ISSN: 2710-0588 DOI: 10.29556/FSE.202106_1(3).0022

Study on Numerical Well Test Method of Two-phase Flow in Fractured Wells Considering Skin Effect

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Abstract

At present, in the existing study of numerical well test interpretation model of oil-gas two-phase flow in fractured wells, the influence of fracture skin on the model is less considered. At the same time, the commonly used linearization method for solving the two-phase flow is IMPES method. Because of the explicit solution of saturation, the calculation stability is poor, the time step is required to be higher, and the actual application effect is not good. Based on the definition of skin factor, a numerical well test interpretation model considering the skin effect of fracture is established in this paper. And through the law of conservation of matter, the relationship curve between oil-gas two-phase pressure and saturation is established. When solving the equation, the improved saturation solution method is used for calculation. Compared with the analytical method and the conventional IMPES method, the skin consideration method is accurate and reliable, the improved saturation solution method is fast and reliable, which provides a reliable and convenient solution method for the numerical well testing of two-phase flow in fractured wells.

Keywords

Oil-gas Two-phase; Numerical Well Test; Fractured Wells; Skin Factor; Law of Conservation of Matter.

1. Introduction

Well testing technology is an important means to evaluate the stimulation effect of hydraulic fracturing wells. The well test interpretation model method of hydraulic fracturing fractured cut wells has been extensively studied at home and abroad, but it is related to the two-phase flow of oil and gas in hydraulic fractured cut wells. Not many papers on numerical well test analysis have been published. By defining the H function, Liu Zhenyu[1] transformed the two-phase flow of oil and gas into the form of single-phase flow and established a theoretical model for well test interpretation. However, this method is only applicable to homogeneous oil reservoirs. Yang Lei [2] applies the principle of material balance to establish a mathematical model of multiphase seepage flow, and converts multiphase seepage flow into single-phase seepage flow by defining a quasi-function, so as to provide a practical method for multiphase flow well testing, but this method is representative of the truth. The relative permeability curve of seepage is very difficult, and the human error in the data processing process is difficult to control. Sun Hedong [3] established a dual well test model with exponential permeability changes based on fractured stress-sensitive experimental data and well test theory, and developed corresponding numerical well test software using finite element methods, but this method only The skin of the wellbore is considered, but the skin of the fracture is not considered. Ouyang Weiping [4] established a well test model for vertical fractured wells with infinite diversion of coalbed methane considering desorption, deduced the finite element equation, and

ISSN: 2710-0588 **DOI: 10.29556/FSE.202106_1(3).0022**

obtained the numerical solution of the model. However, the skin effect of cracks is not considered. Cha Wenshu [5] proposed a numerical well testing method for fractured wells and applied it to the PEBI grid, but this method did not consider the skin effect of fractures.

At the same time, many scholars at home and abroad have studied the linearization method of multiphase flow. Fagin and Stewart [6] proposed the black oil IMPES model in 1966; After that, Young, L.C, Watts, J.W, Wong, T, etc. [7-9] Many scholars gave and compared the derivation of IMPES pressure equation; Huang Tao et al. [10] established a numerical difference model of non-Darcy two-phase flow in low permeability reservoirs and used IMPES method to solve the two-phase flow problem; Sun Jian [11] established a three-dimensional three-phase flow mathematical model for low permeability reservoirs and solved it with IMPES method; Liu Liming [12] proposed an improved IMPES method to make the calculation stability reach the level of the semi-implicit method, but the amount of calculation exceeds twice the IMPES method.

In the numerical well test analysis of fractured wells, the skin effect of fractured wells is not considered enough, and the IMPES method is used for the linearization of the oil and gas two-phase model, and the calculation is faster, however, the calculation stability is poor, the accuracy of the calculation results cannot be guaranteed, and the application is limited. Therefore, starting from the definition of skin, this paper considers the skin effect of fractured wells and uses an improved saturation solution method to solve the two-phase linear equations of oil and gas. Through calculation and comparison analysis, the reliability and practicability of the new method are verified.

2. Establishment of oil and gas two-phase numerical well test model

During the development process, the energy of the reservoir is continuously consumed and the formation pressure continues to drop. When the pressure is lower than the saturation pressure of the reservoir, the reservoir is in a state of dissolved gas flooding, and there are two-phase seepage of oil and gas in the reservoir at the same time. Taking into account the heterogeneity of the reservoir and the irregularity of the boundary, the finite volume dispersion method is adopted in this paper. To carry out the research of numerical well testing.

2.1. Model assumptions

The flow of fluid in the reservoir is isothermal percolation; Reservoir hydrocarbons only contain two components: oil and gas. The oil component is completely present in the oil phase. The gas component can exist as free gas and can be dissolved in the oil phase. There is only gas component in the gas phase; The dissolution and escape of gas in the reservoir are completed instantaneously; the reservoir fluid is weakly compressible; Does not consider the influence of gravity and capillary force in the seepage process; does not consider the wellbore seepage; Considering that the fracture is an infinite diversion fracture, the inner boundary is fixed production, and the outer boundary is closed.

2.2. Mathematical model

The oil phase percolation equation is [13]:

$$\nabla \bullet \left(\frac{KK_{ro}}{B_o\mu_o}\nabla p\right) = \frac{\partial}{\partial t}\left(\frac{\alpha_c S_o \phi}{B_o}\right) \tag{1}$$

The gas flow equation is [13]:

$$\nabla \bullet \left\{\frac{KK_{\mathrm{rg}}}{B_g\mu_g}\nabla p + \frac{KK_{\mathrm{ro}}R_s}{B_o\mu_o}\nabla p\right\} = \frac{\partial}{\partial t}\left(\frac{\phi S_g}{B_g} + \frac{\phi S_o R_s}{B_o}\right) \tag{2}$$

Inner boundary production conditions:

$$\frac{2\pi KK_{ro}h}{\mu_o}\left[r\left(\frac{\partial p}{\partial r}\right)\right]\Big|_{r=r_w} = q_o B_o \tag{3}$$

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Outer boundary closure conditions:

$$\left.\frac{\partial p}{\partial n}\right|_{\Gamma} = 0 \tag{4}$$

In the formula: K is the absolute permeability, μm^2; K_{rg} is the relative permeability of the gas phase, dimensionless; K_{rg} is the relative permeability of the oil phase, dimensionless; B_o is the volume coefficient of the oil phase, m^3/m^3; B_g is the volume coefficient of the gas phase, m^3/m^3; μ_g is the viscosity of the gas phase, mPa·s; μ_o is the viscosity of the oil phase, mPa·s; q_o is oil production, m^3/d; S_o is oil phase saturation, decimal; S_g gas phase saturation, decimal; Φ is porosity, decimal; R_s is the ratio of dissolved gas to oil, m^3/m^3; p is the formation pressure, MPa; t is time, h; α_c is the unit conversion constant, 0.2778.

3. Derivation of Fracture Well Skin Factor

From the perspective of the definition of epidermal factor, Suppose the fracture section of length L and width d is studied, The contaminated model of fractured wells is shown in Figure 1:

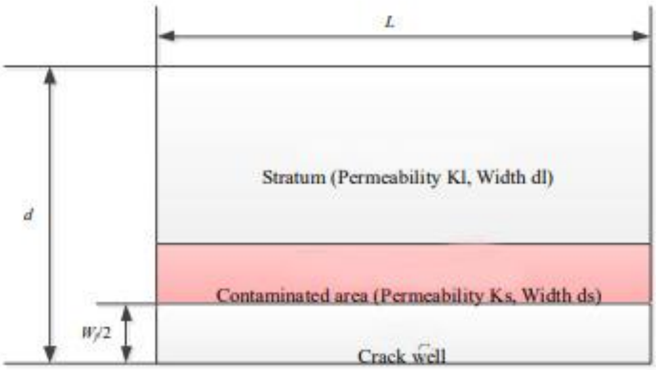

Figure 1. Schematic diagram of polluted model of fractured well

The crack yield is:

$$q_l = \frac{L}{4x_f}\frac{4x_f a_d K_l}{B_l \mu_l}\frac{h}{d_l}\left(p_i - p_{wfs}\right) \tag{5}$$

In the equation: x_f is the half length of the crack, m; ql is the crack yield, m3/d; L is the length of the crack taken, m; K_l is the formation permeability, μm^2; B_l is the fluid volume factor, m^3/m^3; μ_l is fluid viscosity, mPa·s; μ_0 is the viscosity of the oil phase, mPa·s; d_l is the assumed stratum width, m; α_d is the unit conversion constant, 3.6; p_i is the formation pressure, MPa; p_{wfs} is the pressure in the contaminated area, MPa; w_f is the crack width, m.

Make

$$\frac{L}{4x_f} = \theta \tag{6}$$

also because

$$q_l = \frac{4x_f \theta a_d K_s}{B_l \mu_l}\frac{h}{d_s}\left(p_{wfs} - p_{wf}\right) \tag{7}$$

In the equation, K_s is the permeability of the polluted area, μm^2; d_s is the width of the contaminated area, m; p_{wf} is the bottom hole pressure, MPa;

United (5)~(7), Can get

$$p_i - p_{wf} = \frac{q_l B_l \mu_l d_l}{4x_f \theta a_d K_l h} + \frac{q_l B_l \mu_l d_s}{4x_f \theta a_d K_s h} \tag{8}$$

Then

$$q_l = \left(\frac{4x_f \theta a_d K_l h}{B_l \mu_l d_l} + \frac{4x_f \theta a_d K_s h}{B_l \mu_l d_s}\right)\left(p_i - p_{wf}\right) \tag{9}$$

ISSN: 2710-0588 DOI: 10.29556/FSE.202106_1(3).0022

Organize and simplify:

$$q_l = \frac{\theta a_d K_l h}{B_l \mu_l \left(\frac{d_r}{4x_f} + \frac{S_f}{2\pi}\right)} (p_i - p_{wf}) \tag{10}$$

Among them

$$S_f = \frac{2\pi\left(d_r d_s K_s - K d_s^2 - K_s d_r^2\right)}{4x_f(K d_s + (d_r - d_s) K_s)} \tag{11}$$

$$d_r = d - \frac{\omega_f}{2} \tag{12}$$

Then the formation pressure loss is:

$$\Delta p_m = \frac{q_l B_l \mu_l d_r}{4x_f \theta a_d K_l h} \tag{13}$$

The skin pressure loss is:

$$\Delta p_s = \frac{q_l B_l \mu_l}{2\pi\theta a_d K_l h} S_f \tag{14}$$

Considering $L = 4x_f$, we can get from equation (24):

$$q_l = \frac{4x_f a_d K_l h}{B_l \mu_l} \frac{\partial p}{\partial y} \tag{15}$$

Substituting (15) into (14), we can get:

$$p_{wf} = p_f - \frac{2x_f}{\pi} S_f \frac{\partial p}{\partial y} \tag{16}$$

This formula is consistent with the commonly used crack skin formula, Therefore, this definition is accurate.

4. Improved saturation solution method

According to the principle of material balance, the relationship between average formation pressure and formation oil saturation can be obtained:

$$\frac{dS_o}{dp} = \frac{\frac{B_g S_o}{B_o}\frac{dR_s}{dp} + \frac{S_o K_g \mu_o}{B_o K_o \mu_g}\frac{dB_o}{dp} - (1 - S_o - S_{wc})\frac{1}{B_g}\frac{dB_g}{dp}}{1 + \frac{K_g \mu_o}{K_o \mu_g}} \tag{17}$$

When calculating the relationship between pressure and saturation, divide the formation pressure from saturation pressure to atmospheric pressure into several pressure intervals, and calculate from the saturation pressure, and calculate the value of the decrease in formation oil saturation when the formation pressure drops by a pressure interval value ΔS_o. Then calculate the next pressure interval, the starting point value of the pressure in this pressure interval will be $p_i - \Delta p$, At this time, the oil saturation of the formation will be $S_{oi} - \Delta S_o$. When calculating the ΔS_o corresponding to any pressure interval, B_o, B_g, μ_o, and μ_g generally adopt the value at the starting point of this pressure interval, and K_o, K_g adopt the value at the starting point of this ΔS_o interval.

In the calculation, $\frac{dR_s}{dp}$, $\frac{dB_o}{dp}$, and $\frac{dB_g}{dp}$ should also be rewritten into incremental forms $\frac{\Delta R_s}{\Delta p}$, $\frac{\Delta B_o}{\Delta p}$, and $\frac{\Delta B_g}{\Delta p}$, where ΔR_s, ΔB_o, and ΔB_g respectively take the corresponding difference between the starting point and the end point of the pressure interval.

As a result, a series of pressure values and a series of oil saturation values under corresponding pressures can be calculated. After the pressure is obtained implicit expression, there is no need to substitute the pressure into the original equation to solve the saturation. You only need to use the interpolation method to get the pressure Interpolate in the saturation array to get the corresponding oil phase saturation at the pressure, and when the calculation interval in the pressure saturation array is very small, the oil phase saturation calculation result is less affected by the time step.

ISSN: 2710-0588 DOI: 10.29556/FSE.202106_1(3).0022

5. Computational comparative analysis

By writing the analytical solution calculation program for single-phase flow considering the fracture skin and the code for the numerical model of single-phase flow considering the fracture skin,Comparative analysis of the reliability of the skin consideration method, and at the same time, by compiling the calculation program of the conventional IMPES method and the improved IMPES method, comparative analysis of the application effect of the improved IMPES method.

Considering the constant oil production and production of an infinitely conductive and fractured vertical well in the center of a homogeneous reservoir, firstly, the calculation is carried out based on the same set of parameters (as shown in Table 1) using analytical methods and numerical methods,The numerical method uses the PEBI grid, the number of grid cells is 1091, the simulation time is 10,000 hours, and the logarithmic time is used. There are a total of 80 data points. The early time interval is small, and the later time interval is large.

Table 1. Basic parameter table

Effective thickness(m)	10	Porosity	0.1
Crack half length(m)	40	Original formation pressure(MPa)	40
Oil production(m3/d)	2	Epidermal factor	0.1
Wellbore storage factor(m3/MPa)	0.01	Permeability(mD)	1

The calculation results of the two methods are plotted in the same graph, as shown in Figure 2. It can be seen from the figure that the calculation results of the two methods are close. The numerical method and the analytical method basically coincide in the early stage of the well-reservoir skin response period. The difference in the later stage is mainly due to the circular boundary of the analytical method and the rectangular boundary of the numerical method. Explains the reliability of the skin factor consideration method.

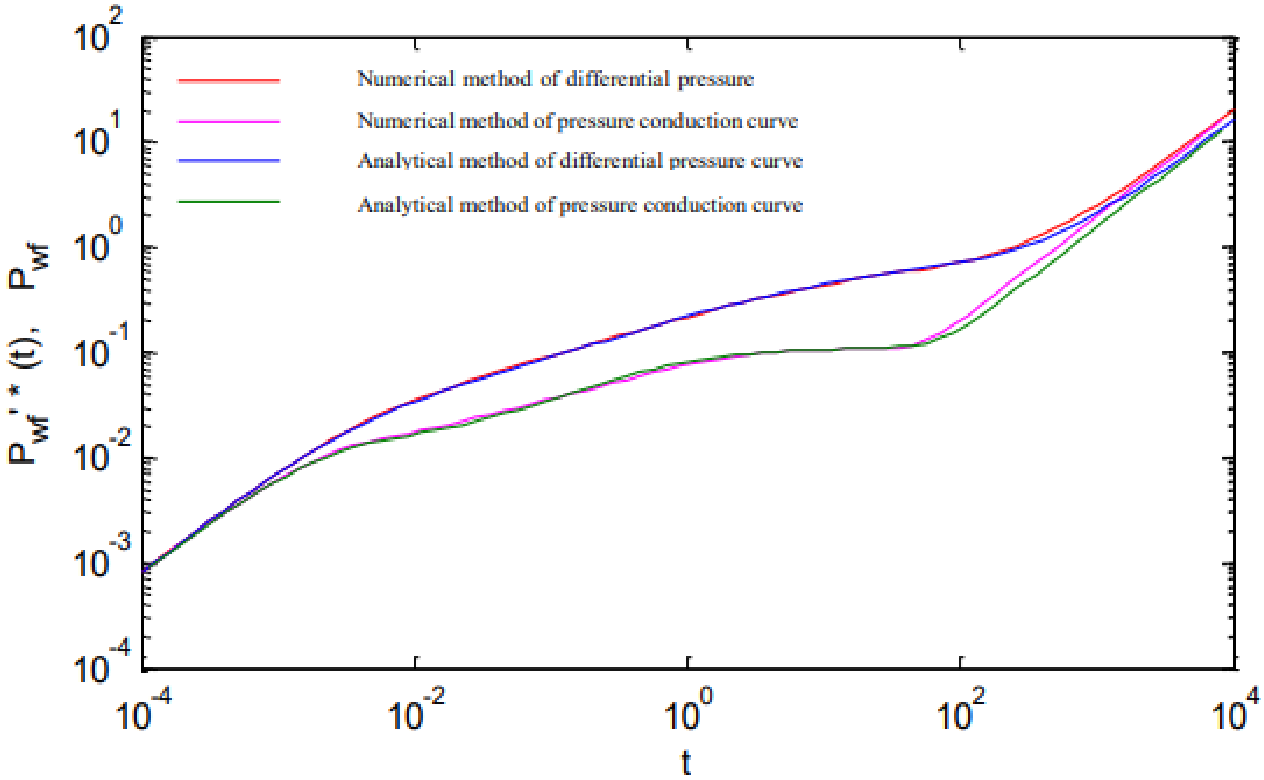

Figure 2. Comparison between analytical method and numerical method

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Similarly, using the above-mentioned reservoir model and grid model. The difference is that the two-phase production of oil and gas is considered, and the conventional IMPES method and the improved IMPES method are used for calculation. Draw a double logarithmic graph of well test pressure, as shown in Figure 3. It can be seen from the figure that the calculation time steps of the two methods are equal, and the conventional IMPES method has poor stability during the calculation process,In the later stage, due to the large time step, the calculation is abnormal and the calculation result is wrong.The improved IMPES method has good stability in the calculation results without obvious fluctuations, and can be calculated normally in the later stage, showing the correct radial flow section and boundary response section.

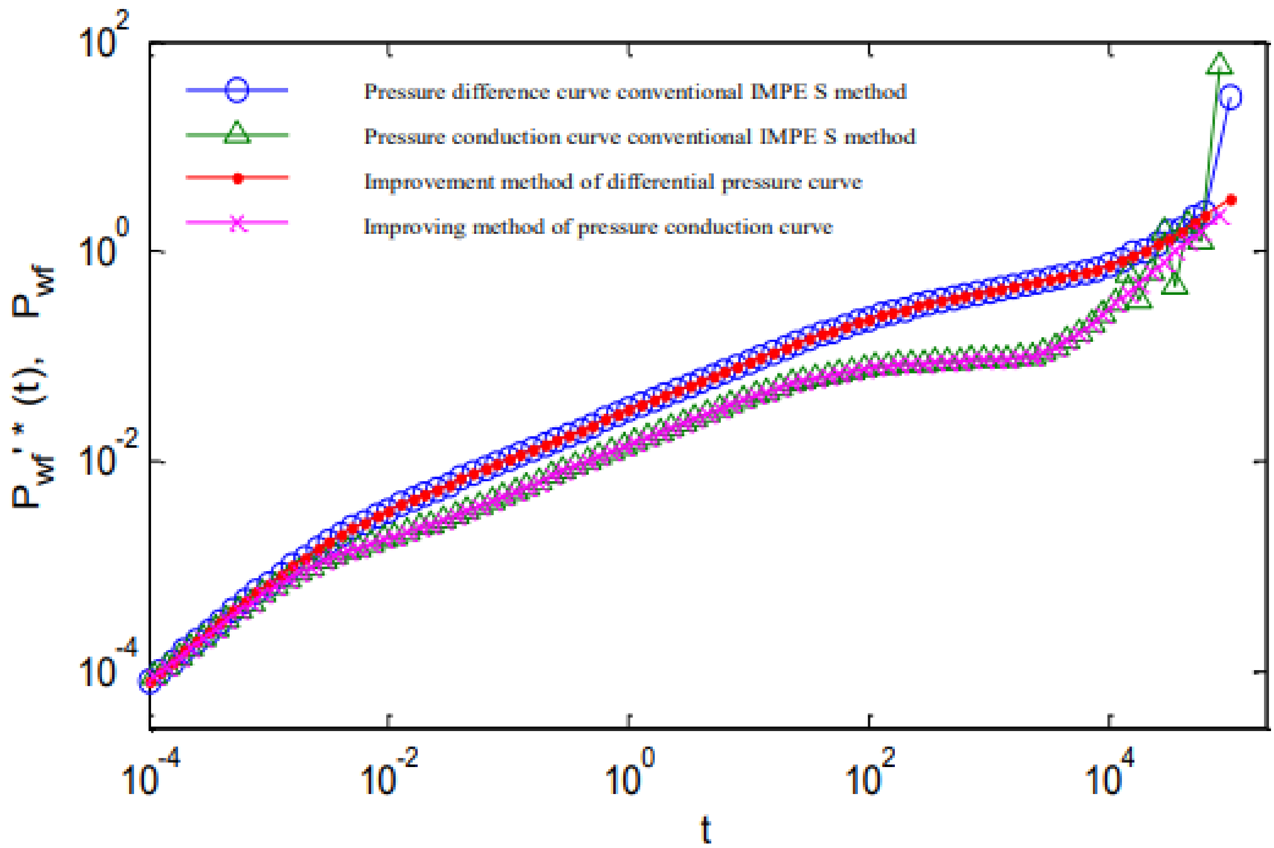

Figure 3. Comparison of results of conventional IMPES method and improved method

At the same time, the calculation time of the two methods is also counted. The calculation time of the conventional IMPES method is 17.2s, and the calculation time of the improved IMPES method is 10.5s.This is because the conventional IMPES method needs to recalculate the phase permeability data of the formation pressure and saturation when iteratively calculates the saturation. Re-substituting the seepage equation to calculate the saturation, resulting in longer calculation time. The pressure saturation array in the improved IMPES method has been calculated before iterative calculation, When calculating the saturation iteratively, only a simple interpolation algorithm can be used to calculate the corresponding saturation, so the calculation time is shorter.

Through the above analysis, it can be seen that the calculation method for the skin factor of fractured wells is accurate and reliable. At the same time, improve the saturation calculation method, the calculation result is stable and reliable, and the calculation speed is faster. The application effect is good in the numerical well test of oil and gas two-phase flow, and it provides a reliable and convenient solution method for the numerical well test analysis of two-phase flow in fractured wells considering the skin effect.

ISSN: 2710-0588 DOI: 10.29556/FSE.202106_1(3).0022

6. Conclusion

(1) Starting from the definition of skin, this paper derives the calculation method of fractured well skin factor. At the same time, based on the principle of material balance, the relationship between pressure and saturation is established to form an improved two-phase flow saturation solution method.

(2) Through calculation and comparative analysis, the analytical solution model and numerical solution model of fractured wells considering the skin factor are compared, and the reliability of the derivation results of the numerical model considering the skin factor is verified, which has certain application value for the consideration of skin treatment of fractured wells.

(3) By comparing the calculation results of the conventional IMPES method and the improved solution method, the results show that the improved method is stable in calculation, fast in calculation, and reliable in calculation results. It can be effectively applied to the solution process of two-phase flow numerical well test analysis and improve the stability of the well test model. Performance and well test analysis and calculation speed.

Acknowledgments

Fund projects: Shaanxi Province Natural Science Basic Research Project (2018JQ4045); Shaanxi Province Major Science and Technology Innovation Project (2014ZKC (1) 03-02).

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