Research on the Applicability Analysis of Double Step Horizontal Wells

Li-jun Zhang[1](✉), Long Peng[2], Guo-qing Han[2], Xian-hong Tan[1], and Jin Shu[2]

[1] CNOOC Research Institute Co, Ltd., Beijing, China
zhanglj8@coori.com.cn

[2] Laboratory of Petroleum Engineering, China University of Petroleum-Beijing, Beijing, China

Abstract. It is difficult to predict the oil and gas productivity when multiple production sections are applied to produce multiple reservoirs at the same time. To solve this problem, a semi-analytical productivity prediction model of double-step horizontal wells is established. Reservoir anisotropy, properties, seepage interference, wellbore pressure drop are considered in this model. The discretization method is applied to divide the double-step horizontal well into several sections for the coupling of reservoir model and wellbore model based on some relevant theories of seepage mechanics, fluid mechanics and numerical analysis. This paper takes stepped horizontal wells as the research object and proposes a set of analysis methods for the applicable conditions of stepped horizontal wells. This method puts forward the concept of non-dimensional production, which is the ratio of the oil production between the lower step section of the stepped well and the upper step section. The non-dimensional production reflects the contribution of the upper and lower step sections to the productivity of the stepped horizontal wells. For the dimensionless production, "three intervals" are defined, which are the "upper step section inefficient area", the "lower step section inefficient area", and the "effective area". The dimensionless production is used as evaluation criteria for the applicable conditions of stepped horizontal wells. In this paper, the applicable condition analysis method of stepped horizontal wells is applied in several oil wells to determine the reasonable permeability difference, viscosity difference, elevation difference, horizontal distance and the two step sections location. This paper proposed an applicable condition analysis method to determine the best characteristic parameters of two stepped horizontal wells.

Keywords: Double step horizontal well · Productivity evaluation · Wellbore-reservoir coupling · Semi-analytical model

1 Introduction

Stepped horizontal well is abbreviated as stepped well. It is a single well type composed of two or more horizontal sections and connecting sections with a certain elevation difference, forming a well trajectory with two or more steps. Stepped horizontal wells are mostly used Develop thin-bed reservoirs or fault-block reservoirs with a certain elevation difference [1]. With the increasing difficulty of oil and gas field development and the

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increasing exploitation technology, thin interbedded oil reservoirs with low exploitation efficiency have gradually shown their development potential, and stepped horizontal well development technology can significantly increase the productivity of thin interbedded reservoirs. At present, there are few studies on the productivity calculation model of step wells at home and abroad, and most scholars summarize them as horizontal wells for simplified calculations. There are two stages in the study of the law of near-well seepage flow in horizontal wells. One is the infinite conductivity stage (without considering the pressure drop in the wellbore), and the other is the combined flow stage of the reservoir seepage and variable mass flow (taking account the pressure drop in the wellbore) [2]. Foreign scholars such as Dikken [3], Ouyang [4], Suzuki [5] established coupling models of reservoir and wellbore from different perspectives, and promoted the development of limited conductivity capacity prediction technology. Many domestic scholars, such as Huang Shijun [6], Lu Cheng [7], Ma Shuai [8] have conducted in-depth research on the productivity calculation model of stepped wells. Stepped horizontal wells have sufficient advantages over conventional horizontal wells. Using stepped horizontal wells will be a low-cost and high-return option. Therefore, studying the applicable conditions of stepped horizontal wells is of great significance for reducing costs and increasing efficiency in oilfields.

2 Model Construction

The semi-analytical prediction model established is to divide the wellbore of a double-step horizontal well into several sections, each section is analytically coupled with reservoir seepage and wellbore pipe flow, and the pressure distribution and flow distribution of each section are solved iteratively. Assuming that the reservoir geological condition is homogeneous, the boundary condition is a constant pressure boundary or a closed boundary, the compressibility of the formation fluid is a slightly compressible fluid, and the compressibility coefficient is a constant. Then the partial differential equation describing the elastically unstable seepage of the micro-compressible fluid is:

$$k_x \frac{\partial^2 p}{\partial x^2} + k_y \frac{\partial^2 p}{\partial y^2} + k_z \frac{\partial^2 p}{\partial z^2} = \phi \mu c_{\mathrm{t}} \frac{\partial p}{\partial t} \tag{1}$$

Using Green's function, three one-dimensional surface source solutions parallel to the coordinate axis can be obtained, and any point $\mathrm{M}_0(x_{\mathrm{D}_0}, y_{\mathrm{D}_0}, z_{\mathrm{D}_0})$ in the three-dimensional space of the box-shaped reservoir can be obtained by superposing according to the Newman product principle [9].

$$p(x_{\mathrm{D}}, x_{\mathrm{D}_0} t_{\mathrm{D}}) = \frac{1}{\sqrt{4\pi t_{\mathrm{D}}}} \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(2n + x_{\mathrm{D}_0} - x_{\mathrm{D}})^2}{4t_{\mathrm{D}}}\right] + \exp\left[-\frac{(2n - x_{\mathrm{D}_0} - x_{\mathrm{D}})^2}{4t_{\mathrm{D}}}\right] \tag{2}$$

$$P(\mathrm{M}_0) = \frac{1}{x_{\mathrm{D_e}}} P(\frac{x_{\mathrm{D}}}{x_{\mathrm{D_e}}}, \frac{x_{\mathrm{D}_0}}{x_{\mathrm{D_e}}}, \frac{t_{\mathrm{D}}}{x_{\mathrm{D_e}}^2}) \times \frac{1}{y_{\mathrm{D_e}}} P(\frac{y_{\mathrm{D}}}{y_{\mathrm{D_e}}}, \frac{y_{\mathrm{D}_0}}{y_{\mathrm{D_e}}}, \frac{t_{\mathrm{D}}}{y_{\mathrm{D_e}}^2}) \times \frac{1}{z_{\mathrm{D_e}}} P(\frac{z_{\mathrm{D}}}{z_{\mathrm{D_e}}}, \frac{z_{\mathrm{D}_0}}{z_{\mathrm{D_e}}}, \frac{t_{\mathrm{D}}}{z_{\mathrm{D_e}}^2}) \tag{3}$$

According to the method of instantaneous point source solution, integrating time and wellbore interval, a continuous line source solution of M0M1 in any section of the box-shaped reservoir can be obtained, thereby obtaining the pressure change of M0M1 at any point in the reservoir at any time:

$$P(\mathrm{M_D}, \mathrm{M_0}, \mathrm{M_1}, \mathrm{t_D}) = \int_{\mathrm{M_0}}^{\mathrm{M_1}} P(\mathrm{M_D}, \mathrm{M_w}, \mathrm{t_D})\mathrm{dM_w} \tag{4}$$

The wellbore flow model considers the steady-state flow of a single-phase fluid and makes the following assumptions: the fluid is a single-phase incompressible Newtonian fluid; there is no heat exchange between the fluid and its surroundings. The momentum equation under the above assumptions is:

$$\frac{dp}{dx} = -2\rho q_I \frac{\mathrm{U}}{\mathrm{A}} - \tau_{\mathrm{w}} \frac{\mathrm{S}}{\mathrm{A}} - \rho g \sin\theta \tag{5}$$

The double-step horizontal well is divided into n sections, mass conservation equations, pressure response equations and combined wellbore pipe flow equations can be established during the coupling process of reservoir seepage and wellbore pipe flow. There are 2n unknowns solved by the model.

$$p_{\mathrm{w}}(i+1) = p_{\mathrm{w}}(i) + \Delta p_{\mathrm{f}}(i+1) + \Delta p_{\mathrm{a}}(i+1) + \Delta p_{\mathrm{g}}(i+1) \tag{6}$$

The order of solving is to first solve the mass conservation equation and the pressure response equation, then solve the wellbore flow equation. In this way, the inflow profile and pressure distribution of any micro-element section of the double-step horizontal well can be calculated.

3 Target Parameters of Stepped Horizontal Wells

3.1 Dimensionless Production

In view of the contribution of different step sections of stepped horizontal wells to oil well productivity, defining the dimensionless production concept:

$$q_{ns} = \frac{q_d}{q_u} \tag{7}$$

where, q_{ns} is the dimensionless production, dimensionless; q_d is the stepped section production of the stepped horizontal well, m^3/d; q_u is the stepped section production of the stepped horizontal well, m^3/d. Dimensionless production is defined as the ratio of the production in the stepped section of the step downhole to the production in the upper step section. It reflects the contribution of the upper and lower steps to the productivity of the oil well.

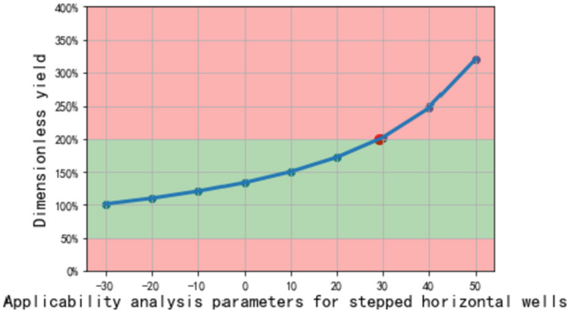

Fig. 1. Schematic diagram of "three intervals" for suitability analysis of stepped horizontal wells.

3.2 "Three Intervals" for Suitability Analysis of Stepped Horizontal Wells

Taking the dimensionless production as the research object, the "three intervals" are specified for stepped wells according to the value range of the dimensionless production, as shown in Fig. 1.

Taking 50% and 200% as the upper and lower dividing lines respectively, the dimensionless output in Fig. 1 is divided into three different intervals. "Upper step section inefficient area" ($q_{ns} > 200\%$): the upper red area, the upper step section's contribution to the oil well's productivity is relatively insufficient due to the high productivity of the lower step section. "Effective area" ($50\% < q_{ns} < 200\%$): the green area in the middle, the contribution of the upper and lower steps to the well productivity is relatively close, and there is no case where a certain step section contributes too much or little. It is recommended to use step wells at this green area. "Lower efficiency zone of lower step section" ($q_{ns} < 50\%$): The red area in the lower part, due to the excessive pressure loss of the wellbore, the lower step section has relatively insufficient contribution to the productivity of the oil well.

4 Applicability Analysis of Stepped Horizontal Wells

4.1 Permeability Differential

Defining the Permeability Differential. The permeability differential is defined as the ratio of the upper step section and the lower step section in the reservoir, which reflects the difference in permeability between the upper and lower stepper horizontal wells.

$$K_{ns} = \frac{K_{\mathrm{u}}}{K_d} \tag{8}$$

where, K_{ns} is the permeability differential dimensionless; K_d is the permeability of the lower reservoir, mD; K_u is the permeability of the upper reservoir, mD.

Applicability Analysis of Permeability Differential. The horizontal permeability of the upper reservoir is 2000 mD and the vertical permeability is 200 mD. Making other parameters unchanged, give a set of lower reservoir permeability: 1000 mD, 800 mD, 600 mD, 400 mD, 300 mD, 250 mD, 200 mD, 150 mD, and 100 mD, so the permeability differentials are 2, 2.5, 3, 3.3, 5, 6.67, 8, 10, 13.3, 20. The basic data of two reservoirs in XX oil reservoir are shown in Table 1.

Table 1. The basic data of two reservoirs in XX oilfield.

	Upper stepped horizontal well	Lower stepped horizontal well
Viscosity (mPa·s)	30	30
Length of horizontal section (m)	160	160
Elevation difference (m)	20	20
Horizontal distance (m)	150	150
Production pressure difference (MPa)	1.1	1.3

The semi-analytical prediction model can be used to obtain the production of the corresponding upper and lower steps of the oil well, and calculate the dimensionless production q_{ns}. Dimensionless production with different permeability is plotted in a coordinate system to obtain a permeability level applicability analysis result, as shown in Fig. 2.

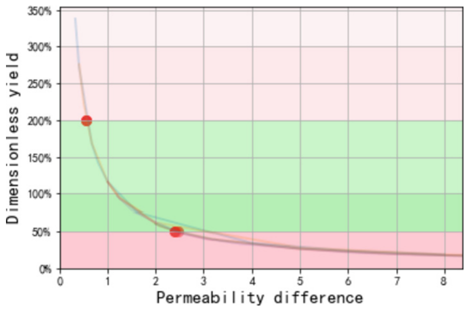

Fig. 2. Applicability analysis of permeability differentials in the upper reservoir.

It can be seen from Fig. 2 that for any upper oil layer permeability, the shape of the permeability gradient curve is similar and the permeability gradient limit is also very close. Therefore, the upper limit of the permeability differential is around 2.5 and the lower limit is about 0.6. This conclusion has a certain accuracy.

4.2 Viscosity Differential

Defining the Viscosity Differential. The viscosity ratio is defined as the ratio of the crude oil viscosity of the upper reservoir and the lower reservoir, which reflects the difference in the viscosity of the crude oil between the upper and lower stepped horizontal wells.

$$\mu_{ns} = \pm\frac{\mu_{\mathrm{u}}}{\mu_{\mathrm{d}}} \tag{9}$$

where, u_{ns} is the viscosity ratio, dimensionless; μ_d is the crude oil permeability of the lower reservoir, mPa·s; μ_u is the crude oil permeability of the upper reservoir, mPa·s. Here, "±" is used to reflect the viscosity of the upper and lower reservoirs. When the viscosity of the lower layer is greater than the viscosity of the upper layer, the viscosity ratio takes a negative value. Conversely, the viscosity ratio takes a positive value.

Applicability Analysis of Viscosity Differential. Taking the crude oil viscosity of the upper reservoir as 30 mPa·s, give a set of crude oil viscosity of the lower reservoir: 30 mPa·s, 40 mPa·s, 50 mPa·s, 60 mPa·s, 70 mPa·s, 80 mPa·s s, 90 mPa·s, 100 mPa·s, and 110 mPa·s. Also, taking the crude oil viscosity of the lower reservoir as 30 mPa·s, give a set of crude oil viscosity of the upper reservoir: 30 mPa·s, 40 mPa·s, 50 mPa·s, 60 mPa·s, 70 mPa·s, 80 mPa·s s, 90 mPa·s, 100 mPa·s, 110 mPa·s. With this method, a set of viscosity ratio can be obtained. The basic data of two reservoirs in ## oil reservoir are shown in Table 2.

Table 2. The basic data of two reservoirs in ## oilfield.

	Upper stepped horizontal well	Lower stepped horizontal well
Horizontal permeability (mD)	1000	1000
Vertical permeability (mD)	100	100
Length of horizontal section (m)	160	160
Elevation difference (m)	20	20
Horizontal distance (m)	150	150
Production pressure difference (MPa)	1.1	1.3

The semi-analytical prediction model are used to obtain the production of the corresponding upper and lower steps of the oil well, and calculate the dimensionless production q_{ns}. Dimensionless production with different viscosity ratios is plotted in a coordinate system to obtain a different viscosity applicability analysis result, as shown in Fig. 3.

It can be shown in Fig. 3 that the thicker the crude oil viscosity in the lower reservoir, the smaller the contribution of the lower step section to the productivity of the oil well. When the viscosity ratio is lower than −3.025, the oil well is in the "lower step section inefficient zone". Also, the thicker the crude oil viscosity in the upper reservoir, the

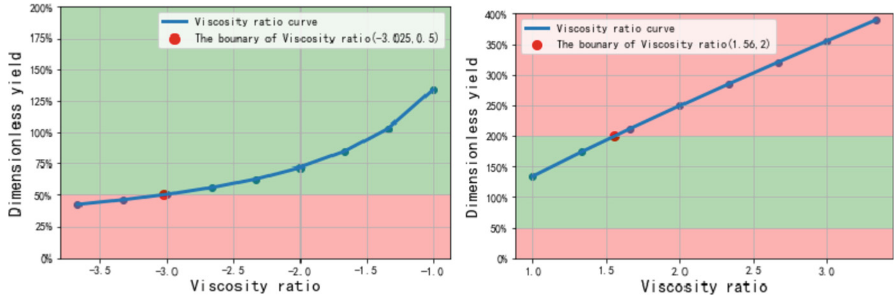

Fig. 3. Applicability analysis of different viscosity differential.

smaller the contribution of the upper step section to the well productivity. When the viscosity ratio is higher than 1.56, the oil well is in the "upper step section inefficient zone".

4.3 Elevation Difference and Horizontal Distance

Elevation difference refers to the vertical distance between two horizontal sections of a stepped horizontal well. Horizontal difference refers to the vertical distance between two horizontal sections of a stepped horizontal well. The elevation difference and horizontal distance mainly affects the gravity pressure drop and frictional resistance in the wellbore. The increase in pressure loss in the wellbore may result in no production in the lower step section. Taking the output curve of the micro-element section with a horizontal distance of 250 m or elevation distance of 50 m, the oil production corresponding to the upper and lower step sections can be obtained in Fig. 4.

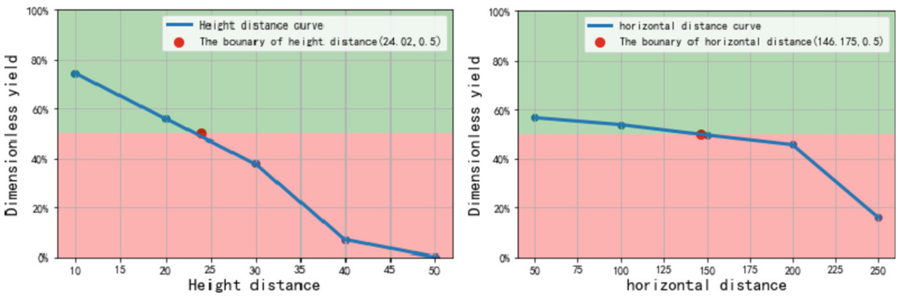

Fig. 4. Applicability analysis of elevation difference and horizontal distance.

It can be seen from Fig. 4 that the larger the elevation difference, the smaller the dimensionless production, and the lower contribution of the lower step section to the productivity of the oil well. When the elevation difference exceeds 24 m, the lower step section does not make enough contribution to the productivity of stepped horizontal wells. In the meanwhile, the larger the horizontal distance, the smaller the dimensionless production, and the smaller contribution of the lower step section to the productivity of the oil well. When the horizontal distance exceeds 146 m, the lower step section makes insufficient contribution to the productivity of the stepped horizontal well.

5 Conclusion

This paper proposes a set of analysis methods for the applicable conditions of stepped horizontal wells. Considering the "three intervals" to analyze the applicability of step wells to provide an evaluation standard for dimensionless production. The applicable conditions for parameters such as permeability, viscosity, elevation difference, and horizontal distance can be obtained in this research.

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