Advances in Engineering Research, volume 114
International Conference on Advances in Materials, Machinery, Electrical Engineering (AMMEE 2017)

Study on Interference Testing of Fractured-Vuggy Carbonate Reservoirs

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Keywords: carbonate reservoirs, fractured-vuggy units, interference test, finite element calculation.

Abstract. Along with the development of oil and gas fields, geological condition and well pattern arrangement are getting complicated. More and more domestic and foreign experts have paid attention to the study of the interference testing to assess the connectivity between wells and solve the reservoir parameters. As far as fractured-vuggy carbonate reservoirs, the existing interference testing analysis become increasingly difficult to apply, because of the big influence on reservoir space made by many factors such as the rock texture, the fracturing of faults affects and soluble ability. Aiming at this problem, a mathematical interference testing model of the fractured-vuggy carbonate reservoirs was established, that then used to test an observation well and two interfering wells in Tarim oilfield. Finally, the discrete numerical model did a reasonably good job of modeling the well pressure changing processes during the whole interference testing, and getting connectivity parameters between wells by fitting calculation, which can give a technic and theory support for application and production.

1. Introduction

In the exploration and development of oil and gas, well test is the key method to reservoir engineering analysis[1-2]. After decades of development, single well test analysis methods and the corresponding interpretation software have been relatively mature[3-6]. However, with the development of oil and gas fields, the geological condition and well pattern arrangement are becoming more and more complex. Studies on interference testing of multiple wells gradually caused the great attention of experts and scholars both at home and abroad

In 1935, Theis[7] gave the solution to the change of pressure that is caused by velocity variation of other points in homogeneous infinite reservoir for the first time, which is called interference test. It was the earliest research on interference test interpretation methods. The word “interference” refers to the comparison between the pressure change caused by one well production while turning off the other well and the pressure change of two wells producing at the same time. In 1943, Guyton[8] thought that using real data and theoretical charts fitting method can calculate reservoir porosity, permeability and other formation parameters. The idea laid a foundation of the plate fitting method for interference testing. After nearly eighty years of development, scholars at home and abroad have obtained a lot of research results in theoretical modeling and analysis methods of interference test[9]. Whereas, in multiple well interference testing of fracture-cavity karst reservoir, the conventional extreme point method and Theis chart method can not obtain satisfactory results because these methods are suitable for homogeneous medium models and the analytical solution existing condition. Fracture-cavity karst reservoir has strong heterogeneity. Pressure transmission has obvious directivity because of the existence of cracks and large fracture-cave cubes. The interpretation of interference test must draw support from numerical methods and then establish a model both in line with the actual reservoir and engineering practice.

Thus this paper proposes an interference test plan, without steady pressure, sets up a interference test numerical model of fracture-cavity karst reservoir, uses finite element numerical method to obtain

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solutions, analyzes effects on the interference curve of distribution of seam caverns, wellbore storage with skin effect, off-time and other factors, applies the proposing interference test plan and the model to the scene. These research results provide theoretical guidance to interference testing of fracture-cavity karst reservoir.

2. Multi-Well Test Model

2.1 Description of Interference Test Physical Model

To establish the mathematical model of interference test of fracture-cavity karst reservoir requires the following assumptions:

(1)Reservoir has uniform thickness. Upper and lower boundary are impermeable. The calculation area of the model is divided into caves area, natural fracture zone and original matrix area according to the characteristics of fracture-cavity karst reservoir. Reservoir in areas can be regarded as homogeneous media, while caves area and natural fracture zone have high mobility and energy storage, their space positions are arbitrary.

(2)For the convenience of theoretical research, the distribution of seam caverns between active well and observation wells is simplified to two modes.

(3)Fluid in the reservoir has constant viscosity. It is weakly compressible, single-phase Newtonian fluid. Fluid in the reservoir is in laminar condition, conforming to darcy law.

(4)Ignore the influence of gravity and temperature change on flow, and do not consider effects of other physical and chemical influences.

2.2 Mathematical Model

Based on the continuity equation, Darcy seepage equation and the state equation, the control equation of the model is presented.

Caves area:

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}=\frac{\omega_{\mathrm{c}}}{M_{\mathrm{c}}\eta}\frac{\partial p}{\partial t} \tag{1}$$

Natural fracture zone:

$$\frac{\partial^2 p_{\mathrm{D}}}{\partial x_{\mathrm{D}}^2}+\frac{\partial^2 p_{\mathrm{D}}}{\partial y_{\mathrm{D}}^2}=\frac{\omega_{\mathrm{f}}}{M_{\mathrm{f}}\eta}\frac{\partial p_{\mathrm{D}}}{\partial T_D} \tag{2}$$

Original matrix area:

$$\frac{\partial^2 p_{\mathrm{D}}}{\partial x_{\mathrm{D}}^2}+\frac{\partial^2 p_{\mathrm{D}}}{\partial y_{\mathrm{D}}^2}=\frac{1}{\eta}\frac{\partial p_{\mathrm{D}}}{\partial T_{\mathrm{D}}} \tag{3}$$

In a unified form:

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}=\frac{\omega_{\mathrm{L}}}{M_{\mathrm{L}}\eta}\frac{\partial p}{\partial t} \tag{4}$$

Initial condition:

$$p\left(x,y\right)=p_{\mathrm{i}} \tag{5}$$

Inner boundary condition (open the well for production):

$$\left.\left(\frac{\partial p}{\partial n}\right)\right|_{r=r_{\mathrm{w}}e^{-S}}=-Q_{\mathrm{s}}-C_{\mathrm{s}}\frac{dp_{\mathrm{w}}}{dt} \tag{6}$$

Inner boundary condition (close the well):

$$\left.\left(\frac{\partial p}{\partial n}\right)\right|_{r=r_{\mathrm{w}}e^{-S}}=-C_{\mathrm{s}}\frac{dp_{\mathrm{w}}}{dt} \tag{7}$$

Outer sealed boundary:

$$\left.\frac{\partial p}{\partial n}\right|_{\Gamma_{\mathrm{out}}}=0 \tag{8}$$

Constant pressure outer boundary:

$$p|_{\Gamma_{out}} = p_i \tag{9}$$

2.3 Discrete Solutions to the Equations

According to Galerkin method of weighted residuals, triangle is selected as the basic unit., its weight function is the interpolation function, as shown in Equation 3-5-7, in which, *i*=1, 2, 3.

$$N_i = a_i + b_i x_D + c_i y_D \tag{10}$$

So: $$\oiint_A N_i^e \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} - \frac{\omega_L}{M_L \eta} \frac{\partial p}{\partial t} \right) dA = 0 \tag{11}$$

The form of weak solution is:

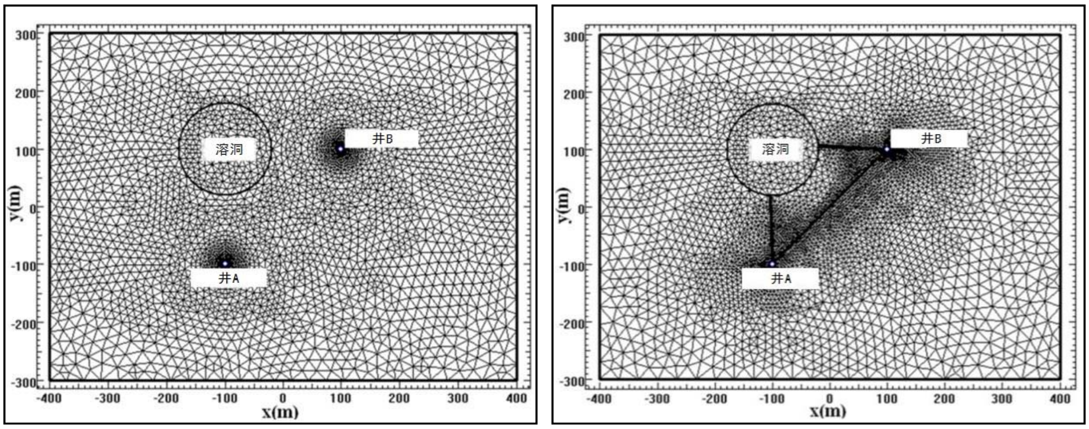
$$\oiint_A \left(\frac{\partial N_i^e}{\partial x} \frac{\partial p}{\partial x} + \frac{\partial N_i^e}{\partial y} \frac{\partial p}{\partial y} + \frac{N_i^e \omega_L}{M_L \eta} \frac{\partial p}{\partial t} \right) dA = \oint_\Gamma N_i^e \frac{\partial p}{\partial n} dl \tag{12}$$

Unit pressure $p^e = p_i^e N_i^e + p_j^e N_j^e + p_k^e N_k^e$, in which, p^e is unit node pressure value. After discretization, the finite element equation is obtained:

$$\begin{aligned} & AM_L \left(b_i^2 + c_i^2 + \frac{\omega_L}{6\eta \Delta t} \right) p_i^{e,n+1} + AM_L \left(b_i b_j + c_i c_j + \frac{\omega_L}{12\eta \Delta t} \right) p_j^{e,n+1} \\ & + AM_L \left(b_i b_k + c_i c_k + \frac{\omega_L}{12\eta \Delta t} \right) p_k^{e,n+1} = \frac{A}{6\eta \Delta t} p_i^{e,n} + \frac{A}{12\eta \Delta t} p_j^{e,n} \\ & + \frac{A}{12\eta \Delta t} p_k^{e,n} + \left(1 - \frac{p_i^{e,n+1} - p_i^{e,n}}{\Delta t} \right) \frac{L}{2} \end{aligned} \tag{13}$$

The last item at the left of Equation 13 only has a value on the internal grid border. Assemble unit equations to system equations and solve the system equations. Pressure value p (x, y) of arbitrary grid point (x, y) at (n+1) time can be obtained.

Discretize the calculation area for finite element calculation. Figure 1 is the grid discretization figure of the calculation area, in which, figure (a) is the grid figure of seam cavern distribution in pattern 1, figure (b) is the grid figure of seam cavern distribution in pattern2. The outer boundary can be arbitrary boundaries. Theoretical research took the rectangle as an example, the instance analysis refers to the actual location.



(a)Grid distribution figure of pattern 1 (b) Grid distribution figure of pattern 2

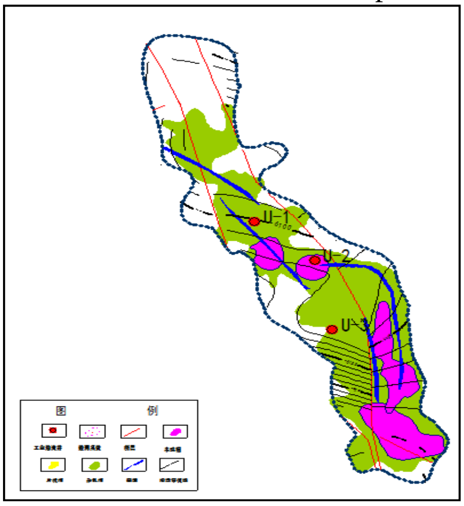
Fig. 1 Grid discretization schematic diagram of the calculation area

3. Multi-Well Test Instances

The discrete seam cavern unit model established in this paper can deal with the conditions of multiple wells and multiple seam-cavern bodies. What follows illustrates the appliance of the model in interpretation of fracture-cavity karst reservoir multiple well interference test, which takes the field test as the example.

3.1 Numerical Well Test Quantitative Interpretation of Test Results

The above analysis is by means of well test curve shape to qualitatively judge the interference exists among wells. The follows use numerical discrete seam cavern well test model established in this paper to conduct quantitative analysis. Using the same modeling process as in the single well instance analysis, establish the corresponding numerical well test model based on seismic data. Fig.2 is the plane figure of the seam cavern unit of three wells. Figure 3 shows meshing after the numerical model established. To ensure calculation precision, densify grid in cracks and seam-cavern bodies.



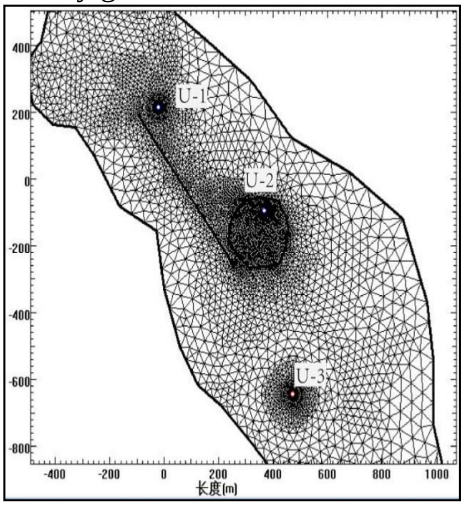
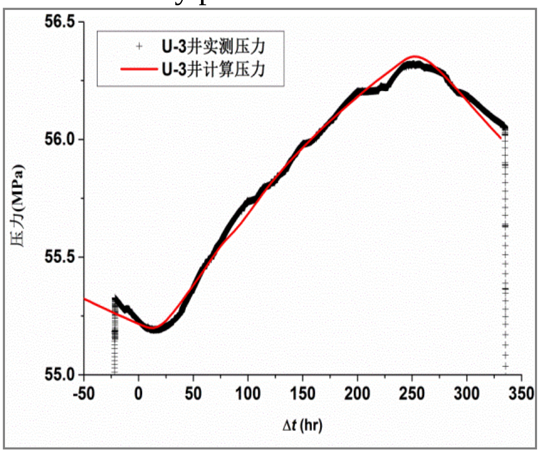


Fig. 2 U seam cavern unit plan Fig. 3 Gird chart of U unit multi-well model

Using multi-well discrete seam cavern numerical model, input injection flow of the active well, fit pressure of two observation wells at the same time, adjust parameters and obtain the better fitting. The fitting results are shown in Fig. 4 and 5. It can be seen that the discrete seam cavern numerical model can simulate pressure change process of observation wells in the whole process of interference test well from the figures. Various parameters of the model can be obtained by fitting, especially interwell connectivity parameters.



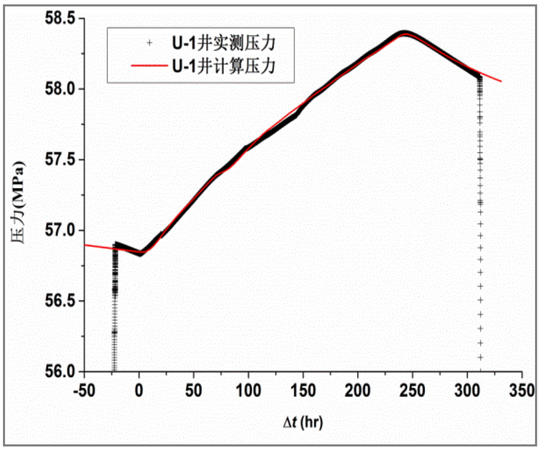


Fig. 4 Well U-3 pressure fitting chart Fig. 5 Well U-1 pressure fitting chart

Fitting parameters are shown in Table 2. Well U-2 and Well U-1 were connected mainly by cracks before according to the model. The two wells had a good connectivity. Well U-2 and Well U-3 were connected mainly by matrix. Their connectivity was poorer. The connectivity parameters can provide basic parameters for late waterflood simulation and scheme adjustment.

Table 1 Interwell interference numerical well test interpretation results

Parameter	Value	Unit
Unit internal matrix permeability	5.75	mD
Cave permeability	738.48	mD
Crack permeability	255.81	mD

4. Conclusions

Interference test is an important technology to confirm interwell connectivity and to solve reservoir parameters. This paper studied interference test methods of fracture-cavity karst reservoir, get the following conclusions:

(1) Fracture-cavity karst reservoir has strong heterogeneity. The conventional extreme point method and Theis chart method can not obtain satisfactory results. Establish a numerical interference test mathematical model of fracture-cavern type carbonate for this characteristic and solve the model by finite element numerical methods. This model can analyze effects on the interference curve of distribution of seam caverns, wellbore storage with skin effect, off-time and other factors.

(2) Carry out the interference test instance appliance of one observation well and two active wells in Tarim Oilfield with the numerical interference test mathematical model of fracture-cavern type carbonate. The mathematical model can well simulate the pressure change process of observation wells during the whole interference test process finally. The model can obtain connectivity parameters of 3 wells by fitting calculation, provides technical theory support for the development and production of fracture-cavity karst reservoir.

Acknowledgements

This work was financially supported by China Postdoctoral Science Fund Project (2016M601142).

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