A Productivity Prediction Model of Multiple Fractures and Vertical Well in Tight Oil Reservoirs

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Abstract

In tight oil reservoirs, there are several special characteristics of low natural yield, rapid decline in production, the difficulty in oil exploitation etc. only through fracturing well to obtain industrial mining value. In this paper, the mathematical model and numerical model of fractured vertical well is established by using the well test method based on the actual vertical well production characteristics of Changqing tight oil reservoirs. According to the established model, the fracturing vertical well productivity prediction in Changqing Oilfield was carried out by VB6.0 programming. The results show that the established numerical model agrees well with the actual production data. Then, the model is used to analyze parameter-sensitive in actual vertical well fracturing drilling works, which mainly include the number of fractures, the length of the crack, the pressure coefficient, the fracture conductivity ability, the crack skin factor, etc. The calculation example shows that the fracture conductivity ability and the crack skin factor have a great effect on production.

Keywords

Tight oil; Fractured vertical well; Productivity prediction; Fracture cracks; Parameter-sensitive analysis.

1. Introduction

Tight oil reservoir is the oil reservoir with reservoir permeability less than 0.5mD, porosity of 6%-10% and conventional technology can't be economically efficient mining [1]. Dense oil resources have several special characteristics of rich oil and gas reserves, more types of reservoirs and widely distributed areas etc. The production of tight oil has exceeded the total output of oil and gas 1/3 [1-3]. Due to poor reservoir properties of tight oil, the development of tight reservoirs encounters many problems in the mining process, including low pressure gradient, strong pressure sensitive, fracture development uneven, and well water breakthrough, produced water, flooding are frequent phenomenon, resulting in high water content, low natural well production, production declines rapidly and great difficulty in mining, which have greatly limited the recovery extent of tight reservoir and recovery. [2]

At present, many domestic and foreign scholars have used different principles and methods to propose a variety of fracturing horizontal well production capacity prediction model[4-8], but the number of vertical fractured well production prediction model is relatively small[9-13]. The details are as follows: Rajagopal S. [4] proposed a mathematical model used to discern the characteristic responses of a multiply-fractured horizontal-well. WANG Zhi-ming [5] et al. established the coupling model of fracture mass flow and reservoir seepage in fractured horizontal well based on the principle of potential superposition and continuity. ZENG Fan-hui [6] et al. established an unsteady state computation model of fractured horizontal well coupling with reservoir based on the superposition principle. In consideration of the matrix-crack-wellbore coupling flow and matrix-wellbore coupling flow in an open-hole fractured horizontal well in low/ultra-low permeability reservoirs. WANG Zhi-ping [7] proposed a mathematical model on the basis of the equivalent flowing resistance method and the superposition principle. Liu, H. [8] established a new nonlinear seepage model of low permeability reservoir based on the nonlinear percolation theory. C.A.Kossack [9] describes a numerical scale-up technique to provide the composite properties and curves to be used in gas-oil displacements in triple porosity systems. A Moctezuma-Berthier [10] studied the single and double phase macroscopic permeability of bimodal reconstructed porous media. Schmoker J W. [11] proposed two basic resource-assessment approaches for unconventional gas systems, the first approach is based on estimates of gas in place, and the second approach is based on the production performance of continuous gas reservoirs. Ali Al-Ghamdi [12] proposed an improved triple-porosity model, which can be used continuously throughout a reservoir with segments composed of solely matrix porosity, solely matrix/fractures, solely fracture/vug, or the complete triple-porosity system. W.Djatmiko [13] described techniques to identify vug in a real pressure buildup data, and proposed a numerical triple porosity model to represent the reservoir.

2. Productivity prediction model

2.1 Physical modeling assumption

Due to the distribution of natural cracks, fracturing cracks and matrix pores in actual tight oil reservoirs are very complex, so the tight oil reservoir model in practical application needs to be reasonably simplified, which consists of two systems: matrix and cracks [1,2,13]. For the convenience of research, the other basic assumptions for multiple fracturing models are as follows: the center of the homogeneous formation with circular constant pressure boundary has a well with constant flow pressure to produce, along the radial direction of vertical well, there are n limited conduction cracks with x_f (length of cracks) and ω_f (width of cracks) symmetrically developed around the vertical well.

2.2 Mathematical modeling.

(1) Fracture equation:

$$\frac{\partial^2 p_f}{\partial r^2} + \frac{2k}{k_f \omega_f}\frac{\partial p}{\partial n} = \frac{\partial p_f}{\partial t}\frac{\mu \phi_f C_f}{k_f} \tag{1}$$

(2) Stratum equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2} = \frac{\partial p}{\partial t}\frac{\mu \phi C_t}{k} \tag{2}$$

(3) Internal boundary condition:

At the connection point of fracture and wellbore, $p_f\big|_{r_w} = p_w$ (3)

Epidermal effect, $(p - p_f)\big|_{\Gamma_f} = \dfrac{S x_f}{2\pi}\dfrac{\partial p}{\partial n}$ (4)

(4) Outer boundary condition:

Fracture, $\dfrac{\partial p_f}{\partial r}\Big|_{x_f} = 0$ (5)

Fixed pressure outer boundary, $p\big|_{r_e} = p_i$ (6)

Closed outer boundary, $\dfrac{\partial p}{\partial r}\Big|_{r_e} = 0$ (7)

(5) Productivity calculation formula:

$$Bq = \left(n\frac{k_f \omega_f h}{\mu}\frac{\partial p_f}{\partial r}\right)\Big|_{r_w} \tag{8}$$

2.3 Numerical modeling

(1) Laplace transform:

Further, the Laplace transform of the above model (formula 1-8) is as follows:

Fracture equation, $$\frac{\partial^2 \overline{p}_{fD}}{\partial r_D^2}+\frac{2}{L_{fD}}\frac{\partial \overline{p}_D}{\partial n_D}=z\eta \overline{p}_{fD} \tag{9}$$

Stratum equation, $$\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial \overline{p}_D}{\partial r})+\frac{1}{r^2}\frac{\partial^2 \overline{p}_D}{\partial \theta^2}=z\overline{p}_D \tag{10}$$

Internal boundary condition at the connection point of fracture and wellbore,

$$\overline{p}_{fD}=\overline{p}_{wD}=\frac{1}{z} \tag{11}$$

Internal boundary condition of epidermal effect, $$(\overline{p}_D-\overline{p}_{fD})\Big|_{\Gamma_f}=S\frac{2}{\pi}\frac{\partial \overline{p}_D}{\partial n_D} \tag{12}$$

Outer boundary condition at fracture, $$\frac{\partial \overline{p}_{fD}}{\partial r_D}\Big|_{r_D=1}=0 \tag{13}$$

Fixed pressure outer boundary condition, $$\overline{p}_D\Big|_{r_D=\frac{r_e}{x_f}}=0 \tag{14}$$

Closed outer boundary condition, $$\frac{\partial \overline{p}_D}{\partial r_D}\Big|_{r_D=\frac{r_e}{x_f}}=0 \tag{15}$$

Productivity calculation formula, $$\overline{q}_D=-nL_f(\frac{\partial \overline{p}_{fD}}{\partial r_D})\Big|_{\frac{r_w}{x_f}} \tag{16}$$

Among formula 9-16, dimensionless Laplace space pressure, $\overline{p}_D=\int_0^{\infty}p_D(r_D,t_D)e^{-zt_D}dt_D$; dimensionless pressure, $p_D=\frac{p_i-p}{p_i-p_{wf}}$; dimensionless distance, $r_D=\frac{r}{x_f}$; dimensionless time, $t_D=\frac{kt}{\mu\phi C_t x_f^2}$; dimensionless diversion capability, $L_f=\frac{k_f\omega_f}{kx_f}$; Fractured matrix pressure coefficient ratio, $\eta=\frac{k\phi_f C_f}{k_f\phi C_t}$; dimensionless production, $q_D=\frac{\mu Bq}{kh(p_i-p_{wf})}$.

(2) Stratum meshing:

The radial direction index grid is divided into N grids,

$$\Delta x=\frac{1}{N}\ln(\frac{r_e/x_f}{r_w/x_f})=\frac{1}{N}\ln(\frac{r_e}{r_w}),\quad r_i=\frac{r_w}{x_f}e^{(i+0.5)\Delta x} \tag{17}$$

Considering the symmetrical distribution of fractures, the angle area between the two adjacent fractures is studied as one study unit, which is divided uniformly into M meshes, that is $\Delta\theta=\frac{2\pi}{n\times M}$.

Stratum is divided into $N\times M$ grids, then stratum grid equation is as follow,

$$aw_{i,j}p_{i-1,j}+ae_{i,j}p_{i+1,j}-(ac_{i,j}+z)p_{i,j}+an_{i,j}p_{i,j-1}+as_{i,j}p_{i,j+1}=0 \tag{18}$$

In equation (18),

$$aw_{i,j}=ae_{i,j}=\frac{1}{r_i^2\Delta x^2},\quad an_{i,j}=as_{i,j}=\frac{1}{r_i^4\Delta\theta^2},\quad ac_{i,j}=aw_{i,j}+ae_{i,j}+an_{i,j}+as_{i,j}$$

(3) Fractures meshing:

The fracture is divided into $L\times 2$ grids, fracture grid equation is as follow,

$$aw_{i,j}p_{i-1,j}+ae_{i,j}p_{i+1,j}-(ac_{i,j}+z\eta)p_{i,j}+an_{i,j}p_{i,j-1}+as_{i,j}p_{i,j+1}=ar_{i,j} \tag{19}$$

In equation (19),

$$aw_{i,j}=\frac{1}{r_i^2\Delta x^2},\ ae_{i,j}=\frac{1}{r_i^2\Delta x^2},\ ac_{i,j}=aw_{i,j}+ae_{i,j}+an_{i,j}+as_{i,j},\ ar_{i,j}=0,$$

$$an_{i,j}=\frac{2}{L_f[r_i\frac{\Delta\theta}{2}(1+\frac{S\Delta x}{\pi\Delta\theta})]},as_{i,j}=0\quad \text{, or } as_{i,j}=\frac{2}{L_f[r_i\frac{\Delta\theta}{2}(1+\frac{S\Delta x}{\pi\Delta\theta})]},an_{i,j}=0$$

(4) Grid correction:

Grid correction at connection point between the fracture and the wellbore,

$$ac_{1,1}\Leftarrow ac_{1,1}-\frac{1}{\tfrac{1}{8}(\Delta x\frac{r_w}{x_f})^2},\quad ar_{1,1}\Leftarrow ar_{1,1}-\frac{1}{\tfrac{z}{8}(\Delta x\frac{r_w}{x_f})^2}$$

Grid correction at the distal end of the fracture, $ae_{1,L-1}=0$.

(5) Calculation formula of wellbore flow:

$$\bar{q}_D=-nL_f\frac{p_1-\frac{1}{z}}{\tfrac{1}{2}\Delta x\frac{r_w}{x_f}} \tag{20}$$

3. Sensitivity analysis

According to the above models and algorithms in section 2-3, we can get the relationship curve between the dimensionless oil yield and the dimensionless time in the single medium. Curve control parameters are mainly n (fracture number), xf (fracture half length), η (pressure conductivity coefficient), Lf (fracture conductivity), S (fracture skin). In the actual production, the fracture parameters and the reservoir type will have an impact on the yield. Therefore, it is necessary to analyze the influence of various factors on the vertical crack well productivity of the multi-fracture system.

3.1 Number of crack branches

Figure 1 shows the influence of the number of crack branches on production with model parameters xf=0.5, η=10, Lf=50, S=5. It can be seen from figure 1: the production capacity of tight oil reservoir with three crack branches, four crack branches and five crack branches are increased in turn. In other words, the more number of the cracks, the greater post-fracturing yield.

3.2 Half-length of fracture

The crack half-length reflects the horizontal extension length of the crack. Figure 2 shows the relationship between crack half-length and the productivity. It can be seen from figure 2: the larger the extension of the cracks, the larger the area of cracks connection, the higher the post-fracturing yield, but the production tends to be consistent in the end period of the production.

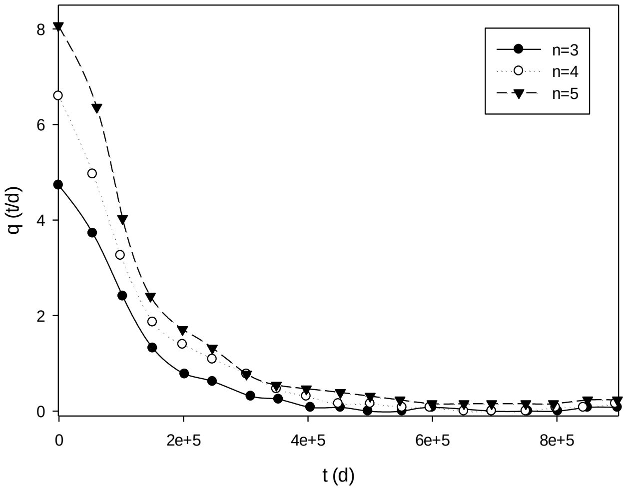

Figure 1. Influence of crack branches number on production

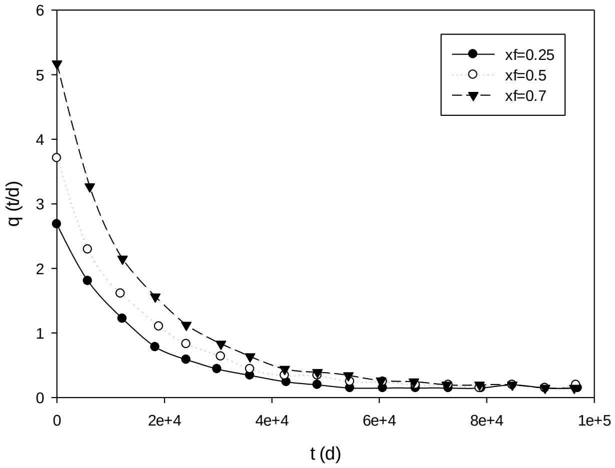

Figure 2. Influence of fracture half-length on production

3.3 Pressure conductivity coefficient

Figure 3 shows the influence of pressure conductivity coefficient on production. It can be seen from figure 3: the bigger the pressure conductivity coefficient, the higher the post-fracturing yield in the early stages of production, but the production tends to be consistent when the system reaches the pseudo-radial flow stage.

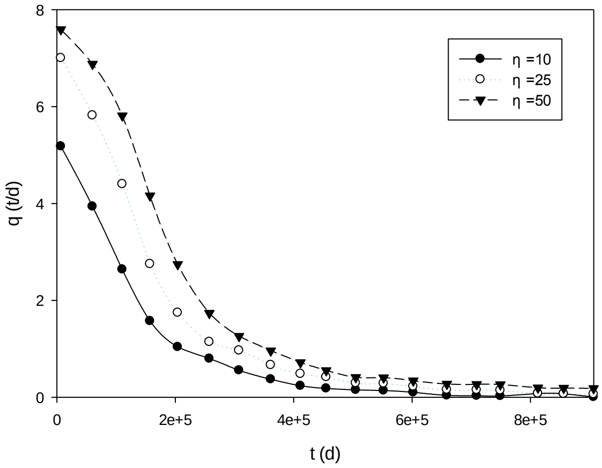

Figure 3. Influence of pressure conductivity coefficient on production

3.4 Fracture conductivity

Fracture conductivity ability is one of the most important parameters of fractured reservoirs and the main manifestation of fracture permeability. Considering that the fracture permeability is mainly affected by the crack width, the size of the crack width determines the strength of the conductivity, the greater the crack width, the stronger the diversion capability, the greater the formation output. Figure 4 shows the influence of fracture conductivity ability on production. It can be seen from the figure: the production of crack wells increased with the increase of fracture conductivity ability in the early stages of production, but the production tends to be consistent when the system reaches certain production period. In addition, the increase in fracture conductivity ability contribution to the increase in production is not infinite, when the fracture conductivity ability increased to a certain extent, if continue to increase the conductivity, the output increase will be reduced.

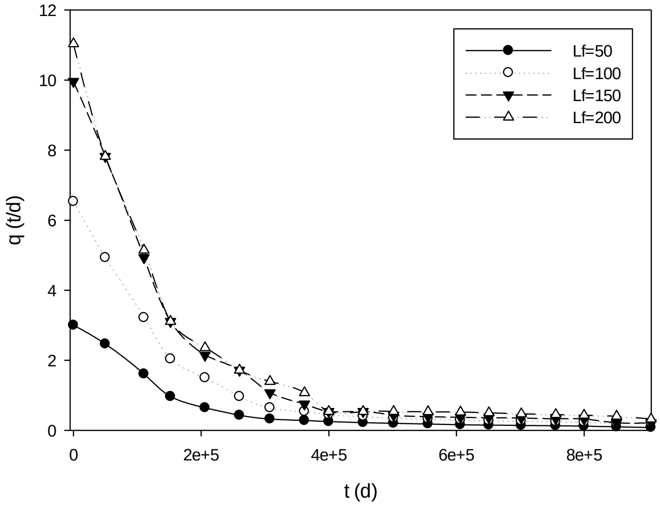

Figure 4. Influence of fracture conductivity on production

3.5 Fracture skin

Figure 5 shows the influence of fracture skin on production. It can be seen from the figure: the smaller the fracture skin, the greater the post-fracturing yield in the early stages of production.

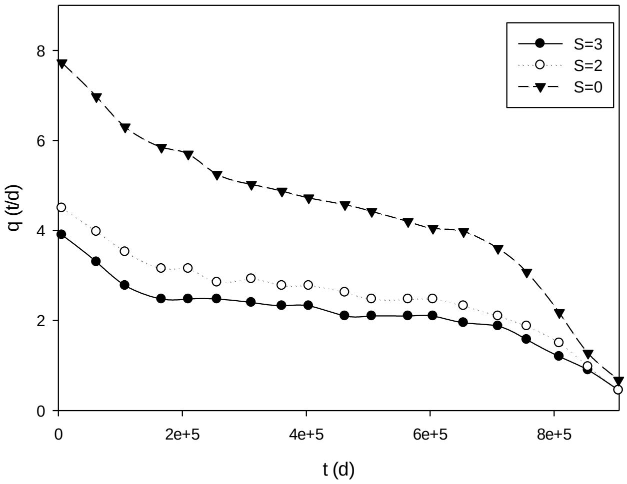

Figure 5. Influence of fracture skin on production

4. Conclusion

Based on the theory of well test and material conservation principle, this paper establishes the production capacity prediction model of multi-fractured vertical well in tight oil reservoir, which taking full account of the characteristics of tight oil reservoir and actual production state with vertical well. Experiments show that the established model can be applied to the actual reservoirs of a block in Changqing Oilfield, China, the established model can play a guiding role in the development technical policies of the vertical well. This paper draws the following main conclusions:

(1) Through the calculation and analysis, the calculated value of the capacity model agrees with the actual value, and the proposed model is suitable for the tight reservoir in the studied area.

(2) The influence of various factors on the production capacity is analyzed by means of the capacity model as the technical means. The results show that fracture conductivity ability and fracture skin factor have great influence on the production capacity. The production of crack wells increased with the increase in the number of crack branches, half-length of fracture, fracture conductivity ability and pressure conductivity coefficient in the early stages of production, but the production tends to be consistent in the stable phase of production, and the production of crack wells increased with the decrease of fracture skin.

The follow-up work will combine the actual production data of similar research blocks, carry out more parameters inversion optimization experiments, to improve the parameters optimization method and to improve the adaptability of the production forecasting model.

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