A New Dynamic Reserve Prediction Model of Fractured Horizontal Well in Tight Gas Reservoir Considering Stress Sensitivity

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Abstract. Since the stress sensitivity and other characteristics of tight gas reservoirs make their seepage mechanism more complex, the accurate calculation of dynamic reserves of fractured horizontal wells in tight gas reservoirs has always been a difficulty in the dynamic evaluation of gas reservoir development. To resolve the calculation problem of dynamic reserves in tight gas reservoirs, a dynamic reserves prediction model of fractured horizontal well which bases on the seepage mechanism of tight gas reservoirs is established by considering stress sensitivity and finite fracture conductivity. Meanwhile, Laplace transformation and Bessel function are used to solve the model of seepage equation. Secondly, Duhamel production transformation is carried out after the superposition of bottom hole pressure which obtains the typical production decline curve of fractured horizontal well and the seepage characteristics of fractured horizontal well are analyzed. Finally, the number of fractures, fracture length, fracture conductivity and stress sensitivity factor of the dynamic reserve calculation model are analyzed. And the production of model is compared with the actual well production to verify the accuracy of the model. The results show that the seepage characteristics of fractured horizontal well can be divided into five stages: early linear flow, mid-term radial flow, mid-term linear flow, systematic radial flow and boundary control flow. The model's production prediction curve is in good agreement with the production curve of actual production well, which verifies the accuracy of the model. The dynamic reserve prediction model innovatively considers the stress sensitivity and the obtained model and method play a certain practical role in the development plan of fractured horizontal well in tight gas reservoir. It has certain guiding significance for forecasting the dynamic reserves fractured horizontal well in tight gas reservoir, deploying well pattern and developing efficiently the tight gas reservoir.

Keywords: Low permeability · Stress sensitivity · Fractured horizontal well · Dynamic reserve · Prediction model · High-efficient development

1 Introduction

The tight gas is one type of unconventional natrual gas and it has the characteristics of large reserves and wide distributions. However, it can't be developed efficiently on account of ultra-low matrix porosity and permeability [1–3]. Indeed, it is successful that the combination of horizontal well and hydrofracture technology has been applied in tight gas reservoir. Nevertheless, it is important and necessary to pay attention to how to accurately forecast the dynamic reserve in tight gas reservoir. In the production process of fractured horizontal Wells, the flow state is unstable most of the time [4]. In different stages of pressure response and production decline, reservoir fluids have different flow patterns, so they have different characteristics of pressure and production decline. To morphological characteristics through the differential of pressure and output to determine fluid flow characteristics and status, solve the problem of practical production, first of all need to build a physical model of fracturing horizontal well each flow period, for each flow stage and the analytical solution of bottom hole pressure, on this basis, using the doha beautiful principle, the production and pressure, production decline curve. And analyze the factors affecting the decline. The conventional prediction methods of dynamic reservefor include volumetric method, material balance and so on. Volumetric method is applied of static reserve and material balance need formation average pressure which is difficult to measure. Aiming at the problem of dynamic reserves calculation of tight gas reservoirs, based on the seepage mechanism of tight reservoirs, this paper establishes a dynamic reserves prediction model of fractured horizontal Wells considering stress sensitivity and limited fracture conductivity [5, 6].

2 Establishment of Prediction Model of Dynamic Reserve

According to the geological conditions of the area, we assume that there is a fracturing horizontal well in the center of the homogeneous gas reservoir. The boundary condition of the model is considered as closed circular, the direction of the crack is vertical transverse, and the length of the horizontal section is L as shown in Fig. 1. Horizontal section is in the direction of Y axis, while fracture surface is perpendicular to horizontal section. The model assumes that the fracturing fracture of horizontal well is limited diversion, and the fracture of each transverse horizontal well has the same attribute, that is, the length, width, height and diversion ability of the fracture are consistent, the fluid flows into the horizontal wellbore through the fracture, and the total flow rate remains unchanged. There are three main aspects of fluid flow in reservoir: first, matrix to fracture flow; second, fracture flow; third, fracture flow to wellbore. Since the reservoir is of tight sandstone, its productivity could be rather low without getting fractured. So the flow from matrix to wellbore is ignored [7].

In the model of fractured horizontal production well in a circular closed gas reservoir, the formation and fluid meet the following conditions:

(1) Assume that the initial pressure of the gas reservoir is Pi and the thickness of the formation is H;
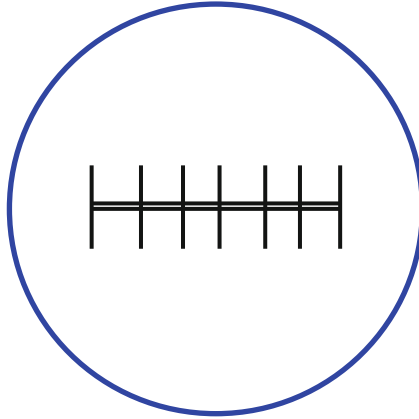
Fig. 1. Fractured horizontal gas well physical model

(2) The gas reservoir is heterogeneous, meaning that the matrix permeability in x, y direction is respectively k_x and k_y. The matrix porosity is Φ_m, the fracture permeability is k_f and the horizontal well's length is L. gas avoidances and circular boundary are impermeable boundary;

(3) The seepage mechanism of gas obeys the Darcy's law; The effect of capillary force and gravity are ignored.

(4) It is assumed that the half-length of the fracture is LF, which is perpendicular to the direction of the wellbore and completely penetrates the reservoir;

(5) The production rate of the gas well remains at q.

Based on the effective horizontal segment length, the following dimensionless variables are defined as:

Dimensionless pseudo-pressure:

$$p_D = \frac{78.489kh}{qT}\left[m(p_i) - m(p)\right] \tag{1}$$

$$m(p) = 2\int_0^p \frac{p}{\mu z}dp \tag{2}$$

Dimensionless Material balance pseudo-time:

$$t_D = \frac{3.6k_m t_{ca}}{\phi\mu_{gi}C_t L^2} \tag{3}$$

Dimensionless distance under cylindrical coordinates:

$$r_D = \sqrt{x_D^2 + y_D^2}$$

$$x_D = \frac{x}{x_f}\sqrt{\frac{k_h}{k_x}}$$

$$y_D = \frac{y}{x_f} \sqrt{\frac{k_h}{k_y}}$$

Dimensionless well bore radius:

$$r_{wD} = \frac{r_w}{L}$$

Dimensionless horizontal well half length

$$L_D = \frac{L}{L_f}$$

For the interference between multiple fractures in fractured horizontal wells, the influence of fracture interference was considered by using the superposition principle of influence function. If the horizontal well contains n fractures, we consider every fracture as a unit in a whole system, so we would have n + 1 unknown quantities. The linear source could be obtained through integration along the fracture's direction from the point source. After that, we superpositioned each influence function, and the problem of inter-fracture's interference was solved. At the same time, the fracture conductivity influence function proposed by professor xiaodong wang was introduced in this study, which carried out dynamic production analysis of fractured horizontal well with limited fracture conductivity [8].

The MBE, state equation and Darcy's law are required for forming partial differential equation.

The continuity equation of the homogeneous formation is as follows:

$$\frac{1}{r} \frac{\partial (r \rho \upsilon)}{\partial r} + \frac{\partial (\rho \phi)}{\partial t} = 0 \tag{4}$$

Real gas law:

$$pM = Z_g \rho R T$$

Radial Darcy's law:

$$\upsilon = -10^{-3} \frac{k}{\mu} \frac{\partial p}{\partial r}$$

Pore's compressibility

$$c_f = \frac{1}{\phi} \frac{\partial \phi}{\partial p}$$

Isothermal compressibility of gas

$$c_g = \frac{1}{\rho} \frac{\partial \rho}{\partial p} = \frac{z}{p} \frac{\partial}{\partial p} \left(\frac{p}{z} \right)$$

The permeability of tight gas reservoirs is relatively small, the flow mechanism in the matrix is considered to be pseudo-steady.

$$\frac{\partial^2 p_p}{\partial r^2} + \frac{1}{r}\frac{\partial p_p}{\partial r} + \gamma\left(\frac{\partial p_p}{\partial r}\right)^2 = e^{(p_{pi}-p_p)\gamma}\frac{\phi\mu_i C_{gi}}{k_i}\frac{\partial p_p}{\partial t} \tag{5}$$

Outer boundary condition:

$$\left.\frac{\partial p_p}{\partial r}\right|_{r=r_e} = 0$$

Inner boundary condition:

$$\left. e^{(p_{pi}-p_p)\gamma} r\frac{\partial p_p}{\partial r}\right|_{r=r_w} = \frac{p_{sc}qT}{\pi khT_{sc}}$$

Initial condition

$$p_p(r, t=0) = p_{pi}$$

Dimensionless the stess sensitivity coefficient:

$$\gamma_D = \frac{qp_{sc}\gamma T}{\pi k_i hT_{sc}}$$

The dimensionless pressure is defined as

$$p_D = \frac{\pi k_i hT_{sc}}{qp_{sc}T}(p_{pi} - p_p)$$

The above dimensionless pressure and stress sensitivity coefficient are introduced into the seepage equation, and the flow equation can be transformed into the following form:

$$\frac{\partial^2 p_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial p_D}{\partial r_D} - \gamma_D\left(\frac{\partial p_D}{\partial r_D}\right)^2 = e^{(\gamma_D p_D)}\frac{\partial p_D}{\partial t_D} \tag{6}$$

Inner boundary condition:

$$p_D(r_D, 0) = 0$$

Inner boundary condition:

$$\left. e^{\gamma_D p_D} r_D\frac{\partial p_D}{\partial r_D}\right|_{r_D=1} = -1$$

Outer boundary condition:

$$\left.\frac{\partial p_D}{\partial r_D}\right|_{r_D=r_{eD}} = 0$$

It is difficult to solve the seepage equation due to its non-linearity. Therefore, to linearize the equation, Pedrosa substitution is carried out for the seepage equation.

3   Model Solution

To solve the differential equation above, firstly the vertical fracture is considered as a line source. Then select one point source from the line source to solve its pressure influence on point (x, y) in the reservoir, where (x, y) is a non-specific point. After that, the pressure influence is integrated to solve the line source's whole pressure influence on point (x, y).

Since the differential equation meets the conditions of Bessel's equation, its general solution is:

$$\bar{\xi}_0 = A_1 I_0\left(\sqrt{sf(s)}r_D\right) + B_1 K_0\left(\sqrt{sf(s)}r_D\right) \tag{7}$$

According to its boundary condition, we have:

$$B_1 = 1; A_1 = \frac{K_1\left(\sqrt{sf(s)}r_{eD}\right)}{I_1\left(\sqrt{sf(s)}r_{eD}\right)}$$

Integrating the pressure solution at a certain point on the fracture's surface along the fracture's direction:

$$\bar{\xi}_0 = \frac{1}{2s} \int_{-1}^{+1} \left[K_0\left(\sqrt{sf(s)}\bar{r}_D\right) + \frac{I_0\left(\sqrt{sf(s)}\bar{r}_D\right)K_1\left(\sqrt{sf(s)}r_{eD}\right)}{I_1\left(\sqrt{sf(s)}r_{eD}\right)} \right] d\alpha \tag{8}$$

Which is:

$$\bar{\xi}_0 = \bar{\xi}_{D\,\mathrm{inf}} + \frac{1}{2s} \frac{K_1\left(\sqrt{sf(s)}r_{eD}\right)}{I_1\left(\sqrt{sf(s)}r_{eD}\right)} \int_{-1}^{+1} \left[I_0\left(\sqrt{sf(s)}\sqrt{(x_D - \alpha)^2}\right) \right] d\alpha \tag{9}$$

$$令\, ts = K_1\left(\sqrt{sf(s)}r_{eD}\right) \Big/ I_1\left(\sqrt{sf(s)}r_{eD}\right)$$

$K_1(x), I_1(x)$ is the first integral of the second transformation function $K_0(x), I_0(x)$.

The ratio of Bessel function: ts is almost zero during the initial stage, which has little effect on the generated pressure drop. However, during the later stage, it is difficult to obtain accurate results, especially for the integration of Bessel deformation function. Therefore, Ozkan's function for the pressure drop generated by a single fractured well in a closed gas reservoir is adopted for the right part of the above formula, which is:

$$\bar{\xi}_0 = \bar{\xi}_{D\,\mathrm{inf}} + \bar{\xi}_{Db} \tag{10}$$

$$\bar{\xi}_{Db} = \bar{\xi}_{Db1} + \bar{\xi}_{Db2} + \bar{\xi}_{Db3}$$

$$\bar{\xi}_{Db1} = \frac{\pi}{x_{eD}s\sqrt{u}} \left\{ \begin{array}{c} \exp[-\sqrt{u}(y_D + y_{wD})] + \exp[-\sqrt{u}(2y_{eD} - y_D - y_{wD})] \\ + \exp[-\sqrt{u}|y_D - y_{wD}|] + \exp[-\sqrt{u}(2y_{eD} - |y_D - y_{wD}|)] \end{array} \right\}$$

$$\left[1 + \sum_{m=1}^{\infty} \exp(-2m\sqrt{u}y_{eD}) \right]$$

$$\bar{\xi}_{Db2} = \frac{2}{s} \sum_{k=1}^{\infty} \frac{1}{k} \frac{\sin k\pi \frac{1}{x_{eD}} \cos k\pi \frac{x_D}{x_{eD}} \cos k\pi \frac{x_{wD}}{x_{eD}}}{\sqrt{u+a}}$$

$$\left\{ \begin{array}{c} \left\{ \begin{array}{c} \exp[-\sqrt{u+a}(y_D + y_{wD})] + \exp[-\sqrt{u+a}|2y_{eD} - y_D - y_{wD}|] \\ + \exp[-\sqrt{u}|y_D - y_{wD}|] + \exp[-\sqrt{u+a}(2y_{eD} - |y_D - y_{wD}|)] \end{array} \right\} \\ \left[1 + \sum_{m=1}^{\infty} \exp(-2m\sqrt{u+a}y_{eD}) \right] + \exp(-\sqrt{u+a}|y_D - y_{wD}|) \sum_{m=1}^{\infty} \exp(-2m\sqrt{u+a}y_{eD}) \end{array} \right\}$$

$$\bar{\xi}_{Db3} = \frac{1}{2s} \int_{-1}^{+1} K_0 \left[\sqrt{(x_D + x_{wD} - \alpha)^2 + (y_D - y_{wD})^2} \sqrt{u} \right] d\alpha$$

$$+ \frac{1}{2s} \sum_{k=1}^{\infty} \int_{-1}^{+1} \left\{ \begin{array}{c} K_0 \left[\sqrt{(x_D - 2kx_{eD} - x_{wD} - \alpha)^2 + (y_D - y_{wD})^2} \sqrt{u} \right] \\ + K_0 \left[\sqrt{(x_D - 2kx_{eD} + x_{wD} - \alpha)^2 + (y_D - y_{wD})^2} \sqrt{u} \right] \\ + K_0 \left[\sqrt{(x_D + 2kx_{eD} - x_{wD} - \alpha)^2 + (y_D - y_{wD})^2} \sqrt{u} \right] \\ + K_0 \left[\sqrt{(x_D + 2kx_{eD} + x_{wD} - \alpha)^2 + (y_D - y_{wD})^2} \sqrt{u} \right] \end{array} \right\} d\alpha - \frac{\pi \exp(-\sqrt{u}|y_D - y_{wD}|)}{x_{eD}s\sqrt{u}}$$

After transformation:

$$\bar{p}_D = -\frac{1}{\gamma_D} L\left\{ \ln\left[1 - \gamma_D \xi(r_D, t_D) \right] \right\}$$

Since the production of the fractured horizontal well is the sum of each fracture's production, the following function can be obtained by applying the Laplace transform to it:

$$\sum_{j=1}^{n} \bar{q}_{Dj}(s) = \frac{1}{s} \tag{11}$$

$$a = k^2\pi^2/x_{eD}^2$$

The system's convolution function is:

$$p_{wD}(t_D) = \sum_{j=1}^{n} \int_0^{t_D} q_{Dj}(\tau) p'_{Djk}(t_D - \tau) d\tau$$

The fracturing horizontal well produces n fractures in the direction of well bore. During production, gas flows to every fracture, resulting in pressure drop. As a result, the pressure drop at any point in the reservoir is equal to the pressure drop from each fracture. The pressure of the ith fracture is:

$$\bar{P}_{wD} = \sum_{j=1}^{n} \bar{q}_{Dj} s \bar{P}_{ij} \tag{12}$$

Because the fractures are unlimited conductive, each fracture's dimensionless pressure is equal.

$$\bar{p}_{wD} = \bar{p}_{wDi=1,n} \tag{13}$$

Therefore, based on n + 1 variables and n + 1 functions respectively from Eq. (12) and Eq. (13), a function matrix is established as follows:

$$\begin{pmatrix} \bar{p}_{wD1,1} & \cdots & \bar{p}_{wD1,n} & -1 \\ \vdots & \cdots & \vdots & \vdots \\ \bar{p}_{wDN,1} & \cdots & \bar{p}_{wDn,n} & -1 \\ 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} s\bar{q}_{D1} \\ \vdots \\ s\bar{q}_{Dn} \\ s\bar{p}_{wD} \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

If the fractures are considered to be limited conductive, there will be pressure drop inside every fracture.

$$\bar{p}_D(xD, yD) = \bar{p}_{\text{infD}}(x_D, y_D) + \bar{p}_b + \bar{f}(c_{fD}) \tag{14}$$

According to the conductivity influence function $\bar{f}(c_{fD})$ established by professor Wang Xiaodong's research based on Reily's study back in 2014:

$$\bar{f}(c_{fD}) = \frac{2\pi}{s} \sum_{n=1}^{\infty} \frac{1}{n^2\pi^2 c_{fD} + 2\sqrt{n^2\pi^2 + s}} \\ + \frac{1}{s} \frac{0.4063\pi}{\pi(c_{fD} + 0.8997) + 1.625s} \tag{15}$$

According to Duhamel's principle, the transformation relationship between dimensionless pressure and dimensionless production in Laplace space is as follows:

$$\bar{q}_D = \frac{1}{S^2 \bar{p}_{wD}} \tag{16}$$

The dimensionless pressure and dimensionless production can be obtained by Stephest inversion.

4   Analysis of Seepage Characteristics of Fractured Horizontal Well

The dynamic curve of fractured horizontal well in closed boundary gas reservoir is shown in Fig. 2 after utilizing Eq. (16) and calculating the bottomhole pressure obtained by Stehfest inversion. Meanwhile, the dimensionless production decline plot can be obtained by applying Duhamel principle, Stehfest inversion and Blasingame method to Eq. (16). According to the formula deduced above, take $r_{eD} = 8$, $z_{wD} = 0.5$, $k_v/k_h = 0.01$, $L_D = 5$, draw the typical curve chart of $q_{Dd} \sim t_{Dd}$, $q_{Ddi} \sim t_{Dd}$ and $q_{Ddid} \sim t_{Dd}$ which is shown in Fig. 2
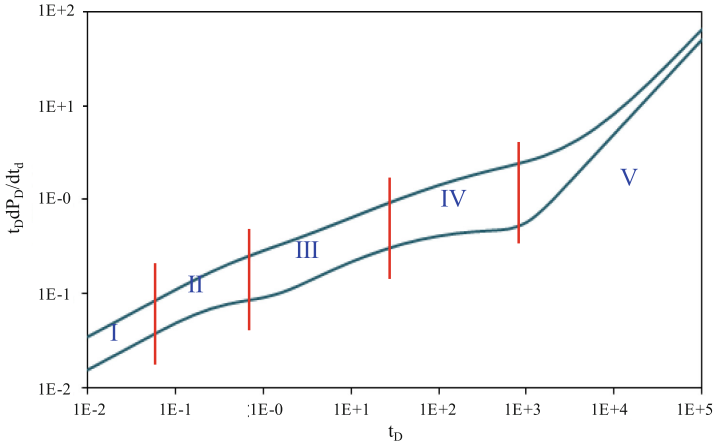
Fig. 2. Transient well test curve of fractured horizontal well

From Fig. 3, the new plot can be divided into two areas. The area containing I, II, III, IV suggests unsteady flow's characteristic while the remaining area suggests boundary control flow characteristic. Compared with the typical Blasingame curve plot of horizontal wells, the production dynamic curve of fractured horizontal wells has more flow stages and more complex curve forms than that of horizontal wells. Therefore, there will be a huge deviation in dynamic reserve result if the production data of fractured horizontal wells is directly fitted with normal horizontal wells' plot.
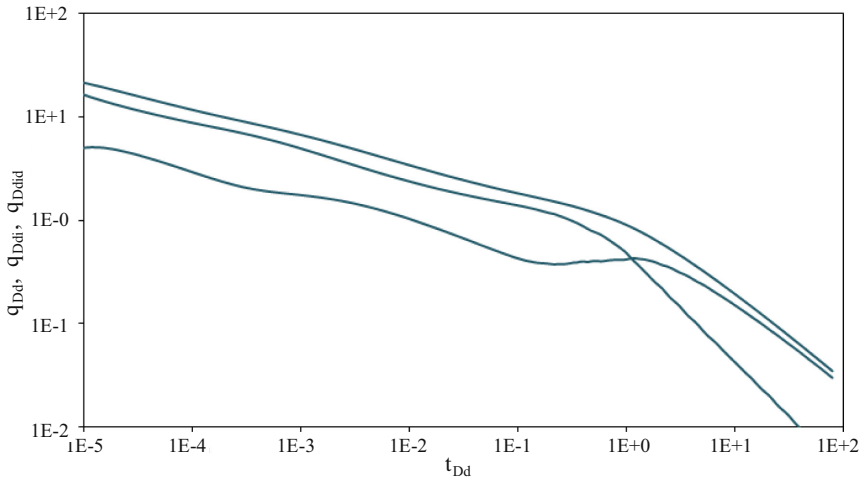
Fig. 3. Dimensionless production decline type curve

The flow regime is usually divided based on the pressure derivative form from well test dynamic curve. The flow regime of fractured horizontal well can be divided into 5 parts according to Fig. 2 and Fig. 3: early linear flow, mid-term radial flow, mid-term linear flow, systematic radial flow and boundary control flow.

5   Sensitivity Analysis

5.1   The Influence of the Number of Fractures

Take $r_{ed} = 40$, $L_f = 80$ m, $L_d = 200$ m, ignore fractures stress sensitivity, the dynamic pressure curve (Fig. 4) and dimensionless production decline curve (Fig. 5) of different number of infinite conductive fractures are formed. The number of fractures is respectively 3, 5 and 7; According to the pressure dynamic curve, the increase of fractures results in better reservoir reconstruction near-wellbore zone, more bottom hole pressure decline, longer radial and linear flow time and less systematic flow time. Also, from the production decline curve, the increase of fractures results in more production and rapid decline for horizontal well. Therefore, the production of horizontal wells can be effectively improved by increasing the number of fractures.
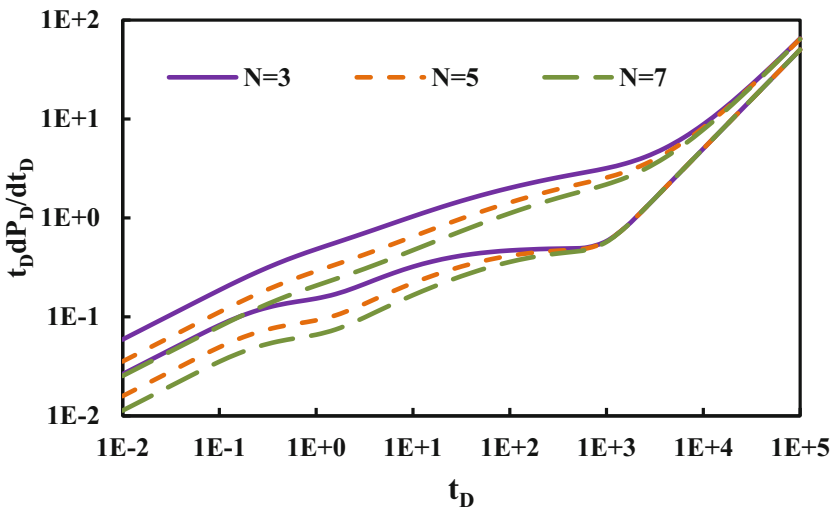
Fig. 4. Pressure type curves with anisomerous fractures
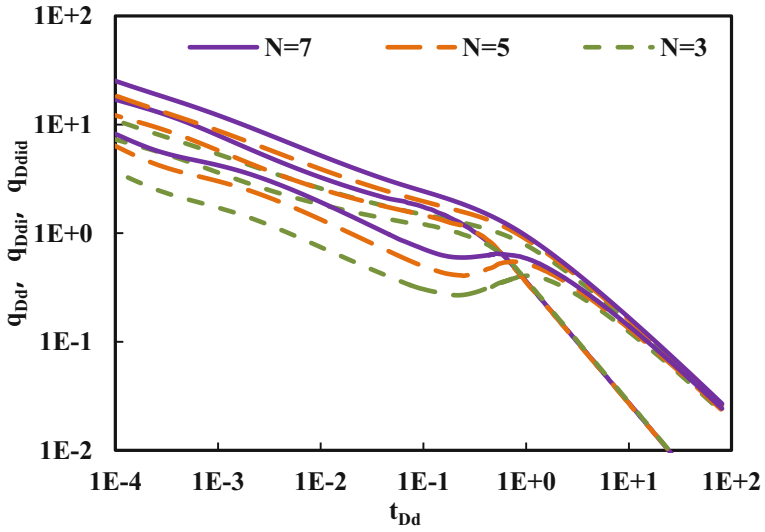
Fig. 5. Dimensionless rate decline curves with anisomerous fractures

5.2 Influence of Fractures Half-Length

Take $r_{ed} = 40$, $N = 5$, $L_d = 200$ m, ingnore fractures stress sensitivity, the dynamic pressure curve (Fig. 6) and dimensionless production decline curve (Fig. 7) of different infinite conductive fractures half-length are formed. The half-length of fractures is respectively 40, 80 and 120. From Fig. 6, fractures half-length mainly affects mid-term linear flow, systematic radial flow and boundary control flow. When other parameters remain unchanged, the longer the fracture half-length is, the longer the linear flow duration in the middle term is, the shorter the radial flow in the middle term is and the greater the pressure drop will become. The production will get higher, though, its decline gets faster.
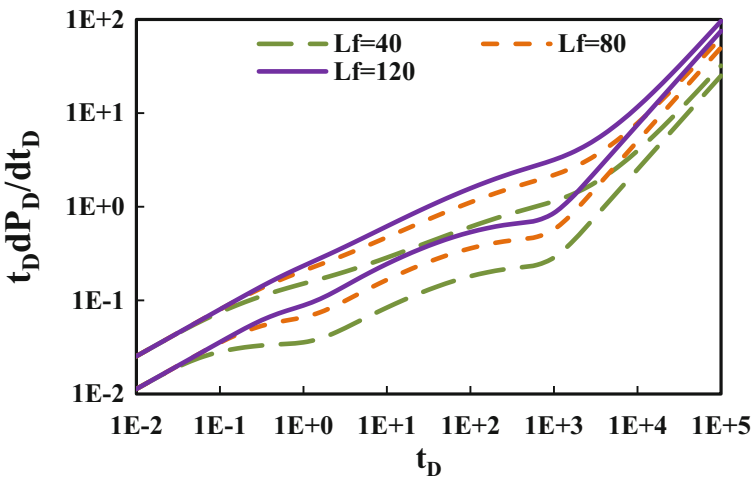
Fig. 6. Pressure type curves with different half fracture length
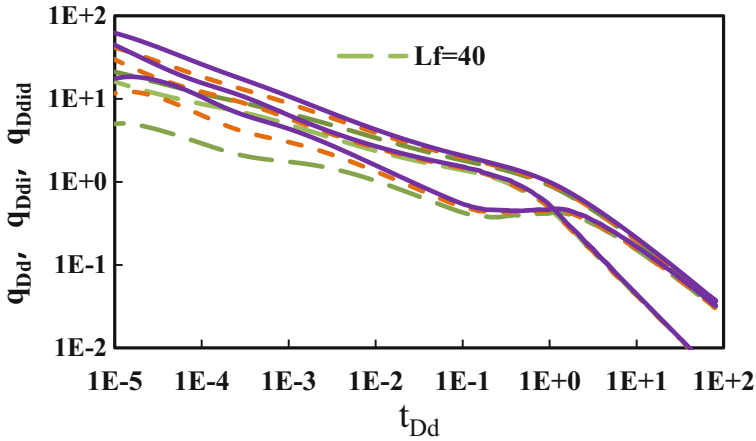
Fig. 7. Dimensionless rate decline curves with different half fracture length

5.3 Influence of Conductivity

Take $r_{ed} = 40$, N = 5, $L_f = 80$ m, $L_d = 200$ m, ingnore fractures stress sensitivity, the dynamic pressure curve (Fig. 8) and dimensionless production decline curve (Fig. 9) of different conductive fractures are formed. The conductivity is respectively: infinite, 3 and 30. Figure 8 suggests that the fracture conductivity mainly affects the duration of the combined effect of linear flow and radial flow in early-formed fractures. The smaller the fracture conductivity is, the faster the transition between the fracture linear flow and the radial linear flow to the formation will be, and the greater the pressure drop caused by this process will be.
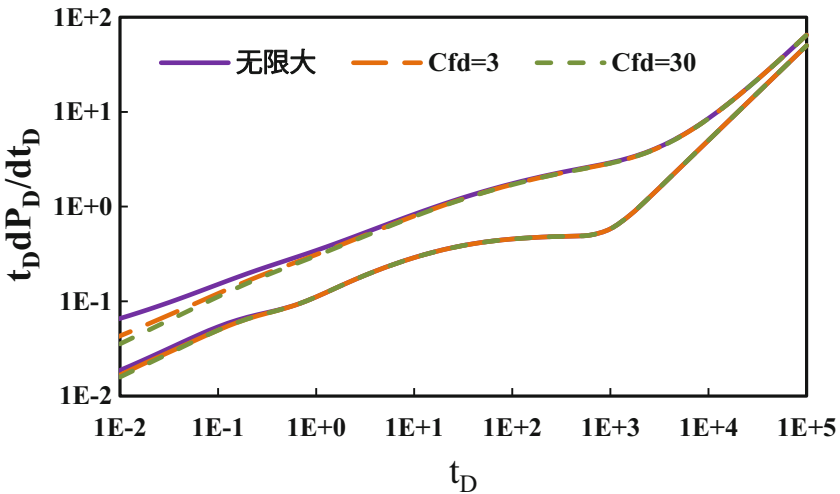
Fig. 8. Pressure type curves with different fracture conductivity
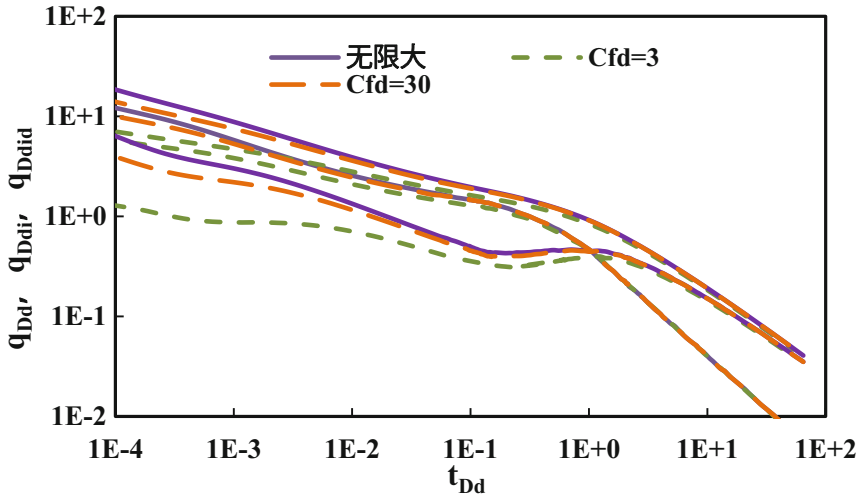
Fig. 9. Dimensionless rate decline curves with different fracture conductivity

5.4 Influence of Stress Sensitivity

Take $r_{ed} = 40$, $N = 5$, $L_f = 80$ m, $L_d = 200$ m, the fractures are infinite conductive, the dynamic pressure curve (Fig. 10) and dimensionless production decline curve (Fig. 11) under different stress sensitivity are formed. The stress sensitivity is respectively: 0, 0.06, 0.08. Figure 10 suggests that stress sensitivity mainly affects the formation boundary control flow. When other parameters remain unchanged, the stronger the stress sensitivity is, the more upward the pseudo pressure and its derivative will become, and the shorter the time of boundary flow is. Besides, stress sensitivity's effect during linear flow and radial flow is rather small. The stronger the stress sensitivity is, the greater the impact on production is. During the pseduo-steady state stage of the curve's form, the larger the production decline range is. Since the production decline curve is no longer harmonic, the available reserves is rather small.
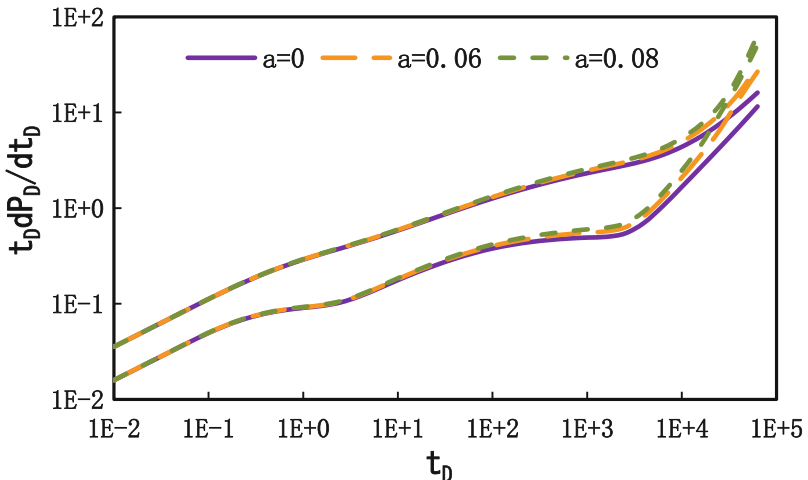

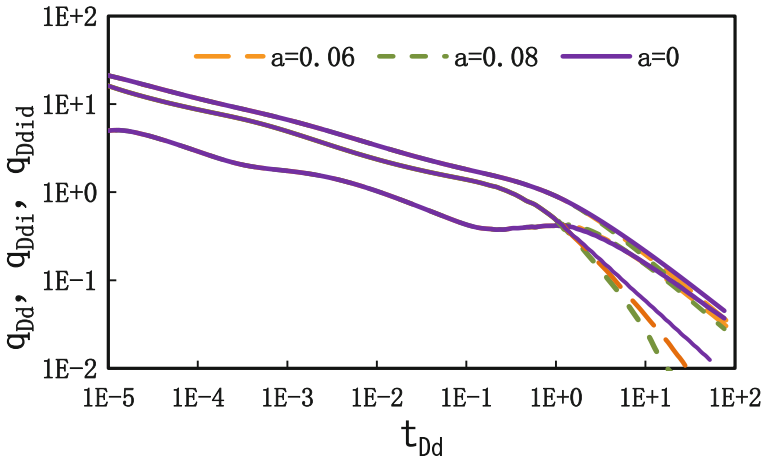**Fig. 10.** Pressure type curves with different pressure sensitivity

Fig. 11. Dimensionless rate decline curves with different pressure sensitivity

6 Application

After calculating the dynamic reserve using the decline curve established above and analyzing the relationship between dynamic reserve and formation properties, it is found that dynamic reserve is positively correlated with permeability and fracturing stage, especially with the single well's control area. Therefore, through orthogonal experiments, we design well patterns for different control of the formation reserves, and then use the black oil module in the Eclipse software to simulate each plan to optimize the best well pattern. Finally, the horizontal wells are optimally deployed based on the sand body characteristics of the actual well area.

Well Su 13-11H started its production in May 2011. The length of its horizontal part is 1025 m, and the logging interpretation gas layer thickness is 231 m. It is divided into six stages, with a medium depth of 3724.32 m and an open flow of 10.05×10^4 m^3/d. Figure 12 suggests the production status of Well Su 9-11H. It can be seen that the well is basically producing at 2.73×10^4 m^3/d and has been 1.45×10^4 m^3/d so far. The oil pressure is stable, and the casing pressure begins to decline rapidly, and is stable at 6.6 MPa.

The bottom hole pressure of well Su 13-11H is also calculated by the method in Sect. 2, as is shown in Fig. 13. After that, the data of flow pressure and production were used for plot fitting, as is shown in Fig. 14. If stress sensitivity is ignored, the dynamic reserve is 41.06×10^6 m^3 while the fitted dynamic reserve is 35.42×10^6 m^3. The reserve loss caused by stress sensitivity is 13.73%, the permeability is 0.08×10^{-3} µm^2, and the drainage radius is 276 m.
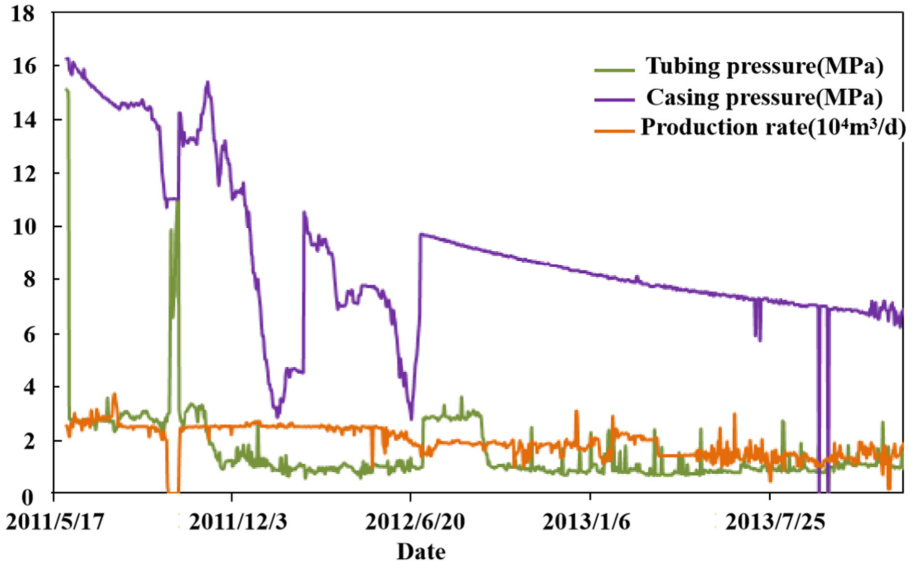
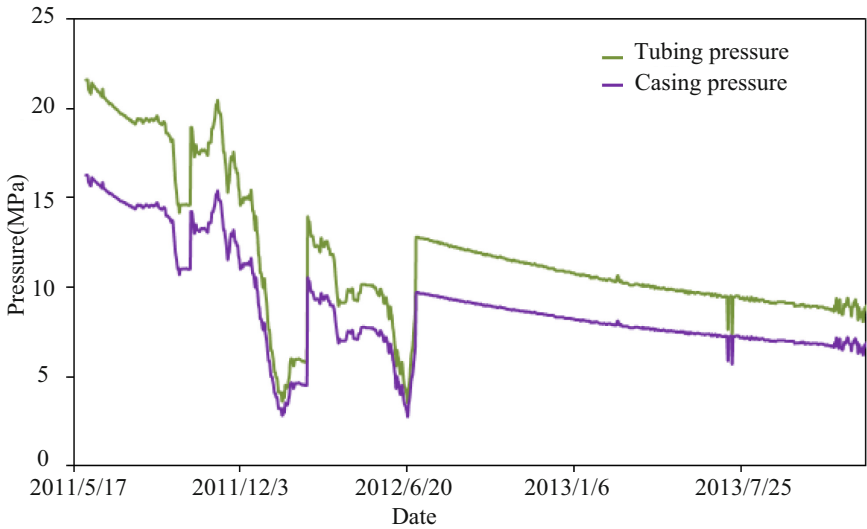**Fig. 12.** Production history of well 13-11H

Fig. 13. Calculated flow pressure history of well 13-11H
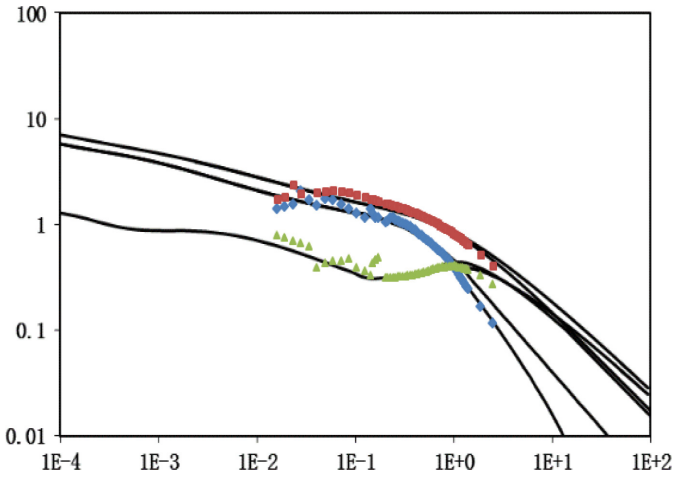
Fig. 14. Type curve match of well 13-11H

7 Results

(1) Based on the analysis of the influencing factors of fractured horizontal well seepage mechanism in tight gas reservoir, the grey correlation method is used to rank the influencing factors according to their effect, which is: fracture number > fracture interval > drainage radius > fracture half-length > conductivity; Through example application, since stress sensitivity affects different stages of the curve plot, the loss of dynamic reserves caused by stress sensitivity ranges from 4%–14%.

(2) Establish an unstable seepage equation for fractured horizontal wells considering stress sensitivity and limited fracture conductivity, solve the seepage equation by Laplace transformation and Bessel function, and then perform Duhamel production transformation after superimposing the bottom hole pressure. Use MATLAB to compile a program to get the theoretical plot of the typical curve of fractured horizontal wells and the corresponding dynamic reserve calculation method.

(3) In the fractured horizontal wells' typical curve plot, the curve forms of fractured horizontal wells with limited conductivity fractures are mainly linear flow and radial flow. According to the derivative curve form, five stages can be divided: early linear flow, mid-term radial flow, mid-term linear flow, systematic radial flow and boundary control flow.

Nomenclature

L the length of horizontal segment, m;
L_f the half-length of fracture, m;
h   the thickness of reservoir, m;
μ   gas viscosity, mPa·S;
Φ   porosity;
C_t the total compressibility coefficient, MPa^{-1};

x_D the dimensionless length in the x direction;
t_D imensionless time;
γ the stress sensitivity coefficient;
y_D the dimensionless length in the y direction;
p_D the dimensionless pressure.

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