Finite Element Numerical Simulation Research on Fractured Horizontal Well in Stress-dependent Tight Reservoirs Based on Heat Transfer Theory

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Abstract. We present an efficient numerical method to handle stress-dependent behavior for fractured wells in tight reservoirs using the large-scale general finite element software ANSYS as the platform. A new similarity criterion is deduced to describe the seepage flow based on the similarity principle. The similarity criterion is a key parameter to transfer unstable heat problems to well performances. Then a comparison between the numerical and history-matched results is made to validate the accuracy of the results, by which effective stress-dependent coefficient calculated by numerical simulation is in agreement with that from experiment. The result shows that it is feasible to apply the ANSYS function of temperature field analysis in the computation of the unstable seepage flow considering permeability change in stress-dependent tight reservoirs. Finally using a certain field data and history-matched reservoir model, the influence of the fractures on horizontal well is investigated, including fracture spacing, fracture length and parameters of fracture with included angle on the basis of the new method. The results from the model considering the stress-dependent factor are significantly different from that without considering the factor. This work provides reservoir engineers with a simple and feasible method for optimizing the fracture parameters of tight oil development.

Keywords: fractured well, productivity, similarity principle, stress-dependent, tight reservoir, finite element numerical simulation method.

1. Introduction
Because of the poor connectivity of low permeability reservoirs and the small pore throat passage, the traditional method is no longer applicable. Therefore, in order to improve production, the method of fracturing multiple fractures in horizontal wells is usually adopted. With the application of fracturing, the design of fracture length and spacing is very important. Due to the existence of fracturing fractures, the flow and pressure distribution near the fractures are also complex. So it is necessary to carry out numerical simulation of reservoir.

In the paper, we will present a new efficient numerical method to handle stress-dependent behavior for fractured wells in tight reservoirs using the large-scale general finite element software ANSYS as the platform. Then a new similarity criterion is deduced to convert transient thermal simulation results into unstable seepage phenomena, which is proved to be feasible in the productivity calculation of fracturing wells in tight reservoirs. Finally case studies are presented. Results show that the new simulation method is appropriate for the optimization of fractured wells in tight reservoirs. Based on the similarity between temperature field and seepage field, the temperature field is used to simulate the seepage problem of horizontal fractured wells, and a new idea is proposed. The temperature field
replaces the seepage field, and the temperature represents the fluid seepage velocity. It provides the simulation study productivity. A new method that is closer to the actual value. Therefore, it is very necessary to perform finite element simulation on it.

2. Methodology
There are similarity mathematical models between heat flow field and seepage field (Arunn, 2012). The similarity of temperature field and seepage field is shown from three aspects: the basic theory, differential equations, initial and boundary conditions. Table 1 shows the physical quantities corresponding to the temperature field and seepage field.

**Table 1. The comparison of physical quantities of temperature field with seepage fields**

| The seepage field | The temperature field |
|-------------------|-----------------------|
| Differential equation | $\nabla^2 P = \mu C_t \frac{\partial P}{\partial t}$ | Differential equation | $\nabla^2 T = C \frac{\partial T}{\partial t}$ |
| Darcy's law | $\nu = -\frac{K}{\mu} \frac{dP}{dL}$ | Fourier law | $q = -K_{\gamma} \frac{dT}{dn}$ |
| The fluid flow | $Q$ | Heat | $Q$ |
| Mobility | $\frac{K}{\mu}$ | Thermal conductivity | $K_{\gamma}$ |
| Seepage velocity | $v$ | Heat flow intensity | $q$ |
| Total compressibility | $C_t$ | Specific heat | $C$ |

$C_t$ — total compressibility, the pore compressibility coefficient and the coefficient of compressibility of reservoir rocks, 1/MPa.

$C$ —The amount of heat absorbed or emitted by a substance of unit mass that rises or falls at a unit temperature. $J/(kg \cdot ^{\circ}C)$.

**Table 2. The comparison of boundary conditions of temperature field with seepage fields**

| Seepage field | Temperature field |
|---------------|-------------------|
| Initial condition | $T|_{t=0} = T_0(x,y,z,0)$ |
| The first boundary condition | $P|_{t_1} = P(x,z,y,t)$ | $T|_{t_1} = T(x,z,y,t)$ |
| The second boundary condition | $K \frac{dP}{dL}|_{f_2} = -v(x,z,y,t)$ | $K_{r} \frac{dP}{dL}|_{f_2} = -q(x,z,y,t)$ |

The differential equation of seepage flow is:

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial P}{\partial z} \right) = 0 \quad (1)$$

The differential equation of heat conduction is:

$$\frac{\partial}{\partial x} \left( K_{\alpha} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{\beta} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{\gamma} \frac{\partial T}{\partial z} \right) = 0 \quad (2)$$

3. The Application of New Simulation Method in ANSYS
Because reservoir permeability is low, fracture length is long and reservoir flow time is long, the transient effect can not be ignored, but the transient effect is more complex in well entry and around
the fracture. In order to take into account the effect of stress sensitivity, we propose to use the transient heat transfer module in ANSYS to simulate the incoming wells and fractures. According to the given field oil well data and similarity index, ANSYS thermal module is used for numerical simulation. The change of effective fracturing will change the fluidity. The fluidity corresponds to the thermal conductivity in the temperature field, which will also change. Fig. 1 shows the distribution of temperature field simulated by ANSYS software, which can be compared intuitively. Fig.1 (a) and (b) show the temperature distribution considering the influence of thermal conductivity or not respectively. The area within the isotherm line of 1.84 °C in Fig.1 (b) is significantly larger than that in Fig.1 (a). The isotherm line in temperature field corresponds to the isopiestic line in seepage field, the area within the isotherm of 1.84 °C in temperature field corresponds to the area within the isopiestic line of 18.4 MPa in seepage field. The area within isopiestic line of 18.4 MPa without considering stress-dependent effect is significantly greater than that considering stress dependent effect. In other word, the drainage area around the wellbore in no stress-dependent reservoir is greater than that in stress-dependent reservoir.

![Figure 1. Temperature distribution around the wellbore](image)

The transient thermal simulation results are transformed to equivalent seepage parameters by the new similarity criterion for specific heat capacity and the comprehensive coefficient in stress-dependent media. After the production performance history curves of the fractured vertical wells are matched, the stress-dependent coefficient is determined as 0.055MPa⁻¹ in Fig. 2. The results show that production performance considering reservoir stress-dependent properties can be simulated well using the ANSYS finite element method.

![Figure 2. Production Fitting Chart of Vertical Well Considering Pressure Sensitivity](image)

4. Optimization of Fractured Horizontal Well in Tight Reservoirs with Finite Element Numerical Simulation

4.1. Free Surface Adapting Grid of Fractured Horizontal Well

For the half of the velocity vector diagram near wellbore area in Fig.3 (b), the isopiestic line is denser at periphery fracture shown in Fig.3. The part of the eservoir fluid directly flows into the wellbore, but
most of the fluid flows into the wellbore through the fracture, and the seepage velocity is also different at different endpoints of fracture.

Figure 3. Seepage chart of near wellbore in fractured horizontal well

4.2. The Sensitivity Analysis of Fracture Parameters in Stress-dependent Tight Reservoirs

4.2.1. The Fracture Number. Assumed that stress-dependent coefficient is 0, 0.03 and 0.08, the fracture half-length is 150 m, the horizontal well length is 1000 m. The finite element software ANSYS is applied to simulate oil production rate with different fractures number of 2, 3, 4, 5, and 6. As shown in Fig.4, the recovery ratio of fractured horizontal well in stress-dependent reservoirs generally increases with the increase of the number of fractures when the fracture length is constant. The higher the stress correlation coefficient, the higher the oil content. Meanwhile with the gradual increase of the fractures number, oil production rate increases first and then gradually decreases since the fracture interference results in. To efficiently develop fractured horizontal well, we optimize the number of fracture to reduce fracture interaction.

Figure 4. Productivity of fractured horizontal well effect with different fracture number

4.2.2. The Fracture Half-length. In this section, we assumed that the horizontal well has three hydraulic fractures with fractures spacing of 270 m. The finite element numerical simulation software ANSYS is applied to simulate the oil production with fracture half-length of 125 m, 150 m, 175 m, 200 m, 225 m, 250 m, respectively. As shown in Fig.5, the recovery ratio of fractured horizontal well in stress-dependent reservoir generally increases with the increase of fracture half-length. When the crack length is constant, the smaller the stress coefficient is, the larger the recovery is.

Figure 5. Productivity of fractured horizontal well effect with different fracture half-length
4.2.3. The Fracture Spacing. As shown in Fig. 6, if other fracture parameters remain unchanged, the production of fractured horizontal wells in formation generally decreases first with the increase of fracture spacing, and decreases with the increase of stress correlation coefficient. This is mainly due to the short distance between cracks and the serious interference of cracks. Therefore, in fracturing design of horizontal wells, fracture spacing should be optimized.

Figure 6. Productivity of fractured horizontal well effect with different fracture spacing

4.2.4. The Fracture Angle. In Fig. 7, it can be seen that, for the same fracture half length, fracture number and fracture spacing, the higher fracture angle yields the higher oil production rate. In addition, the larger the stress-dependent coefficient is, the lower the oil production rate is. For example, in Figure 8, the fracture angle of 60°, the larger the heat capacity is, the smaller the low-temperature region area forms. In other word, converted into seepage field, the larger reservoir stress-dependent coefficient results in the smaller flowing area controlled by the fractures and wellbore and the lower production of the fractured horizontal well. When the crack Angle 90°, the highest yield, the effect is best. Reason is that as the Angle between the fracture plane and the horizontal wellbore is more and more big, the greater the vertical distance between cracks, the less the cause mutual interference between cracks, increasing the effective drainage area, so as to increase the oil production.

Figure 7. Productivity of fractured horizontal well effect with different fracture angle

(a) Pressure sensitive coefficient 0.03  (b) Pressure sensitive coefficient 0.08

Figure 8. The temperature distribution of the same fracture angle of different pressure sensitive coefficient on fractured horizontal well
From Fig. 4-7, the greater the pressure sensitivity coefficient of the reservoir, the greater the rate of decline in horizontal fracturing production, and the lower the production of fracturing horizontal wells. The pressure sensitivity of the reservoir has a considerable effect on the productivity of the fractured horizontal well. Due to the rapid change of the near well zone pressure in the fracture and the horizontal well, the pressure loss mainly occurs in the small area near the wellbore, and the average pressure is getting closer to the initial pressure of the reservoir.

5. Conclusions
The paper presents a new efficient numerical method to handle stress-dependent behavior for fractured wells in tight reservoirs using the large-scale general finite element software ANSYS as the platform. It is feasible to apply the ANSYS function of temperature field analysis in the computation of the unstable seepage flow considering permeability change in stress-dependent tight reservoirs. It is very convenient to use ANSYS transient thermal model in reservoir with single phase slightly compressible fluid and deformed porous media. Considering the economic benefit, there should be an optimal crack length. As the supply radius increases, the daily output decreases gradually. Daily production increases with the increase of fracture spacing. Oil production is greatest when fractures are distributed in a fishbone-like manner. The greater the Angle between the fracture plane and the horizontal wellbore, the greater the production of fracturing the horizontal well. The higher the pressure sensitivity, the lower the oil production.

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References
[1] Arunn N (2012) Essentials of heat and fluid flow in porous media. CRC Press, Taylor & Francis/Ane Books Pvt. Ltd., pp 92-95
[2] Norbeck J, Huang H, Podgorney R, et al. (2014) An integrated discrete fracture model for description of dynamic behavior in fractured reservoirs SPEJ 253:183-194
[3] Chen JH, Kang YL, You LJ, et al (2011) Review and prospect about study on stress-sensitivity of low-permeability reservoir. Natural Gas Geoscience, 22(1): 31-34.
[4] Burgoyne MW, Little AL (2012) From high perm oil to tight gas - a practical approach to model hydraulically fractured well performance in coarse grid reservoir simulators. SPE#156610 presented in the SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia
[5] Geiger S, Matthai S, Niessner J, et al (2009) Black-Oil simulations for three-component, three-phase flow in fractured porous media. SPE#107485 prepared for presentation at the SPE European/EAGE Annual Conference and Exhibition, London, United Kingdom
[6] Hoteit H, Firoozabadi A (2006) Compositional modeling by the combined discontinuous Galerkin and mixed methods. SPE#90276 prepared for presentation at the SPE Annual Technical Conference and Exhibition, Houston, Texas, USA
[7] Ibrahim M (2013) Development of new well index equation for fracture wells. SPE#164017 prepared for presentation at the SPE Middle East Unconventional Gas Conference and Exhibition
[8] Joun Gyun Kim, Milind D. Deo (2000) Finite element, discrete-fracture model for multiphase flow in porous media AIChE Journal, 46(6):1120–1130
[9] Lei ZhD, Tian ChB, Wang F, et al (2014) A dynamic discrete fracture model for simulation of tight low-permeability reservoirs IPTC-17992 prepared for presentation at the international Petroleum Technology Conference, Kuala Lumpur, Malaysia
[10] Lin M, Chen S, Xu J (2014) Fractured reservoir modeling: effects of hydraulic fracture geometries in tight oil reservoirs. SPE#167761 presentation at the SPE/EAGE European Unconventional Conference and Exhibition, Vienna, Austria