Evaluation of Volume Fracturing of Vertical Well in Tight Gas Reservoirs Using Numerical Simulation

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Abstract. Slickwater volume fracturing with high pump rates and large fluid volumes may form a complex fracture network, and achieve more large-scale stimulated reservoir volume than a conventional fracturing treatment in tight gas reservoirs. These complex fracture networks are composed of main induced fractures and multiple branch fractures. Therefore, the conventional bi-wing fracturing model can not characterize its characteristics sufficiently. However, quantifying the complex fracture network still faces a significant challenge. Both a new and more accurate volumetric fracturing modeling and evaluation technology are urgently needed. Based on the geological properties and fracturing treatment parameters of a single vertical well in a tight gas reservoir, a heterogeneous seepage model is established. We propose a composite multi-porosity flow model coupled with multiple linear flow regimes. The main fracture and multiple branch fractures orthogonal to it are used to represent the complex fracture network, and the number of branch fractures is used as an evaluation index for the effectiveness of reservoir simulation. Taking the vertical tight gas well as an example, the conventional and volume fracturing numerical models are established respectively. The accuracy of the two fracturing models is compared and analyzed by history matching methods, and the fracturing performances of the vertical well are evaluated. The results show that the reservoir properties obtained by history matching conventional fracturing are unreasonable, while the accuracy rate of the volume fracturing of the numerical model reaches 90%. On the basis of the volume fracturing modeling, as the scale of treatment increases, the production will increase to a certain extent. The proposed volume fracturing modeling provides a new approach for evaluating the effectiveness of the tight gas reservoir stimulation, which is of great significance to fracturing treatment design.

Keywords: Volume Fracturing, Fracturing Modification,

1 Introduction

The tight gas reservoir is characterized by its extremely tight rock formations with very low pore connectivity, which results in low production and low efficiency in conventional fracturing[1]. It is necessary to adopt large pump rate and large fluid volume fracturing to improve the productivity and achieve economic and effective recovery of single well[2]. Compared to conventional fracturing, volumetric fracturing breaks up the tight reservoir into complicated networks composed by a main fracture and numerous branch fractures, which can effectively increase the seepage capacity of the gas well in the near-wellbore zone , thereby significantly increasing tight gas production.The condition of underground reservoir is complicated and difficult to estimate for conventional evaluation methods to effectively explain whether complex fracture network is formed after hydraulic fracturing.Currently, there are three main types of common evaluation methods.The first is to use measuring instruments, such as downhole microseismic monitor[3-5] surface inclinometer, distributed acoustic sensor crack monitor[6-8], etc. which are characterized by limited measurement accuracy and are expensive to use.The second is direct near-wellbore Techniques, such as radioative tracers method, temperature logging, sonic logging, etc. However, this type of fracture monitoring technology is usually used as a supplement to the selected application technology. The third is to use numerical simulation methods to evaluate. Recently, statistic analysis of quantities of production data have proved that after hydraulic fracturing of tight gas reservoirs, the higher productivity is obtained with the more complex internal fracture network. However, most studies at home and abroad only mentioned how to describe the complex fractures formed by volume fracturing, while there are few studies based on productivity to evaluate the complexity of fractures. Meanwhile, there are great differences in the productivity performance of different reservoirs with the same stimulated reservoir volume (SRV). The fracture degree of the reservoir rock, that is, the density of the fracture network, is one of the main reasons for the difference in productivity. Therefore, it is urgent to study the branch fracture density after fracturing and to establish a corresponding mathematical model[9]. Therefore, a new volumetric fracturing numerical simulation evaluation method is proposed in this paper. Taking a vertical well in tight gas reservoir as an example, a main fracture and multiple branch fractures orthogonal to it are used to characterize the complex fracture network formed by volumetric fracturing.A composite porous linear flow model with multiple linear flow regions in vertical wells is proposed to divide the near-wellbore zones into multiple seepage areas[10-12].The number of branch joints is used as the evaluation index for the effect of reservoir fracturing. The conventional fracturing and volumetric fracturing numerical model of vertical well are established respectively ,of which the accuracy is compared and corrected by the production history fitting method to evaluate the effect of volume fracturing of vertical wells in tight gas reservoirs and to predict the production capacity of different scales on this basis.This provides a new idea for evaluating the effects of volumetric fracturing in tight gas reservoirs, which is of great significance to subsequent production and adjustments.

2 Fracturing mathmatical model for vertical well

A fractured vertical well in tight gas was selected as the basic research unit to study and establish conventional fracturing and volumetric fracturing seepage models.The multi-linear flow method is used to process the model, and the fluid flow in matrix and fracture is considered to be linear flow, thus the whole flow process is simplified into multiple linear flows connected end to end[13-15].

2.1 Mathematical model of conventional fracturing

In the conventional fracturing seepage model of vertical well, the fluid flows in two areas. During production, it is considered that the fluid in zone 1 flows linearly from the matrix to the fracture zone, and the fluid in zone 2 flows linearly from the fracture tip to the wellbore, thus simplifying the conventional fracturing seepage process of a vertical well into two linear flow processes, forming a bilinear vertical well Flow fracturing seepage model, as shown in Fig. 1 below.

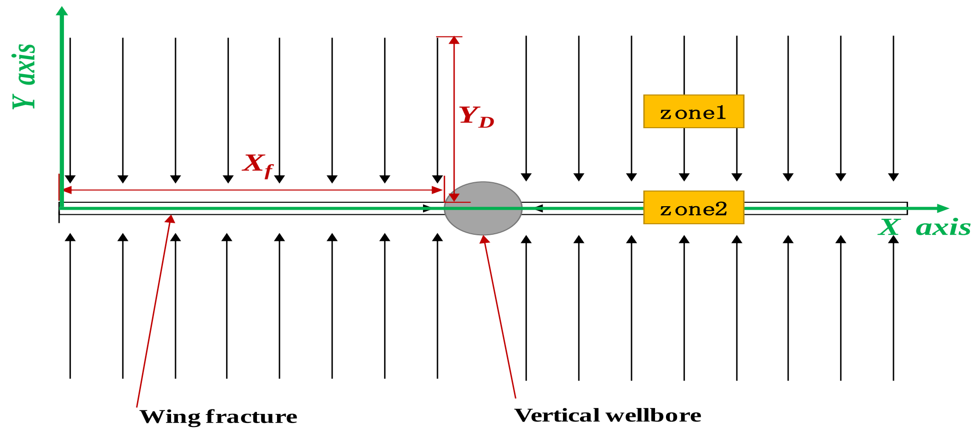

Fig. 1 Vertical well conventional fracturing model

2.2 Mathematical model of volumetric fracturing

Taking a vertical well in a tight gas reservoir as the research object, we select the basic research unit shown in Fig. 2 to study and establish volume fracturing seepage model of a vertical well. In the model, the fluid flows in 6 areas. It is considered that regions 1 and 2 are non fractured areas, regions 3 and 4 are fractured areas, and regions 5 and 6 are fracture areas. During production, the fluid in zone 1 flows linearly from the non fractured area to the fractured area, the fluid in zone 2 flows linearly from the non fractured area to the branch fracture area, and the fluid in zone 3 flows linearly from the fractured area to main fracture area,the fluid in area 4 flows linearly from the fractured area to the branch fracture area, the fluid in area 5 flows linearly from the branch fracture area to the main fracture area, and the fluid in area 6 flows linearly from the main fracture area to the wellbore, thus simplifying the vertical well volume fracturing seepage process into multiple linear flow processes[16].

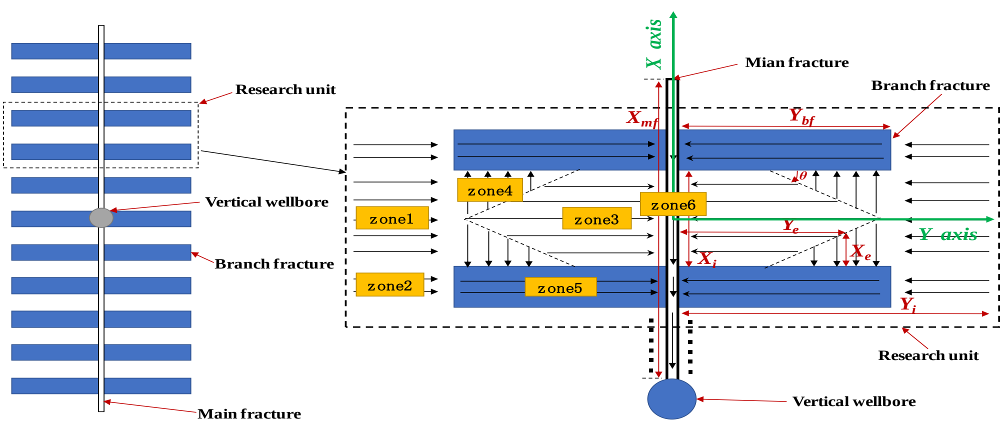

Fig. 2 Vertical well volume fracturing model

The main fracture direction is set as X direction, the branch fracture direction is Y direction, the fracture half-length is $X_{mf}(m)$, the branch fracture half-length is $X_{bf}(m)$, and the branch fracture spacing is $X_i(m)$. It is assumed that there is an non fracturted area near the main fracture and the spacing is $Y_i(m)$. The permeability of area 1 and 2 are $K_1(mD)$and $K_2(mD)$, the porosity is φ_1 and φ_2, the pressure is $P_1(MPa)$and $P_2(MPa)$, and the comprehensive compressibility is C_{1t} $(Mpa^{-1})$and $C_{2t}(Mpa^{-1})$. The permeability of area 3 and 4 are $K_3(mD)$and $K_4(mD)$, the porosity is φ_3 and φ_4, the pressure is $P_3(MPa)$and $P_4(MPa)$, and the comprehensive compressibility is $C_{3t}(Mpa^{-1})$and $C_{4t}(Mpa^{-1})$. The permeability of area 5 and 6 in the branch fracture and main fracture areas are K_5 $(mD)$and $K_6(mD)$, porosity is φ_5 and φ_6, pressure is $P_5(MPa)$and $P_6(MPa)$, and comprehensive compressibility is $C_{5t}(Mpa^{-1})$and $C_{6t}(Mpa^{-1})$.The fluid viscosity is $\mu(mPa.s)$, the volume coefficient is B, the fracture width is $W_f(m)$, the flow rate within a single fracture is $q_f(m^3/d)$, and the thickness of reservoir is $h(m)$. It is assumed that the both wings of the fracture are symmetric, each branch fracture is evenly distributed along the main fracture, the length of branch fractures is the same, the thickness of reservoir is the same, and the fracture penetrates the whole reservoir longitudinally. The seepage is isothermal, and the pressure loss in the horizontal well and gravity effect are ignored[17-18].

（1）Fracturing seepage mathematical model in non fractured area:

①Mathematical model of fluid seepage in zone 1：

$$\frac{\partial^2 P_1}{\partial y^2} = \frac{(\phi_1 \mu C_{1t})}{0.0864 k_1} \frac{\partial P_1}{\partial t}$$

Inner boundary condition: $P_1\big|_{y=Y_{bf}} = P_1\big|_{y=Y_{bf}}$

Outer boundary condition: $\left.\frac{\partial P_1}{\partial y}\right|_{y=y_i} = 0$

The initial condition: $P_1\big|_{t=0} = P_i$

②Mathematical model of fluid seepage in zone 2：

$$\frac{\partial^2 P_2}{\partial y^2} = \frac{(\varphi_2 \mu C_{2t})}{0.0864 k_2} \frac{\partial P_2}{\partial t}$$

Inner boundary condition: $P_2\big|_{y=Y_{bf}} = P_5\big|_{y=Y_{bf}}$

Outer boundary condition: $\left.\frac{\partial P_2}{\partial y}\right|_{y=Y_i} = 0$

The initial condition: $P_2\big|_{t=0} = P_i$

（2）Fracturing seepage mathematical model in fractured area:

①Mathematical model of fluid seepage in zone 3：

$$\frac{\partial^2 P_3}{\partial y^2} + \frac{k_1}{Y_{bf} k_3} \left.\frac{dP_1}{dy}\right|_{y=Y_{bf}} = \frac{(\varphi_3 \mu C_{3t})}{0.0864 k_3} \frac{\partial P_3}{\partial t}$$

Inner boundary condition: $P_3\Big|_{y=\frac{W_f}{2}} = P_6\Big|_{y=\frac{W_f}{2}}$

Outer boundary condition 1: $\left.\dfrac{\partial P_3}{\partial y}\right|_{y=y_{bf}} = \dfrac{k_1}{k_3}\left.\dfrac{\partial P_1}{\partial y}\right|_{y=y_{bf}}$

Outer boundary condition 2: $\left.\dfrac{\partial P_3}{\partial y}\right|_{y=Y_e+\frac{x-X_e}{\tan\theta}} = \dfrac{k_4}{k_3}\left.\dfrac{\partial P_4}{\partial x}\right|_{x=X_e+(y-Ye)\tan\theta}$

The initial condition: $P_3\big|_{t=0} = P_i$

②Mathematical model of fluid seepage in zone 4：

$$\frac{\partial^2 P_4}{\partial x^2} + \frac{k_1}{k_4}\left.\frac{dP_1}{dy}\right|_{y=Y_{bf}} = \frac{(\varphi_4 \mu C_{4t})}{0.0864\, k_4}\frac{\partial P_4}{\partial t}$$

Inner boundary condition: $P_4\Big|_{x=\frac{X_i}{2}} = P_5\Big|_{x=\frac{X_i}{2}}$

Outer boundary condition: $\left.\dfrac{\partial P_4}{\partial x}\right|_{x=X_e+(y-Y_e)\tan\theta} = \left.\dfrac{\partial P_3}{\partial y}\right|_{y=Y_e+\frac{(x-X_e)}{\tan\theta}}$

The initial condition: $P_4\big|_{t=0} = P_i$

（3）Fracturing seepage model in fracture area:

①Mathematical model of fluid seepage in branch fracture zone 5：

$$\frac{\partial^2 P_5}{\partial x^2} + 2\frac{k_4}{W_{bf} k_5}\left.\frac{dP_4}{dx}\right|_{x=\frac{X_i}{2}} + \frac{k_2}{W_{bf} k_5}\left.\frac{dP_2}{dy}\right|_{y=Yi} = \frac{(\phi_5 \mu C_{5t})}{0.0864\, k_5}\frac{\partial P_5}{\partial t}$$

Inner boundary condition: $P_5\big|_{y=0} = P_6\big|_{y=0}$

Outer boundary condition: $\left.\dfrac{\partial P_5}{\partial y}\right|_{y=y_{bf}} = 0$

The initial condition: $P_5\big|_{t=0} = P_i$

②Mathematical model of fluid seepage in mian fracture zone 6：

$$\frac{\partial^2 P_6}{\partial x^2} + 2\frac{k_5}{W_f k_6}\left.\frac{dP_5}{dy}\right|_{y=Y_{bf}} + 2\frac{k_3}{W_f k_6}\left.\frac{dP_3}{dy}\right|_{y=Y_e\pm\frac{x-X_e}{\tan\theta}} = \frac{(\varphi_6 \mu C_{6t})}{0.0864\, k_6}\frac{\partial P_6}{\partial t}$$

Inner boundary condition: $0.0864\dfrac{k_6}{v} W_f h \left.\dfrac{\partial P_6}{\partial y}\right|_{y=0} = \dfrac{q_f}{2}B$

Outer boundary condition: $\left.\dfrac{\partial P_6}{\partial y}\right|_{x=X_f} = 0$

The initial condition: $P_6\big|_{t=0} = P_i$

2.3 Solution of Mathematical Model

According to the law of conservation of mass, momentum and energy, a set of partial differential equations, auxiliary equations and definite solution conditions for describing reservoir fluid flow are established. The continuous physical relationship in the seepage equation is approximately expressed as a finite number of interconnections with spatiotemporal nodes[19]. Then, the numerical discretization method is used to divide the entire seepage area into a number of regular-shaped small units. Each small unit is approximately treated as homogeneous to establish the relational expression of the fluid flow of each unit underground. Thus, the irregular and heterogeneous problems are transformed into homogeneous problems with regular shapes.To meet the requirement, the number of units is determined and the time period is divided for unsteady flow. Finally, the approximate solution of the model is obtained by combining the local integration and the definite solution conditions.

3 Numerical fracturing model and post-fracturing evaluation

3.1 Basic model parameters

Before evaluating the numerical simulation after fracturing, some basic data need to be collected, including static data and dynamic data, as shown in Table 1 below. The actual geological parameters, phase permeability data (shown in Fig. 3 below), and production performance data of Well W were collected.Based on these data,conventional fracturing and volume fracturing numerical model are established to be researched and analysised.

Table 1　Parameters required for vertical well fracturing modeling

Data type	Data Range
Depth in the middle of the reservoir（m）	5300
Permeability per layer(md)	0.05-0.5
Porosity of each layer（%）	3.8-6.3
Effective reservoir thickness（m）	50
Net gross ratio	45-70
gas density	0.5611
Temperature in the middle of the reservoir（℃）	185-190
Current formation pressure coefficient	1.15
Relative permeability curve	As shown in Fig. 3
Production data	Omitted here

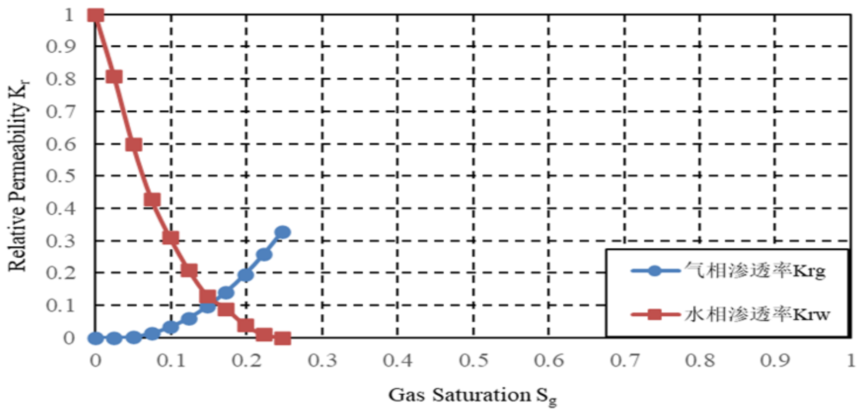

Fig. 3 Relative permeability curve of adjacent well of well W

3.2 Numerical fracturing model

Based on the data in table 1, a basic geological model was established. Combined with fracturing construction data, the fractures were simulated, and were imported into the model. And the numerical simulation models of conventional fracturing and volumetric fracturing were established respectively, as shown in fig. 4 and 5 below.

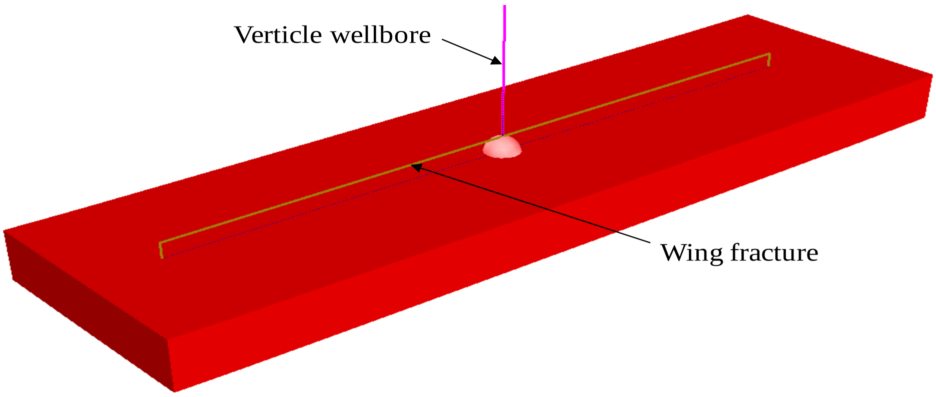

Fig. 4 Conventional fracturing numerical simulation model of well W

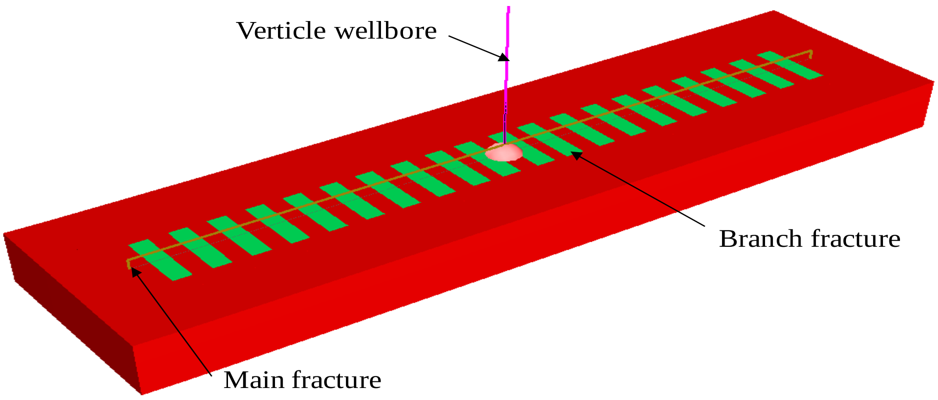

Fig. 5 Volume fracturing numerical simulation model of well W

Among them, a complex fracture network structure will be formed after volume fracturing. The spatial extent of the fracture network is the SRV, which can be approximated as the cloud volume of microseismic events[20]. Therefore, a main fracture and multiple branch fractures are imported into the model to represent the volume fracturing numerical model. The branch fractures are evenly distributed with the same length and perpendicular to the main fracture. Meanwhile, the length of main fracture and branch fracture are determined by the scope of microseismic fracture monitoring and interpretation. According to the microseismic data of well w, the total length of fracture network ranges from 270m to 320m, with an average of about 300m. The width of fracture network ranges from 40m to 80m, with an average of about 60m. And the height of fracture network ranges from 40m to 55m, with an average of about 50m.

3.3 Evaluation of post-fracturing performance

After conventional fracturing of tight gas reservoirs, a symmetrical bi-wing fracture will be formed around the wellbore. Meanwhile, the half-length and the conductivity of the fracture are the main factors affecting productivity. However, after volume fracturing, the productivity depends not only on the half-length and conductivity of the fracture, but also on the size of the SRV and the density of the fracture in it. The higher productivity is obtained with the more complex fracture network in the SRV.Microseismic data can reflect the size of SRV to a certain extent, but the density and conductivity of fractures in SRV cannot be determined. Thus it needs to be determined by combining history matching methods.

History matching is the process of recognizing the reservoir through dynamic data and numerical simulation methods. It is the key to numerical modeling research. The daily production data of well W is used as the fitting index. Combined with the seepage characteristics of different fracturing models, the two numerical simulations of conventional fracturing and volume fracturing are performed for modeling correction to evaluate that whether there is a conventional bi-wing fracture or a complex fracture network after fracturing. The correction results are shown in Fig. 6, 7 and table 2 below.

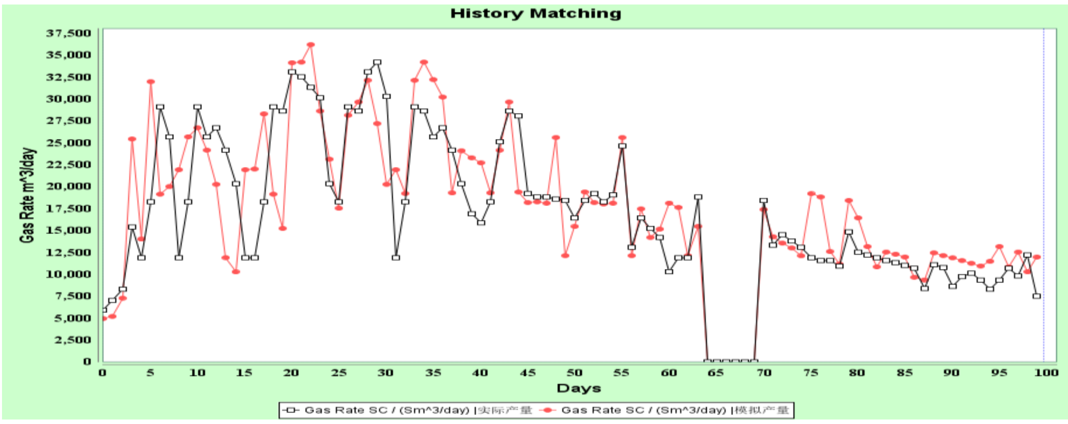

Fig. 6 Volumetric fracturing production history fitting diagram of well W

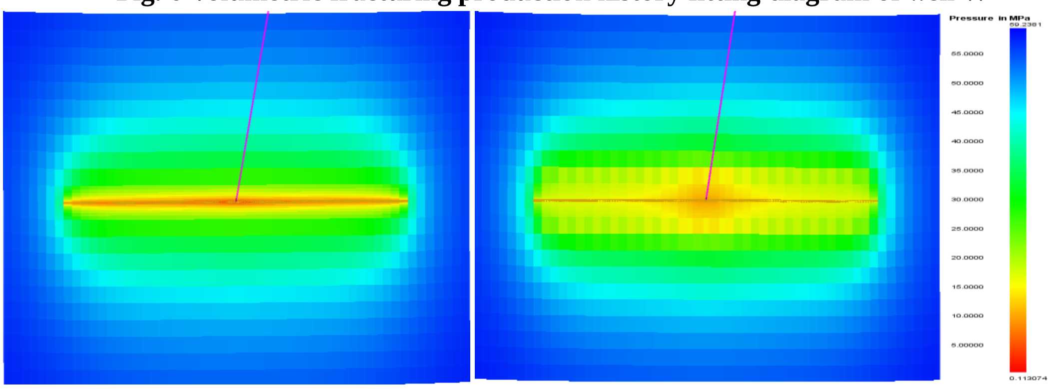

Fig. 7 Conventional and volume fracturing production pressure diagram of well W

Table2 Volume and conventional fracturing production history fitting results of well W

Data Type	Fitted parameters	
Conventional fracturing	The multiple of the reservoir permeability obtained by fitting and the original parameters	15
	Fracture length (m)	300
	Fracture width(mm)	5
	Fracture conductivity(md.m)	600
	Fracture hight(m)	50
Volume fracturing	Number of branch fracture(m)	20
	Permeability of branch fracture(md)	40
	Branch fracture length(m)	30
	Branch fracture width(m)	15
	Main fracture length(m)	300
	Main fracture width(mm)	5
	Main fracture conductivity(md.m)	600
	Main fracture hight(m)	50

During the volume fracturing treatment, the reservoir is broken up by injecting fracturing fluid to form a main fracture. Then the generated fracturing fracture is connected with the natural fractures in tight gas reservoirs to form a complex fracture network. Thus, in this study, a main fracture and multiple branch fractures orthogonal to it are used to characterize the fractures of volume fracturing. The greater the fracture density in SRV (i.e. the more the number of branch fractures) indicates that the more complex the fracture network is, so as to the shorter the seepage distance from the fluid in the matrix to the fracture, the higher the oil and gas well productivity, and the better the reconstruction effect of fracturing engineering.

The results in table 2 show that there is one branch fracture for every 30m of the main fracture half-length, which is equivalent to increasing the reservoir parameters of conventional fracturing modeling to 15 times the original parameters. This shows that if reservoir is broken up to form a conventional bi-wing fracture, the original reservoir production will not match the actual production data. According to the comparison results of history matching, the coincidence rate of the volume fracturing model is more than 90%, which can effectively indicate whether the fracturing finally forms a conventional fracture or a complex fracture network of volume fracturing.

4. Field case study

A total of 3 months of daily production data of well W were historically fitted. The production data of the following 2 months of of well W were used as the evaluation index to predict the production on the basis of the fitted and corrected model. The results show that the accuracy rate of prediction is up to 85%. And on the basis of this model, a comparative study of different fracturing scales is carried out to guide the subsequent fracturing construction plan of adjacent wells.

On the basis of this prediction scheme, a total of 5 plans were designed for offset Wells. Plan 1 was designed that injection displacement is 6-10m^3/min, total fluid volume is 9321m^3, sand volume is 300m^3, the number of branch fracture is 20, and the length of main fracture is 240-260m. Plan 2 was designed that displacement is 6-10m^3/min, total liquid volume is 9700m^3, sand volume is 382m^3, the number of branch fracture is 24, main fracture length is 290-310m; Plan 3 was designed that displacement is 6-10m^3/min, the total liquid volume is 10625m^3, the sand volume is 514m^3, the number of branch fracture is 28, and the length of main fracture is 340-360m. Plan 4 was designed that displacement is 6-10m^3/min, total liquid volume is 13096m^3, sand volume is 739m^3, the number of branch fracture is 32, main fracture length is 390-410m; Plan 5 was designed that displacement is 6-10m^3/min, total liquid volume is 16147m^3, sand volume is 998m^3, the number of branch fracture is 36, main fracture length is 440-460m. The accumulative gas production of 5 plans was simulated for 3 months. It was found that the accumulative gas production increased with the increase of reconstruction scale, and plan 4 was optimized by comprehensive economic benefit evaluation. The follow-up production of the offset well was about 10% higher than the W well. It is verified by the field actual data that this evaluation method of volume fracturing effect can accurately evaluate whether conventional fractures or volume fracturing fractures are generated after tight gas vertical well pressure, and effectively guide the volume fracturing construction of adjacent Wells, laying a foundation for efficient development of tight gas accumulation and fracturing vertical Wells.

5. Conclusions

(1) There is one branch fracture for every 30m of the main fracture half-length, which is equivalent to increasing the reservoir parameters of conventional fracturing modeling to 15 times the original parameters.

(2) The greater the fracture density in SRV (i.e. the more the number of branch fractures) indicates that the more complex the fracture network is, so as to the shorter the seepage distance from the fluid in the matrix to the fracture, the higher the oil and gas well productivity.

(3) With the increase of the fracturing construction scale, the production has been improved to a certain extent.

(4) Verified by field data, this method of evaluating the effect of volume fracturing can more accurately evaluate whether a tight gas vertical well is a conventional fracture or a volume fracturing after the pressure, and it can effectively guide the volume fracturing operation of adjacent wells. Efficient development of volume fracturing vertical wells has laid the foundation.

6.Acknowledgments

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