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A Well Performance Analysis about Vertically Fractured Well with a Non-Uniform Conductivity Hydraulic Fracture in Tight Sandstone Gas Reservoirs Based on Discrete Fracture-Matrix model

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ABSTRACT

Tight gas is an unconventional gas resource. Hydraulic fracturing is necessary to the development of tight sandstone gas reservoirs[1-5].

In this paper, a Discrete fracture and matrix model is based on the open-source reservoir simulation software, MRST. It is also called Non-uniform DFM-WPA. It includes gas transport, non-linear gas properties and non-uniform conductivity hydraulic fracture.

We demonstrate the application of the new formulation to model the performance of the vertical well with a non-uniform conductivity hydraulic fracture in tight sandstone gas reservoirs by use of the Non-uniform DFM model.

Numerical examples are presented to prove the capabilities of the proposed approach. The application of this field case is also to prove the availability of this approach. It can overcome the limitation of conventional discrete-fracture matrix model about the characterization of non-uniform conductivity hydraulic fracture.

Keywords: tight sandstone gas reservoirs,non-uniform discrete fracture and matrix,non-uniform conductivity hydraulic fracture,well performance analysis (WPA), vertically fractured well

NONMENCLATURE

Abbreviations

DFM	Discrete Fracture and Matrix
WPA	Well Performance Analysis
AD	Automatic Differentiation
NWM	Near Wellbore Model
FVM	Finite Volume Method
TPFA	Two Point Flux Approximation
BHP	Bottomhole Pressure
DP	Dual Porosity Model
DK	Dual Permeability Model
EDFM	Embedded Discrete Fracture Model
DFN	Discrete Fracture Network

Symbols

D	Day
M	Matrix
HF	Hydraulic Fracture
W	Well
G	Gas

1. INTRODUCTION

As one of the world's largest economies and leading energy consumers, China is actively pursuing its own pathways towards low-carbon development and driving the energy revolution. To achieve its net-zero goals, the country must significantly reduce the use of high-emission fuels and extensively deploy renewable energy sources. Natural gas aligns perfectly with China's strategies to play an increasingly important role in low-carbon transitions, both in terms of status and functionality [5].

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DFM method can represent the spatial position and geometry of the fracture more explicitly and precisely, and provide better accuracy than other fracture models do, such as Discrete Fracture Network(DFN), Embedded Discrete Fracture Model(EDFM),Dual Porosity model(DP),Dual Permeability(DK) and so on.

This method is much closer to the real field condition than other models. In the past, Kim, Karimi-Fard and other researchers[6-8]used dimensionality reduction method in discrete fracture and matrix model to solve 2D domain problems. After the improvement of many researchers, we can model 3D fracture[9-11]. It can be applied in p3D/3D fracture model. Azim and Sheik[11] made use of 3D DFM model to evaluate the water coning in naturally fractured reservoirs and characterized the 3D fracture based on the pressure derivatives. Mallison, Hui and other researchers[12-17]contributed a lot to the field case about fractured reservoir ,fracture characterization. They combined DFM model with unstructured grid and used this method to deal with this challenge about the fracture characterization for the fractured reservoir.

In this paper, we use the real field case to prove my non-uniform DFM-WPA's availability and accuracy. A field example about separate layer fractured well is calculated to demonstrate that our model is practical to the industry.

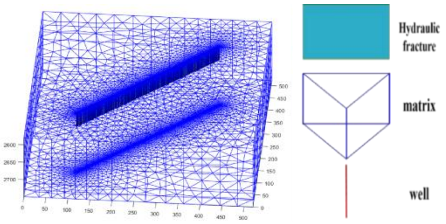


Fig. 1. Schematic diagram of vertically fractured well with a non-uniform conductivity fracture in tight sandstone gas reservoirs

The following physical assumptions are made:

A vertically fractured well with a single non-uniform conductivity hydraulic fracture lies in the center of the reservoir. The following assumptions are made:

(1)The reservoir belongs to the homogeneous reservoir with isotropic permeability. And any point in the formation has the same initial reservoir pressure;

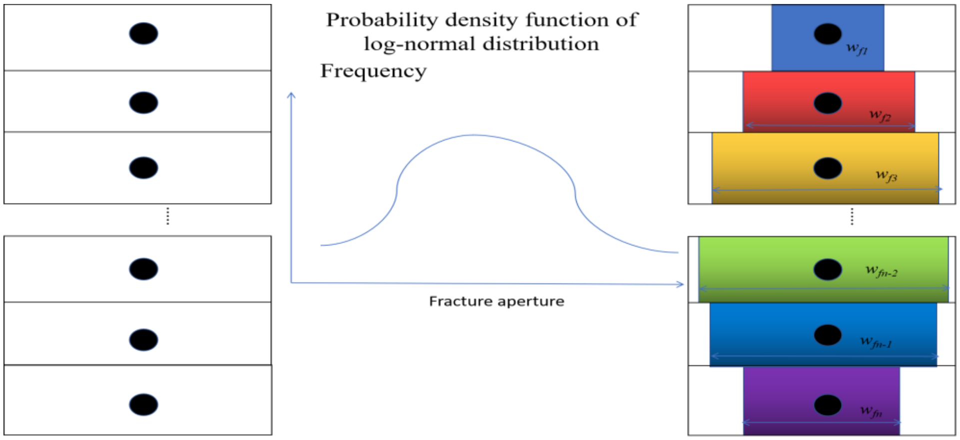
(2)Single-phase gas exists in the formation and the residual water saturation is less than 30.5%;

(3)As Fig. 2 shows that the hydraulic fracture is made up of several segments, the distribution of fracture segment's apertures meets log-normal distribution.

(4)The single non-uniform conductivity hydraulic fracture fully penetrates the formation;

(5)Gas flow in the matrix obeys Darcy's Law;

(6)Flow in the fracture obeys modified cubic law;



(a) Grid domain

(b) Fracture aperture: Log-normal distribution

(c) Computational domain

Fig. 2. The distribution of fracture apertures within a single fracture(modified from SYIHAB et al.[24-26])

(7)Skin effect and gravity effect can be considered;

(8)The distribution of apertures' values within a single hydraulic fracture fits log-normal distribution, like in Fig. 2 and Fig. 3.

2. METHODOLOGY

2.1 Physical model

Fig. 1 is the schematic of physical model about the vertical well with a non-uniform conductivity hydraulic fracture in tight sandstone gas reservoir.

2.2 Mathematical model

Based on the physical assumptions that are mentioned in the former part of this chapter, we treat the single-phase gas flow in fractured porous media with gravity effect as isothermal process.

The general governing equations for tight gas flow in matrix(M) and a non-uniform conductivity hydraulic fracture(*HF*)can be expressed as following parts of this chapter:

2.2.1 The flow equation for matrix

$$u_m = -\frac{k_m}{\mu_g}\nabla\left(p-\rho_g g\right) \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho\phi_m\right)+\nabla\bullet\left(\rho u_m\right)=Q_m \tag{2}$$

$$\int_{\Omega_m}\frac{\partial}{\partial t}\rho_g\phi_m d\Omega_m+\int_{\Omega_m}\frac{\partial}{\partial t}\rho_g v\bullet n d\sigma=\int_{\Omega_m}q_m d\Omega_m \tag{3}$$

Where, Ω_m is the control volume element about matrix, ρ_g is gas density, kg/m^3; ϕ_m is the rock porosity about matrix, %; σ_m is the boundary of control volume about matrix,Ω_m; v is seepage vector, m/s, n is the normal unit vector about boundary σ_m; q is source(sink) term.

2.2.2 The flow equation for non-uniform conductivity hydraulic fracture(HF)

Because of the reservoir geomechanics' condition and Mineral components of fractures, we cannot think of the fracture aperture as a smooth parallel plate in the DFM model(As Fig. 3 shows). The distribution of fracture apertures within a hydraulic fracture meets log-normal distribution.

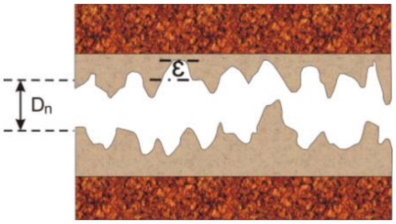


Fig. 3.The schematic plot of rough walled fracture(modified from SYIHAB et al[24-26])

We use the Probability density function of log-normal distribution that is expressed by the following equation[24-26] , and the relevant functions are shown in the below*:*

$$PDF=\frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{\left(\ln(x)-\mu\right)^2}{2\sigma^2}} \tag{4}$$

We use the cumulative density function for log-normal density distribution. It is shown in the below:

$$CDF=\int_0^x\frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{\left(\ln(x)-\mu\right)^2}{2\sigma^2}}dx=\frac{1}{2}+\frac{1}{2}erf\left(\frac{\ln(x)-\mu}{\sqrt{2}\sigma}\right) \tag{5}$$

where, μ is the mean of fracture apertures 'values within a single hydraulic fracture; σ is the standard deviation; x is the hydraulic fracture's aperture.

A great many researchers used the friction factor *f* to characterize the heterogeneity of fracture apertures. So , the equation of fracture permeability is modified in the below:

$$f=1+8.8\left(\frac{\varepsilon}{D_h}\right)^{1.5} \tag{6}$$

$$k_{hf}^{*}=\frac{w_{hf}^{2}}{12f} \tag{7}$$

$$u_f=-\frac{k_{hf}^{*}}{\mu_g}\nabla_T\left(p-\rho_g g\right) \tag{8}$$

$$\frac{\partial}{\partial t}\left(\rho\phi_{hf}\right)+\nabla_T\bullet\left(\rho u_{hf}\right)=Q_m \tag{9}$$

$$\int_{\Omega_{hf}}\frac{\partial}{\partial t}\left(\rho\phi_{hf}\right)d\Omega_{hf}+\int_{\Omega_{hf}}\frac{\partial}{\partial t}\rho u_{hf}\bullet n d\sigma_{hf}=\int_{\Omega_{hf}}Q_m d\Omega_{hf} \tag{10}$$

Where, ε is the absolute roughness about the hydraulic fracture;D_h is the hydraulic aperture of the hydraulic fracture;Ω_{hf} is the control volume element about hydraulic fracture ; ρ_g is gas density ,kg/m^3; ϕ_{hf} is the rock porosity about hydraulic fracture,%; σ_{hf} is the boundary of control volume about hydraulic fracture, Ω_{hf} ; *v* is seepage vector, m/s, *n* is the normal unit vector about boundary σ_{hf} ; *q* is source(sink) term.

2.3 Well model

On the basis of Peaceman model's equivalent radius[18-20], the well-fracture intersections is (as shown in Fig. 1) in the DFM, as follows :

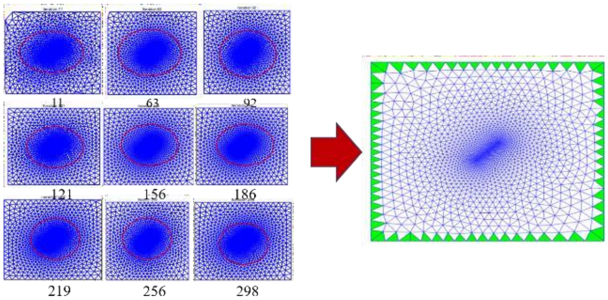
$$WI_{w-hf}=\frac{k_{hf}w_{hf}H_w}{d_{s-w}} \tag{11}$$

Where, k_{hf} is the non-uniform conductivity hydraulic fracture permeability; w_{hf} is the hydraulic fracture's aperture, m; d_{s-w} is the average normal distance between the wellbore axis and the non-uniform conductivity hydraulic fracture segment; H_w is the height of the well in the fracture's segment.

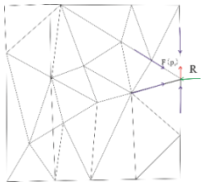
3.GRID GENERATION AND LOCAL GRID REFINEMENT

3.1 Grid Generation

In this study, we combine the efficient grid generator called DistMesh[21] with near wellbore model(NWM)[22] to construct the 2.5D grid. As Fig. 4 shows, we use the process of optimization to create grid of good quality.And then,we extrude the 2D triangular grid of good quality into 2.5D grid. The construction of 2.5D grid requires topology structure of tessellation grid and 3D curved surface's point set. And then, we add fracture grid into 2.5D grid.



a)the process of mesh's optimization



b) the schematic of Force Equilibrium

Fig. 4. Optimization of triangular grid: a)the process of mesh optimization ,b) the schematic of Force Equilibrium

3.2 Local grid refinement（LGR）

In terms of the fracture characterization method that is named after discrete fracture and matrix (DFM), this method requires more grids about fracture. And then, the fracture grid's size is much finer than that for a standard full-field simulation. Because of many more nodes that are necessary, the grid scale near wellbore and fractures must be refined. We use *functions* $d(x,y)$ and $h(x,y)$ to make local grid refinement[21]. These functions are $d(x,y)$ and $h(x,y)$.

$$\begin{cases} d(x,y) \\ h(x,y) \end{cases} \tag{12}$$

Where, $d(x,y)$ is the signed distance function; $h(x,y)$ is the relative element size function.

3.3 Lower dimensional fracture grid

In terms of the 2D domain, as Fig.5 shows that these fractures can be treated as several lines(1D).

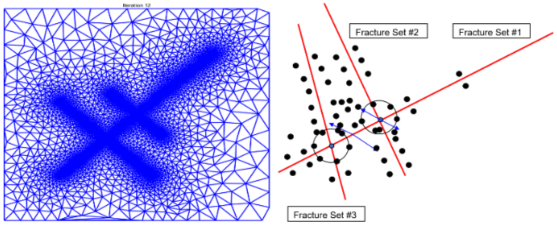


Fig.5. The fracture representation in the 2D domain.

The method is also called lower dimensional method. Therefore, in terms of the 3D domain, as the Fig.6 shows that the only one hydraulic fractures can be thought of as a plane(2D).

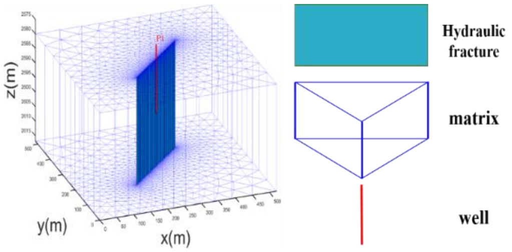


Fig.6. The fracture representation in the 3D domains.

As discussed in the former part of this paper, we can't think of the fracture as a parallel plate in the DFM model. The apertures within a single hydraulic fracture follow log-normal distribution[24-26](As Fig.2 shows).We use the grid index to give the values about log-normal distribution on the apertures of a fracture elements within a single hydraulic fracture .

4. NUMERICAL SOLUTIONS

In this paper, we set up an improved tight sandstone gas reservoir simulation code that is called non-uniform DFM-WPA. On the basis of the open source software called MRST, it is developed using several modules in the open-source software MATLAB Reservoir Simulation Toolbox (MRST), such as discrete fracture and matrix (DFM), near wellbore model(NWM)[22] and Openshale[23]. Two-point flux approximated finite volume method (TPFA-FVM) is applied for discretizing the governing equations (Eq.3 and Eq.10). All nonlinear functions for tight gas properties as well as non-linear effect are defined as other separate functions. The non-uniform conductivity hydraulic fractures are explicitly modeled using DFM.

5. RESULTS AND DISCUSSTIONS

The case in this paper is about the vertically fractured well with a non-uniform conductivity hydraulic fracture in the Shenmu gas field. The simulation model in this paper contains a vertically fractured well with a non-uniform conductivity fracture lies in the center of a squared-shaped reservoir. The gas reservoir about Shenmu gas field is reported to be a typical tight sandstone gas reservoir.

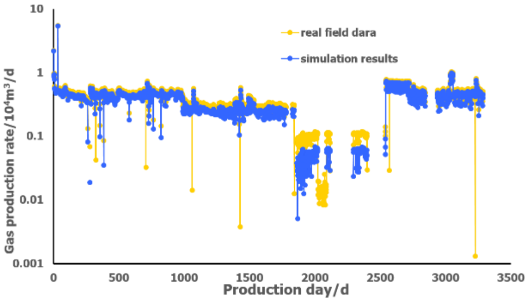


Fig.7. Comparison of the gas flow rate for the study between Non-uniform DFM-WPA and real field data of gas well B1 from Shenmu gas field.

Fig. 7 gives the comparison of the calculation results and real field data of well B1. According to the figure, it shows that the great conpliance between results generated using the proposed method and that from data from well B1.

6. SENSITIVITY ANALYSIS

In this paper,we do some sensitivity analysis on the two parts of non-uniform conductivity hydraulic fracture's properties, such as the mean aperture within a single hydraulic fracture and the deviation factor about fracture apertures.These analyses are shown in the following parts of this chapter.

6.1 The influence of mean aperture within a single hydraulic fracture

The Fig. 8 is about the influence of BHP's curves for different mean apertures of hydraulic fractures.It shows that the more the mean aperture of hydraulic fracture is, the less the bottomhole pressure(BHP) drops.

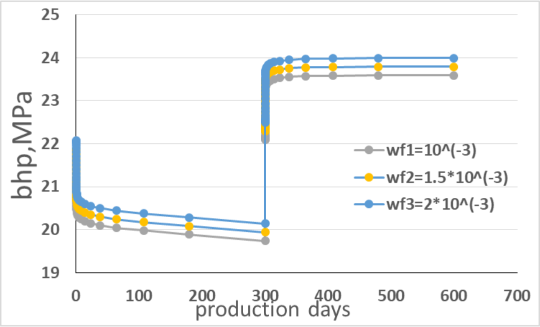


Fig. 8. The influence of BHP's curves for different mean apertures of hydraulic fractures

6.2 The influence of deviation factor about hydraulic fracture apertures

The Fig.9 is about the influence of BHP's curves for different deviation factors(sigma) of HFs.It shows that the more the deviation factor is, the more bottomhole pressure drops.

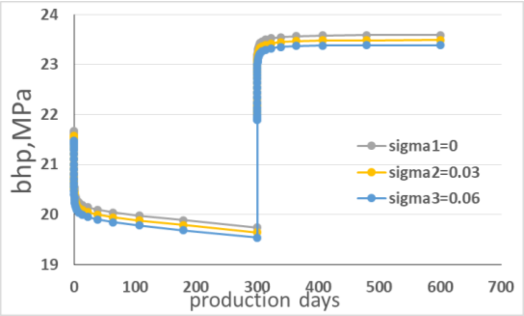


Fig. 9. The influence of BHP's curves for different deviation factors(sigma) of HFs.

7. CONCLUSIONS

(1)The FVM-TPFA solution derived in this work is a generalized formulation applicable to tight sandstone gas reservoirs. This attempt is very useful for us to analyze the well performance on the vertical well with a non-uniform conductivity hydraulic fracture in tight sandstone gas reservoir.

(2)The proposed solution mentioned above has demonstrated a high degree of compliance with actual field data, indicating a strong agreement between the predicted outcomes and the observed results.

(3)We developed an improved tight gas framework called Non-uniform DFM-WPA. It has been developed and verified. And then the improved framework solves the analysis of real-world tight gas challenges. These challenges include non-uniform conductivity fracture's properties and non-linear gas properties. They are the real challenges in the Shenmu gas field.

(4)We take fracture's non-uniform properties into consideration. The more the mean aperture of fracture is, the less bottomhole pressure drops; The more the deviation factor is, the more bottomhole pressure drops.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.All authors read and approved the final manuscript.

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