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Productivity Evaluation Method of Horizontal Well Volume Fracturing in Tight Oil Reservoir

SHI Xiaodong[a],[b],*; AI Chi[a]; ZHAN Jianfei[b]; HUANG Shijun[c]; HU Chaoyang[a]

[a] Northeast Petroleum University, Daqing, China.
[b] Exploration and Development Research Institute of Daqing Oilfield Company Ltd, Daqing, China.
[c] China University of Petroleum, Beijing, China.
*Corresponding author.

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Abstract
Tight oil resources in north Songliao basin is rich and abundant, which is the most important energy sources foundation of stable and raising oil production in Daqing oil field. However, it is difficult to develop such oil resources by the regular ways for the poor reservoir property and thin reservoir thickness. Using the way of horizontal well by volume fracturing can increase contract area of well and the reservoir, improve reservoir flow performance and reach the high oil production, which has showed good results up till now. The accurate productivity evaluation of volume fracturing horizontal well is an important content of reservoir and production engineering field, which is also to develop solutions and decision-making basis. The current formula of horizontal well in low permeability reservoirs production did not consider the effect of seepage volume form fracturing, so it is poorly adapt to calculate the productivity of volume fracturing horizontal well. Based on the tight oil reservoir geological characteristics and seepage characteristics, equation are solved coupling with flow through fractures in the substrate, productivity prediction model is established and the innovation is based on considering horizontal well reservoir heterogeneity, fracturing scale and any artificial fracture distribution form, the results of which can provides a reliable theoretical basis for tight oil reservoir developed effectively.

Key words: Tight oil; Horizontal well; Volume fracturing; Productivity prediction

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INTRODUCTION
Tight oil reservoir in Daqing oilfield has the characteristics of low porosity, low permeability, many oil-bearing strata and serious vertical heterogeneous, it is difficult to develop by the regular ways. For such poor reservoir, the way of horizontal well by volume fracturing is used to increase improve reservoir flow performance and oil production. At present, the main research methods of fracturing well productivity evaluation from domestic scholars are stable seepage and unstable seepage[1-8]. Stable seepage flow method is mainly from the theory of potential function and conformal transformation, but there is a certain deviation between the steady-state productivity calculation results and the real value for reservoir pressure in the production process is constantly changing. Unstable seepage flow method mainly adopts Green's function, Newman and Laplace transform method[9-14], in which bottom hole pressure is solved under the proration productivity, but problems from volume fracturing has not been solved satisfactorily, such as how to solve the productivity-changing in proration bottom hole pressure, how to describe the impact on production from heterogeneity of reservoir on the longitudinal, how to simulating the effect of seepage characteristics from reservoir volume fracturing.

In this paper, on the basis of the source function solution under closed boundary Laplace space derived by

Ozkan[15], the semi-analytical solution of fractures discrete units is built, fractures flow is treated as stable seepage flow and the flow equation from reservoir to the fractures is coupling solved, the productivity-changing in proration bottom hole pressure is solved using the method of multi-layer flow superposition regardless of the interporosity flow conditions in the longitudinal layer. Thus, volume horizontal well fracturing productivity prediction method in tight oil is formed which can calculate the productivity considering any artificial fracture forms.

1. SEEPAGE MODEL CONSIDERING TIGHT OIL RESERVOIR HETEROGENEITY

With a greater length of horizontal wells in tight oil reservoir and the reservoir property differences along the direction of the horizontal wellbore is significant, this heterogeneity has obvious effect on productivity. In this paper, based on the Green function under Laplace space bounded, separating partition area of fractures with different permeability are discrete, using the boundary element numerical method, finite diversion fracturing horizontal well productivity calculation model is established in the condition of partition permeability.

1.1 Model Assumption

In this paper, model along the direction of the horizontal wellbore reservoir can be divided into many period of heterogeneous reservoirs with different permeability, which is showed as Figure 1. The reservoir boundary is closed, pressure and flow is continuous at interface of different permeability partition.

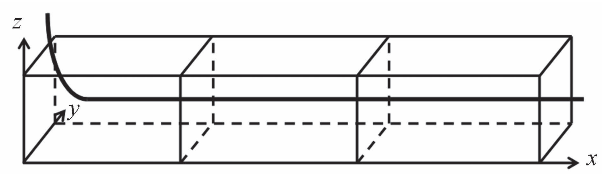


Figure 1
Heterogeneity Reservoir Model of Fracturing Horizontal Well

In order to describe the fluid flow law of heterogeneity of reservoir, the following hypothesis are put forward: (a) the reservoir is homogeneous and isotropic strata in each partition areas; (b) the fractures have connected the whole reservoir on the longitudinal; (c) fluid flow should correspond to two-dimensional and single-phase slightly compressible unsteady seepage; (d) ignore the effect of gravity; (e) fracture diverting capacity does not change with time.

1.2 Reservoir Flow Model

For single phase fluid flow in the reservoir which is closed around with isotropic flow, the seepage equation is transformed by using the Laplace method, the expression can be expressed as:

$$\beta_c\left(\frac{\partial^2 \overline{p}_d}{\partial x^2}+\frac{\partial^2 \overline{p}_d}{\partial y^2}\right)=\frac{s}{\eta^n}\overline{p}_d, \tag{1}$$

$$p_d = p_i - p, \tag{2}$$

$$\eta^n = \frac{K^n}{\phi_m{}^n \mu^n C_t^n}, n = 1, 2, \cdots, N_K. \tag{3}$$

Where β_c is unit conversion factor (β_c = 0.0864); p_d is pressure drop at any point of formation, MPa; $\overline{p}$ is value of p_d in the Laplace space, MPa; p_i is original formation pressure, MPa; s is Laplace variables; p is pressure at any point of layer, MPa; n is numbers of oil layers; η^n is pressure transmitting coefficient in each permeability partition, 1×10^{-6} m^2; K^n is permeability in each partition, 1×10^{-3} μm^2; ϕ_m^n is matrix porosity in each partition; μ is formation oil viscosity in each partition, mPa·s; C_t^n is fluid compressibility, MPa^{-1}; N_K is numbers of permeability partitions.

Using the parallel plate theory and tensor theory, the fractured reservoir is simplified to anisotropic equivalent continuous medium, the equivalent permeability of fractured rock mass in the model is equal to the permeability tensor sum of the permeability of the rock matrix with no fracture and permeability of the fracture system. Reservoir seepage inside complete mathematical model is established under initial condition $\overline{p}_d$=0 and in-out boundary conditions, cracks grid and boundary grid are treated as Laplace space integral solutions of point source function under the sealed the area around, the basic solution of Green's function at any point in different permeability partitions can be expressed as:

$$\overline{G}_B^n(\xi,\zeta,x_{wi}^n,y_{wi}^n,l_{wi}^n)=\frac{\mu}{2\beta_c K^n h^n x_e^n}\left\{\frac{ch(\sqrt{s}(y_e^n-|\zeta-y_{wi}^n|))+ch(\sqrt{s}(y_e^n-(\zeta+y_{wi}^n))}{\sqrt{s}sh(\sqrt{s}y_e)}\right.$$
$$+\frac{4x_e^n}{\pi l_w}\sum_{\alpha=1}^{+\infty}\frac{1}{\alpha}\cos\frac{\alpha\pi\xi}{x_e^n}\cos\frac{\alpha\pi x_{wi}^n}{x_e^n}\sin\frac{\alpha\pi l_{wi}^n}{2x_e^n}\cdot$$
$$\left.\left[\frac{ch(\sqrt{s+(\frac{\alpha\pi}{x_e})^2}(y_e^n-|\zeta-y_{wi}^n|))+ch(\sqrt{s+(\frac{\alpha\pi}{x_e})^2}(y_e^n-(\zeta+y_{wi}^n))|}{\sqrt{s+(\frac{\alpha\pi}{x_e})^2}sh(\sqrt{s}y_e^n)}\right]\right\}. \tag{4}$$

Where $\overline{G}_B^n$ is the basic solution of Green's function; ξ is x-coordinate of any point in permeability partition, m; ζ is y-coordinate of any point in permeability partition, m; x_{wi}^n is x-coordinate of grid cell in permeability partition, m; y_{wi}^n is y-coordinate of grid cell in permeability partition, m; l_{wi}^n is length of grid cell in permeability partition, m; h^n is effective thickness of permeability partition, m; x_e^n is the maximum x-coordinate of permeability partition, m; y_e^n is the maximum y-coordinate of permeability partition, m.

The fracture and partition boundary are transformed into the discrete grid which as Figure 2, the seepage boundary integral equation of matrix is established and expressed as:

$$\lambda(\xi,\zeta)\overline{\Delta p}_d^n(\xi,\zeta)=\int_\Gamma \overline{G}_B^n(x,y;\xi,\zeta)\overline{q}_b^n-\overline{\Delta p}_d^n(x,y)\frac{\partial\overline{G}_B^n(x,y;\xi,\zeta)}{\partial n}\mathrm{d}\Gamma$$
$$+\int_\Omega \frac{1}{K^n h^n}\overline{q}_{mf}^n(x,y,s)\overline{G}_B^n(x,y;\xi,\zeta). \quad (5)$$

Where $\overline{q}_b^n$ is the boundary flow of different permeability partition under the Laplace space, $\overline{q}_{mf}^n$ is the fracture unit flow of different permeability partition under the Laplace space. The boundary outside conditions should be that the toe of fracture is closed and doesn't flow, boundary inside conditions should be that bottom hole flowing pressure is constant value.

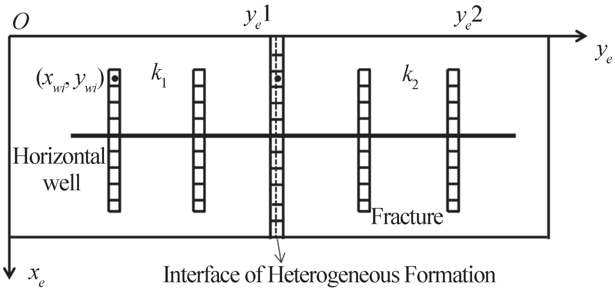


Figure 2
Discrete Grid Schemes

A single fracture is considered to 2×m discrete evenly spaced grid, according to the symmetry, pressure difference at any neighboring grid center can be expressed as:

$$\overline{p}_{f(i)}-\overline{p}_{f(i+1)}=\frac{\mu}{\beta_c K_f W_f h^n}(\overline{Q}_i+\frac{3}{2}\overline{q}_i+\frac{1}{2}\overline{q}_{i+1})l_w, i=1,2,\cdots,m-1 \quad (7)$$

$$\overline{Q}_i=\sum_{j=1}^{i-1}\overline{q}_i. \quad (8)$$

Where Q_i is flow rate of fracture into fracture unit i, m^3/d; Q_i is value of $\overline{Q}_i$ in the Laplace space. According to the far end of fracture is closed boundary and flow into the first grid is zero, bottom hole flowing pressure of the well perforation is constant value, MPa; $\overline{p}_{wf}$ is value of p_{wf} in the Laplace space. Relational expression of wellbore grid and flowing bottomhole pressure can be expressed as:

$$\overline{p}_{f(m)}-\overline{p}_{wf}=\frac{\mu}{\beta_c K_f W_f h^n}(\frac{1}{2}\overline{Q}_m+\overline{q}_m)l_w. \quad (9)$$

For the flow of the fracture, because pressure in artificial fracture is equal to the pressure in fracture interfaces of reservoir, so the pressure relationship between single fracture left unit and bottom hole can be expressed as:

1.3 The Flow Model in Artificial Fracture

Fluid flow in the artificial fracture can be simplified to be linear stability for the characteristics of small porosity and high flow conductivity in artificial fracturing cracks, Laplace stable seepage equation in fracture can be expressed as:

$$\frac{\partial^2\overline{p}_f}{\partial x^2}+\frac{\mu}{\beta_c K_f W_f h^n}\overline{q}_m=0. \quad (6)$$

Where p_f is pressure in the fracture, MPa; $\overline{p}_f$ is value of p_f in the Laplace space; K_f is fracture permeability, 1×10^{-3} μm^2; W_f is fracture width, m; q_m is flow of matrix to fracture, m^3/d; $\overline{q}_m$ is value of q_m in the Laplace space.

$$\begin{cases}\overline{p}_{\mathrm{f}(i)}-\overline{p}_{\mathrm{wf}}=\sum_{j=i}^{m-1}\frac{\mu}{\beta_c K_f W_f h^n}(\overline{Q}_j+\frac{3}{2}\overline{q}_j+\frac{1}{2}\overline{q}_{j+1})l_w+\frac{\mu}{\beta_c K_f W_f h^n}(\frac{1}{2}\overline{Q}_m+\overline{q}_m)l_w, \\ \qquad i=1,2\cdots m-1 \\ \overline{p}_{\mathrm{f}(m)}-\overline{p}_{\mathrm{wf}}=\frac{\mu}{\beta_c K_f W_f h^n}(\frac{1}{2}\overline{Q}_m+\overline{q}_m)l_w\end{cases}. \quad (10)$$

1.4 Model Verification

The models are verified for the accuracy by comparing with the results of CMG numerical simulation software under the conditions of the same reservoir physical parameters, the production curve and reservoir pressure field calculated by this models and CMG are showed as Figures 3 and 4.

It is can be found by the contrast that the model calculation results and the CMG numerical simulation results are basically identical when the conditions of reservoir physical parameters are same. The production curve and reservoir pressure field calculated by this model is consistent with the output of CMG. The characteristics of same pressure expansion are showed by the two results and it is closely relative to the pressure drop and reservoir permeability when oil well produces at constant pressure. The greater the reservoir permeability, the bigger the pressure conductivity, the faster the pressure ripple. Therefore, pressure drop of high permeability zone is great, by contrast, pressure drop of low permeability zone is small for its slower pressure transmission speed.

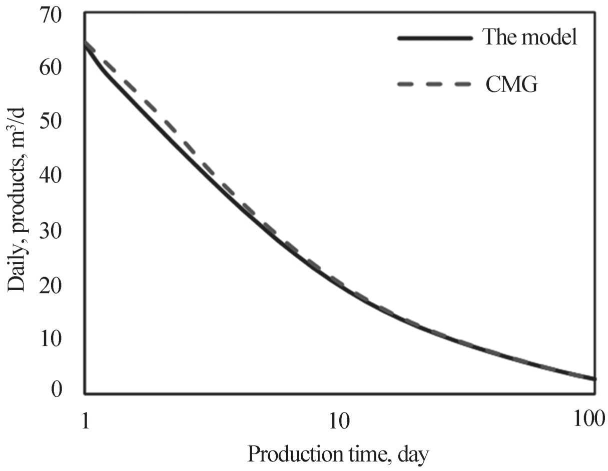


Figure 3
Production Curve Results of the Model and CMG

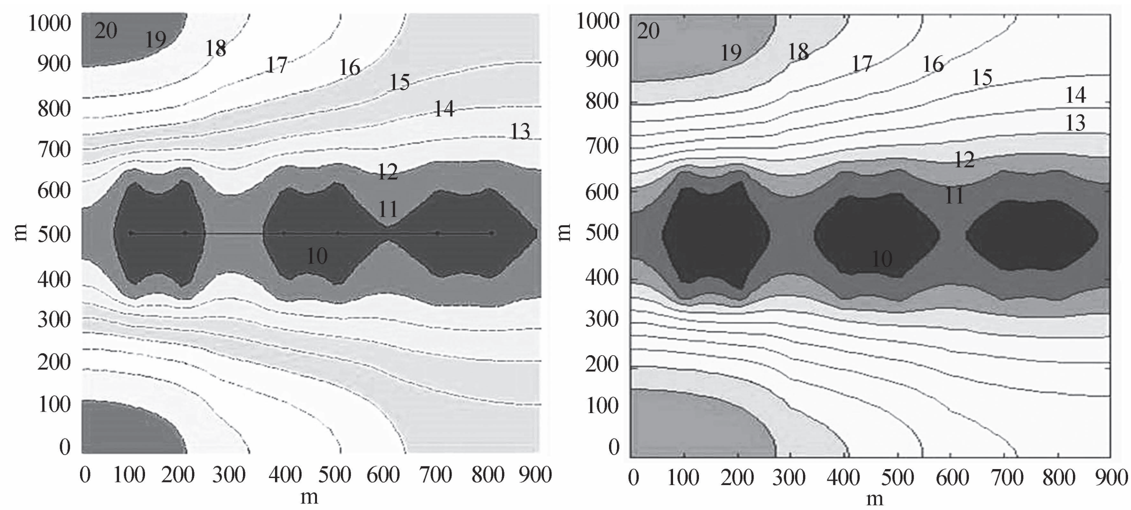
2. PRODUCTIVITY PREDICTION PARTITION MODEL OF VOLUME HORIZONTAL WELL FRACTURING IN TIGHT OIL RESERVOIR

2.1 The Classification of Partition Seepage Model

Reservoir volume fracture distribution near wellbore will be different after volume fracturing because of the differences of fracturing parameters and reservoir properties. Partition seepage models volume fracturing horizontal well in tight reservoir will be different when the distribution of reservoir fractures are different.

2.2 The Basic Model of Mathematical Methods

It is assumed that the reservoir of the model is composed of matrix, primary fracture and secondary fracture in the process of volume fracturing, meanwhile, the area within the secondary fracture is double medium, which can be showed as Figure 5. The order of the flow model solution is that, matrix outside the SRV zone should be calculated first, then matrix inside SRV zone, finally inside the main fracture and horizontal well, which can be showed as Figure 6.



(a) CMG (b) The Model

Figure 4
Reservoir Pressure Field Results of the Model and CMG (Mpa)

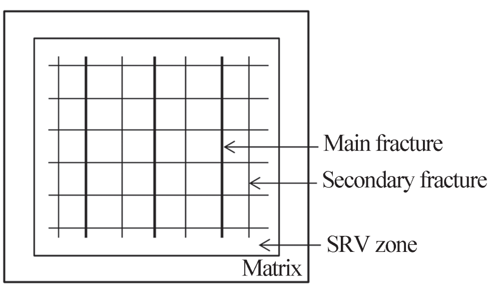


Figure 5
Assumptions of the Flow Model

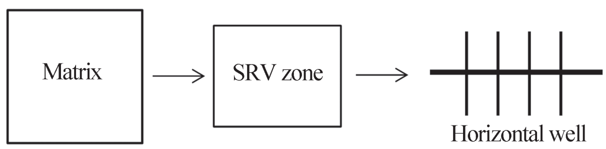


Figure 6
The Order of the Flow Model Solution

2.2.1 Seepage Model of Volume Fracturing Horizontal Well Established Under the Laplace Space

The seepage equation for flow form matrix to SRV zone can be expressed as:

$$G_1(s)=\frac{1}{2\pi}K_0\left(\sqrt{\frac{s}{\eta_m}}r\right). \quad (11)$$

The seepage equation for flow from SRV zone to fracture can be expressed as:

$$G_2(s)=\frac{1}{2\pi}K_0\left(\sqrt{\frac{s}{\eta_m}}f(s)r\right). \quad (12)$$

2.2.2 Seepage Model for the Flow in Artificial Fracture

The flow in the artificial fracture can be described by importing additional matrix according to the Darcy law, which is showed as Figure 7.

2.2.3 Coupling of Three Kinds of Flow States

The seepage model is established to describe three kinds of flow states which should be from matrix to natural fracture, natural fracture to artificial fracture and artificial fracture to horizontal well bore. Calculation formulas of coupling flow are expressed as Equations (13)-(15), flow coupling matrix is showed as Figure 8.

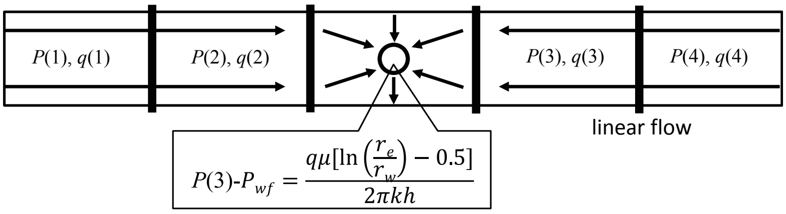


Figure 7
Flow in the Fracture

$$-\nabla\cdot\left[\rho\frac{\boldsymbol{K}}{\mu}(\nabla p+\rho g\nabla z)\right]+\phi\frac{\partial\rho}{\partial t}=F(\boldsymbol{x},t), \quad (13)$$

$$\nabla^2 p=-\nabla\Theta\cdot\nabla p+\psi\frac{\partial p}{\partial t}-\psi F \text{ on } \Lambda,\ t>t_0, \quad (14)$$

$$-2\pi\lambda p(\boldsymbol{x}_i,t)+\int_\Gamma\left[p\nabla G\cdot\boldsymbol{n}+G\frac{1}{K}q_n\right]d\Gamma+\int_\Gamma G\left[-\nabla\Theta\cdot\nabla p+\psi\frac{\partial p}{\partial t}-\psi F\right]d\Gamma=0. \quad (15)$$

Matrix to matrix	SRV to matrix	
Matrix to SRV	SRV to SRV	SRV to fracture
	Fracture to SRV	Fracture to fracture

Figure 8
Flow Coupling Matrix

2.3 Productivity Calculation Module

The volume fracturing horizontal well productivity model is solved by application of Matlab software programming, in which it affords users to define fracture half length, fracture angle and shape of fracturing area by themselves.

3. PRODUCTIVITY CALCULATION EXAMPLE

Tight oil test areas in Daqing oilfield are taken as examples to predict volume fracturing horizontal well productivity under different fracturing scale by using the actual reservoir physical parameters, which is showed as Figure 9 and Table 1. Predictions of volume fracturing horizontal well productivity are close to the actual production capacity. Because of the error of artificial fracture microseismic monitoring and the difference of flow back working system, there are calculation error in individual wells. However, the overall prediction accuracy is higher and the average coincidence rate can be 81.1%. This method can provide a reliable theoretical basis for tight oil reservoir developed effectively in Daqing oilfield, which have a vital role on the oilfield continuous production.

Table 1
Predictions of Volume Fracturing Horizontal Well Productivity in Tight Oil Reservoir

Well number	Length (m)			Thickness (m)		Cluster distance (m)	Half-fracture length (m)	Angle of well and fracture ()	Flowing pressure (MPa)	Productivity (m^3/d)	
	Horizontal	Sand	Oil	Sand	Oil					Predictions	Actual value
yp1	2,660	1,484	1,159	3.2	1.2	50	115~310	50	10.5	25.1	22.8
qp2	1,187	1,187	1,168	1.6	1.3	30	284~381	80	11	25.3	22.3
Lp26-5	2,014	1,994	1,876	4.5	2.2	60	140~210	75	8.1	17.5	14.3
Lp26-6	1,505	1,360	1,250	5	4	80	134~264	84	7.4	45.4	40.3
yp1-4	1,468	1,446	1,434	3.5	2.6	60	148~196	83	5.6	29.6	23.7
yp1-5	990	961	840	3.2	1.7	55	138~186	87	11.5	26.8	21.4
yp1-7	1,547	935	920	5	2.8	65	108~304	52	7.3	18.2	15.5
yp1-8	1,027	281	213	3.6	2.3	60	154~197	81	10.6	19.8	15.8

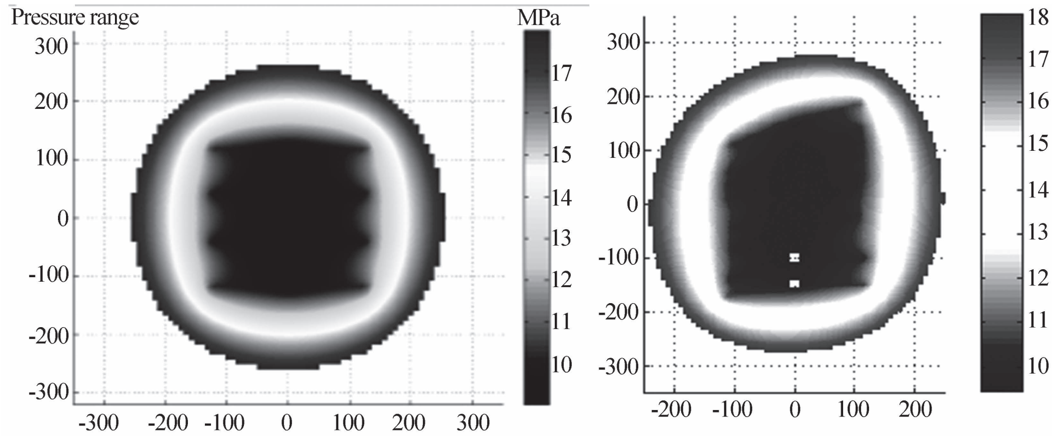


Figure 9
Calculation Interface of Volume Fracturing Horizontal Well Productivity in Tight Oil Reservoir

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