fully reflect the capacity situation of the whole production stage. But the numerical simulation method can fully reflect the productivity of the whole production stage. With the rapid development of computer technology, and because the numerical simulation method can fully reflect the productivity characteristics of the whole production stage, the study of predicting the productivity of horizontal wells and fractured horizontal wells by numerical simulation method has gradually aroused people's attention.

S.A. Holditch [31] used two-dimensional single-phase reservoir numerical simulator to study the optimization of fracture length of fractured wells in low permeability gas reservoirs. It was proposed that fracture length and fracturing flow ability of hydraulic fracturing can be considered as parameters to be controlled. The main factors determining these two parameters are reservoir permeability and oil and gas saturation. But the influence of fracture orientation was not considered in the research process.

Pieters and Al-Khalifa [32] used three-dimensional reservoir models to study and compare the development effects of horizontal and vertical wells for heterogeneous carbonate reservoirs. Their research showd that if vertical wells could penetrate the whole reservoir, the cumulative oil production from horizontal wells and vertical wells was not much different.

Dyksra and Dickinson [33] calculated the crude oil recovery of vertical and horizontal wells during gravity drainage. They considered that the production effect of horizontal wells was better than that of vertical wells if the reservoir thickness was greater than this value, when there was no gravity drive in horizontal reservoirs and the reservoir thickness was less than 85% of the well spacing. In the absence of gravity flooding, the reservoir thickness affects the production ratio of horizontal well to vertical well.

J. Taber and R. Seright [34] had studied the advantages of horizontal wells relative to vertical wells under water flooding conditions. They believed that the plane sweep efficiency of horizontal wells can be 25% to 75% higher than that of straight wells, and the advantages of horizontal wells in water flooding development of thin reservoirs were more obvious than that in water flooding development of thick reservoirs.

Joshi [35] used two-dimensional reservoir numerical simulator to study.He believed that horizontal wells as water injection wells or production wells could not improve area sweep efficiency, but horizontal wells as production wells can improve productivity, as injection wells can improve injection capacity, and in reservoirs with lower permeability, this advantage was more significant.

Ferreira [36] used numerical simulation method to study. He believed that the ratio of vertical permeability to horizontal permeability, injection-production ratio and reservoir thickness had less influence on a certain fluidity than crude oil recovery in water flooding process, but the development effect of horizontal wells in water flooding process was obviously better than that of ten traditional vertical wells.

Gharbi [37] used three-dimensional chemical flooding model to study the immiscible flooding characteristics of vertical and horizontal wells in heterogeneous reservoirs, and the influence of horizontal section length and horizontal to vertical permeability ratio on displacement effect. It was considered that the degree of reservoir heterogeneity had a great influence on the immiscible flooding of horizontal wells, and that in highly heterogeneous reservoirs. Flat section length colud not guarantee higher oil recovery, that was, the effect of horizontal wells to enhance oil recovery was greatly affected by permeability changes and reservoir heterogeneity.

Popa and Cliea [38] had studied the law of pressure drop along horizontal section of horizontal well and the influence of well pattern geometry on sweep efficiency of water drive. It was proposed that the development effect of horizontal well injection was better than that of horizontal well injection.Algharaib et al. [39-40] considered that the vertical-horizontal well combination has similar development effect.

He Yanqing et al. [41] established a two-dimensional single-phase reservoir and fracture model, studied the production prediction method of fractured vertical wells, taking into account the changes of fracture conductivity with time, sand filling in the middle and tail of fractured wells, and drew dimensionless typical curve.

Miao Heping [42] has established a two-dimensional two-phase seepage model for predicting single fracture production after fracturing in horizontal wells. The prediction period was divided into three stages: early, middle and late stages, which greatly reduced the amount of calculation. The essence of the model was to use numerical method to calculate multi-fracture production in the early stage, while analytical method was used in the middle and late stages..

Xu Hao [43] used the numerical simulation method to study the water flooding recovery of five-point pattern of horizontal well injection-production. He proposed that the vertical permeability and horizontal permeability ratio, injection-production speed and reservoir thickness had little influence on the recovery when the water-oil fluidity ratio was fixed, which proved that the oil recovery ratio of horizontal well system was higher than that of vertical well system. The correlation curve of volumetric displacement efficiency with fluidity ratio in the hypothetical five-point well pattern was derived, which can estimate recovery factor in the range of parameters.

Chen Chongxi et al. [44] proposed a horizontal well flow model considering the flow resistance in both linear and non-linear wellbore flow regimes, and took the inner boundary at the outlet of the horizontal well to avoid the difficulty of assuming the flow distribution and head distribution when describing the horizontal wellbore with line sinks.

On the basis of numerical simulation, Zhang Xuewen [45] quantitatively analyzed the relationship between fracture length and conductivity of fractured vertical wells and cumulative oil production.

Li Liuren [46] used a three-dimensional three-phase full-component reservoir numerical simulator to predict the natural energy depletion recovery process of vertical fractured wells with hydraulic fracturing in low permeability oil, and compared it with the natural energy depletion recovery process without fracturing. It was considered that the vertical fracturing by hydraulic fracturing improved the recovery rate, but affected the recovery rate. It was not very large, and was analyzed by the method of material balance.

Liu Xiangping [47] put forward a new method to study dimensionless inflow performance curve of horizontal wells in dissolved gas drive reservoirs by numerical simulation method, which should first make IPR curve when average reservoir pressure was constant, then dimensionless, and put forward a new unified equation to describe dimensionless IPR curve of horizontal wells in dissolved gas drive reservoirs.

Li Junshi and Hou Jianfeng [48] reasonably assumed and simplified the flow problem of fractured horizontal wells in three-dimensional reservoirs. On this basis, the unsteady seepage system model of three-dimensional reservoir with limited conductivity fracturing horizontal wells was established. The bottom hole pressure and flow distribution were solved by the combination of semi-analytical method, and the bottom hole pressure curve was also carried out flow stage analysis.

In view of the limitation of the conventional orthogonal optimization algorithm, Song Daowan and Zhang Fengxi [49] used genetic algorithm to optimize the parameters of horizontal section length, fracture number, fracture half-length, conductivity and well row spacing. Using the interface between numerical simulation software and programming software, the automatic optimization software of fractured horizontal well pattern was developed.

Wang Zhiming and Jinhui [50] set up the coincidence model of fractured horizontal wellbore fractured horizontal well fractured section inflow, horizontal wellbore section inflow and reservoir percolation, and considered the influence of horizontal wellbore completion section production, fracture length, conductivity, spacing, and angle between fracture and horizontal wellbore on production.

To sum up, there are three main numerical methods for solving differential equations: finite difference method, finite element method and boundary element method. The main advantages of finite difference method are simple form and less machine memory. The disadvantage is that the difference equation does not reflect the physical significance. Although the finite difference method can be applied to irregular regions, the continuity of the region is more stringent. The basic idea of finite element method is to discretize the solution domain into a group of finite elements which are connected together in a certain way. Because the element can be divided into different shapes and sizes, it can deal with the complex geometry of the solution domain. The basic solution of differential operator used in boundary element method can satisfy the condition of infinite distance automatically, so it is especially convenient to deal with infinite domain and semi-infinite domain problems. The main disadvantage of boundary element method is that it is difficult to solve the problem of inhomogeneous anisotropy.

4. Difficulties and development trends of fracturing productivity prediction for horizontal wells

4.1 Difficulties in prediction

(1) Establishment of productivity model

Horizontal wells often need fracturing to produce multiple fractures, and the geometric size and conductivity of each fracture may not be the same. In addition, the calculation of productivity of horizontal wells after fracturing is more complicated because of the interference between them during production. In addition, the loss of flowing pressure in wellbore also affects the calculation of productivity. In order to simulate the productivity of fractured horizontal wells with multiple fractures more accurately, a productivity calculation model of horizontal wells with multiple fractures interfering with each other should be established in the course of research, combining with the actual shape of fractured horizontal wells after fracturing, which can provide precise reference for the optimal design of fracturing and the optimization of construction parameters of horizontal wells and improve the success rate of fracturing for the horizontal wells.

(2) Reservoir-fracture system meshing

The meshing of reservoir-fracture system is a complex problem. In 1996, Hegre simulated and evaluated the effect of different meshing on simulated fracturing and grid sensitivity analysis. The situation of single fracture in reservoir in Cartesian coordinate system was studied. It was considered that different meshing had a great influence on pressure drop in early flowing stage. It is pointed out that the mesh near the crack must be relatively small to simulate the instantaneous pressure, but no exact criterion for mesh partition is given. It is also considered that the mesh size to achieve a certain accuracy depends on the crack size. If the fracture is small, the mesh size required is also small.

(3) Treatment of fracture conductivity

Because the fracture and formation are regarded as the same seepage fluid system, the fracture is usually regarded as a row of grids separately in the grid division, but the width of the fracture formed in the underground is only 0.002-0.005m, so in the actual calculation, the permeability and flow rate in the fracture will be very large. In order to ensure the convergence and stability of the calculation, it is required to be certain. Fractures are enlarged to a grid by reducing permeability under conductivity. The flow in a fracture is generally assumed to be stable radial flow, but in actual production after fracturing, the flow velocity in the fracture is higher, so the additional pressure loss caused by the flow velocity in the fracture must be considered.

4.2 Trend of development

Productivity prediction of fractured horizontal wells includes two key issues: 1. flow mechanism in matrix and fracture (natural fracture and induced fracture); 2. characterization and prediction of fracture and fracture network. From the current research point of view, it emphasizes the flow mechanism of tight sandstone reservoir, shale gas matrix and fracture, but at the same time, it should be recognized that the understanding of fracture and fracture network development characteristics is still weak. For tight reservoirs, there is almost no oil and gas production under the condition of non-fracturing, so the influence of fracture network on productivity and prediction can not be ignored when the reserves are determined. Therefore, on the basis of perfecting seepage mechanism, the following aspects need to be paid enough attention to.

(1)More attention should be paid to the extension mechanism, development characteristics and monitoring methods of fractures.

(2)The study of fluid flow mechanism in reservoir caused by the change of stress field in the fracturing process needs to be strengthened. Because of the poor physical properties and strong stress sensitivity of tight reservoirs, the productivity changes caused by stress changes can not be ignored.

(3)Pay attention to the combination of field test and numerical simulation. At present, the development of tight oil and gas in our country mainly adopts horizontal well fracturing technology. On-site drilling provides a large number of actual test data, the comprehensive analysis of the data combined with physical simulation and numerical simulation can better understand the law of productivity change and improve the accuracy of productivity prediction.

References

[1] Joshi S D. Augmcntation of Well Production Using Slant and Horizontal Wells[R]. SPE 15375, 1986: 729-739.

[2] Renard G I, Dupuy J M. Influence of Formation Damage on the Flow Efficiency of Horizontal Wells[C]//Formation Damage Control Symposium, Lafayette, Louisiana, February. 1990: 22-23.

[3] Elgaghah S A, Osisanya S O, Tiab D. A Simple Productivity Equation for Horizontal Wells Based on Drainage Area Concept[C]//SPE Western Regional Meeting. Society of Petroleum Engineers, 1996.

[4] Fan Zifei.Formula for Steady-state Solution of Horizontal Wells in Fractured Gas Reservoirs[J].Petroleum exploration and development,1997,24(5):67-71.

[5] Lang Zhaoxin, Zhang Lihua. Study on Productivity of Fractured Horizontal Wells [J]. Journal of Petroleum University: Natural Science Edition, 1994, 18(2): 43-46.

[6] Guo Jianchun, Zhao Jinzhou. Single Well Performance Prediction of Hydraulic Fracturing [J]. Drilling and production technology, 2006, 19 (1): 23-27.

[7] Ning Zhengfu, Han Shugang, Cheng Linsong, et al. Calculating Method for Productivity of Fractured Horizontal Wells in Low Permeability Reservoirs [J]. Journal of Petroleum, 2002, 23 (2): 68-71.

[8] Li H, Jia Z, Wei Z. A New Method to Predict Performance of Fractured Horizontal Wells [C]//International Conference on Horizontal Well Technology. Society of Petroleum Engineers, 1996.

[9] Li Xiaoping. Seepage Problems and Pressure Drop Curves of Horizontal Wells Passing Through Multiple Vertical Fractures [J]. Journal of Petroleum, 1996, 17(2): 91-97.

[10] Liu Pengcheng, Wang Xiaodong, Li Suzhen, et al. [J].Journal of Southwest Petroleum Institute, 2004, 26(5): 37-41.

[11] Guo G, Evans R D. Inflow Performance of a Horizontal Well Intersecting Natural Fractures [C]//SPE Production Operations Symposium. Society of Petroleum Engineers, 1993.

[12] Yue Jianwei, Duan Yonggang, Qingshaoxue, et al. Study on Productivity of Horizontal Fractured Gas Wells with Multiple Vertical Fractures [J].Natural Gas Industry, 2004, 24 (10): 102-104.

[13] Jiang Tingxue, Lang Zhaoxin, Shanwenwen, et al. Finite Element Method for Dynamic Prediction of Fractured Wells in Low Permeability Reservoirs [J]. Journal of Petroleum, 2002, 23 (5): 53-58.

[14] Jiang Tingxue, Shanwen. Calculation of Steady-state Productivity of Vertical Fractured Wells [J]. Petroleum Exploration and Development, 2001, 28 (2): 61-63.

[15] Ding Yiping, Wang Xiaodong, Xingjing. A Productivity Calculation Method for Fractured Horizontal Wells [J]. Special Oil and Gas Reservoirs, 2008, 15(2): 64-68.

[16] Zhang Gongshe, Tang Guangcai, Wan Xiaoyong, et al. New Method for Productivity Prediction of Horizontal Fractured Wells by Hydraulic Fracturing [J]. Journal of Petroleum and Natural Gas, 2009, 31 (1): 121-123.

[17] Wang Xiaoquan, Zhang Shouliang, Wu Qi, et al. Influencing Factors of Multi-stage Fracture Productivity in Horizontal Well Fracturing [J]. Petroleum Drilling and Production Technology, 2016, 31(1): 73-76.

[18] Shining Congxin, Li Xiaoping, Qin Haifei, et al. Study on Unsteady Productivity Model and Calculation Method for Multi-fracture Horizontal Wells [J]. Oil and Gas Well Test, 2018, 17 (6): 5-7.

[19] Lian Peiqing, Tongdeng Ke, Cheng Linsong, et al. Productivity Analysis Under Unsteady Conditions of Vertical Fracturing Horizontal Wells [J]. Journal of China University of Petroleum: Natural Science Edition, 2009 (4): 98-102.

[20] Mou Zhenbao, Yuan Xiangchun, Zhu Xiaomin. Calculating Method for Productivity of Fractured Horizontal Wells in Low Permeability Reservoirs [J].

[21] Sun Liangtian, Sun Yijian, Huang Zhiwen, et al. Horizontal Well Fracturing Optimization Design for Low Permeability Reservoirs [J].Journal of Xi'an Petroleum University: Natural Science Edition, 2009, 24(3): 45-48.

[22] Ma Hui. Research and Application of Fracturing Productivity Prediction Method for Horizontal Wells [J]. Oil and Gas Field Surface Engineering, 2019, 28 (5): 8-10.

[23] Karcher B J, Giger F M, Combe J. Some Practical Formulas to Predict Horizontal Well Behavior[C]//SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1986.

[24] Giger F M. Low-permeability Reservoirs Development Using Horizontal Wells[C]//Low Permeability Reservoirs Symposium. Society of Petroleum Engineers, 1987.

[25] Elrafie E A, Wattenbarger R A. Comprehensive Evaluation of Horizontal Wells with Transverse Hydraulic Fractures in a Layered Multi-phase Reservoir[C]//Permian Basin Oil and Gas Recovery Conference. Society of Petroleum Engineers, 1996.

[26] Soliman M Y, Hunt J L, Azari M. Fracturing Horizontal Wells in Gas Reservoirs[C]//SPE Mid-Continent Gas Symposium. Society of Petroleum Engineers, 1996.

[27] Brown J E, Economides M J. An analysis of Hydraulically Fractured Horizontal Wells[J]. paper SPE, 1992, 24322.

[28] Norris S O, Hunt J L, Soliman M Y, et al. Predicting Horizontal Well Performance: A Review of Current Technology[C]//SPE Western Regional Meeting. Society of Petroleum Engineers, 1991.

[29] Hegre T M, Larsen L. Productivity of Multifractured Horizontal Wells[R]. Society of Petroleum Engineers, Richardson, TX (United States), 1994.

[30] Aboaba, A. L. (2010). Estimation of Fracture Properties for a Horizontal Well with Multiple Hydraulic Fractures in Gas Shale. Dissertations & Theses - Gradworks.

[31] Holditch S A, Jennings J W, Neuse S H, et al. The Optimization of Well Spacing and Fracture Length in Low Permeability Gas Reservoirs[C]//SPE Annual Fall Technical Conference and Exhibition. Society of Petroleum Engineers, 1978.

[32] Pieters D A, Al-Khalifa A J. Horizontal Well Performance in a Layered Carbonate Reservoir[C]//Low Permeability Reservoirs Symposium. Society of Petroleum Engineers, 1991.

[33] Dykstra H, Dickinson W. Oil Recovery by Gravity Drainage into Horizontal Wells Compared with Recovery from Vertical Wells[J]. SPE Formation Evaluation, 1992, 7(03): 255-260.

[34] Taber J J, Seright R S. Horizontal Injection and Production Wells for EOR or Waterflooding[C]//Permian Basin Oil and Gas Recovery Conference. Society of Petroleum Engineers, 1992.

[35] Joshi S D. Horizontal Well Technology[M]. PennWell Books, 1991.

[36] Ferreira H, Mamora D D, Startzman R A. Simulation Studies of Waterflood Performance with Horizontal Wells[C]//Permian Basin Oil and Gas Recovery Conference. Society of Petroleum Engineers, 1996.

[37] Gharbi R B, Peters E J, Garrouch A A. Effect of Heterogeneity on the Performance of Immiscible Displacement with Horizontal Wells[J]. Journal of Petroleum Science and Engineering, 1997, 18(1): 35-47.

[38] Popa C G, Clipea M. Improved Waterflooding Efficiency by Horizontal Wells[C]//SPE International Conference on Horizontal Well Technology. 1998: 195-202.

[39] Algharaib M, Ertekin T. The Efficiency of Horizontal and Vertical Well Patterns in Waterflooding: A Numerical Study[C]//SPE Mid-continent Operations Symposium. 1999: 505-512.

[40] Al Gharaib M, Gharbi R C. A Comparative Analysis of Waterflooding Projects Using Horizontal Wells[C]//SPE Middle East Oil and Gas Show and Conference. Society of Petroleum Engineers, 2005.

[41] He Yanqing and Wang Hongxun. Predicting the Production Performance of Fractured Wells by Numerical Simulation [J]. Journal of China University of Petroleum: Natural Science Edition, 1990, (5): 16-25.

[42] Miao Ping, Wang Hongxun. Prediction of Production and Optimization of Fracture Number after Horizontal Well Fracturing [J]. Petroleum Drilling and Production Technology, 2002, 14 (6): 51-56.

[43] Xu Hao, Zhang Zhigen. Water Injection Performance Simulation of Horizontal Wells [J]. Oil and Gas Recovery Technology, 2007, 4 (2): 74-78.

[44] Chen Chongxi, Wang Xusheng, Hu Litang. Water Level Correction of Pumping Wells In Groundwater Flow Numerical Simulation [J]. Journal of Water Resources, 2015, 38 (04): 481-485.

[45] Zhang Xuewen. Study on Numerical Simulation of Fractured Vertical Well Development in Low Permeability Reservoirs [J]. Fault Block Oil and Gas Fields, 2016, (04): 20-22.

[46] Li Liuren, Zhou Jungang. Numerical Simulation Evaluation of Vertical Fracture Stimulation Effect of Hydraulic Fracturing in Low Permeability Oilfields [J].Journal of Xi'an Petroleum Institute: Natural Science Edition, 2017, 15(5): 29-31.

[47] Liu Xiangping, Jiang Zhixiang, Liu Xiangyao, et al. Numerical Simulation of IPR in Horizontal Wells of Dissolved Gas Drive Reservoirs [J].Journal of Petroleum, 2004, 21(1): 60-63.

[48] Li Junshi, Hou Jianfeng, Hu Yongle, et al. Analysis of Unstable Seepage in Fractured Horizontal Wells [J]. Petroleum Exploration and Development, 2008, 35(1): 92-96.

[49] Song Daowan, Zhang Fengxi, An Yongsheng, et al. Study on Automatic Optimization of Well Pattern Parameters of Fractured Horizontal Wells [J]. Special Oil and Gas Reservoirs, 2019, 16(4): 101-103.

[50] Wang Zhiming, Jinhui, Wei Jiangguang. Coupling Model of Variable Mass Inflow and Reservoir Seepage in Fractured Horizontal Wells [J]. Hydrodynamics Research and Progress, 2019, 24 (2): 172-179.