Study on Pressure Propagation in Tight Oil Reservoirs with Stimulated Reservoir Volume Development

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ABSTRACT: The stimulated reservoir volume fracturing development in tight oil reservoirs is characterized by multiscale flow of the reservoir matrix, fracture network, and hydraulic fracture. Therefore, the flow field structure is extremely complex. Multiscale flow characteristics have been revealed through the systematical experiments including the threshold pressure gradient and stress sensitivity. Based on the theory of elliptical flow model, a comprehensive and practical mathematical model of multiregion coupling flow is established to characterize the multiscale flow, and the pressure distribution equation is derived. The calculation method of moving boundary is established to simulate the dynamic supply boundary and the dynamic pressure distribution by using the steady-state sequential replacement method. The characteristics of multiscale flow, multistage development state, and stress sensitivity are considered, especially the different stress sensitivity characteristics in different regions. Finally, the pressure propagation in tight reservoirs is clarified and the influence of matrix permeability, stress sensitivity characteristics, and drawdown pressure on the distance at the dynamic supply boundary are revealed. The research results provide theoretical basis for the development effect evaluation.

1. INTRODUCTION

In order to enlarge the ultimate recovery, stimulated reservoir volume (SRV) technology has become the main development mode for tight oil reservoir instead of conventional hydraulic fracturing technology. A complex fracture network is formed with a large amount of fracturing fluid injected into the reservoir, which makes the development process have multiscale flow characteristics of the reservoir matrix in nanometer scale, microfracture in micron scale, and artificial fracture in millimeter scale.1−8 In order to guide the efficient development of the tight reservoir, it is necessary to establish a mathematical model to characterize the multiscale flow characteristics.

Previous scholars have made many contributions in the mathematical model of the multiscale flow. The dual-porosity reservoir model introduced by Warren and Root9 and discussed by Odeh10 has been extended by a number of authors. They assumed that a reservoir can be represented by a set of building blocks where the blocks represented the matrix and the fracture spacing. They also assumed that the flow in the fracture was the unsteady state, while in the matrix, it was the steady state. Huyakorn and Blesset et al.11−13 established the discrete fracture network model to simulate the volume fractured well in an unconventional reservoir. A parallel-plate model is usually used to simulate fluid flow in the fractures which are assumed to be smooth and parallel. On the other hand, in order to simulate the multiscale flow, many scholars divided the flow field structure into several regions, and a multiregion coupled model that clearly expresses the flow characteristics of each region is widely used; there are mainly two types: multilinear flow model and elliptical flow model. Ozkan, Brown et al.14−16 developed linear flow models based on the trilinear flow model which includes the hydraulic fracture, inner region, and outer region. Ren et al.17−19 established a semianalytical model to analyze the transient pressure behavior of horizontal wells with complex fracture networks, which defined five regions. Many scholars demonstrated a composite elliptical mathematical model to simulate the fractured well, and they analyzed the pressure transient and rate transient behaviors in tight reservoirs with SRV.20−24 Based on the investigation and summary of the above mathematical model of multiscale flow in fractured well, their essential differences, pros, and cons are comparative analyzed which is shown in Table 1.
Table 1. Comparative Analysis of Each Multiscale Flow Model

| model                          | typical references | characteristics                              | advantages                               | disadvantages                           |
|-------------------------------|--------------------|----------------------------------------------|------------------------------------------|-----------------------------------------|
| the dual-porosity model       | Warren and Root    | simple flow of matrix to fracture            | simple model, mature calculation         | the fluid in matrix only flows into the  |
| the discrete fracture network model | Zhang              | a parallel-plate model is used to simulate the hydraulic fractures | accurately simulate fracture             | fracture system                         |
| multiregion coupled model     |                     | divide the flow field into several rectangular areas | clearly expresses the flow characteristics of each region | difficult to simulate the radial flow in the later stage of development |
| multilinear flow model        | Ozkan, Ren        | flow field structure is conjugate ellipse    |                                          | complex boundary conditions             |
| elliptical flow model         | Badazhkov, Zhang   |                                              |                                          |                                        |

The pressure propagation does not reach the supply boundary instantly with the influence of the threshold pressure gradient during the development process, and the flow law in the tight oil reservoir has the characteristics of moving boundary. In view of the multiscale nonlinear flow characteristics of the reservoir matrix, fracture network, and hydraulic fracture caused by stimulated reservoir volume fracturing technology, the pressure propagation is more complex. It is necessary to clarify the dynamic pressure propagation law in a tight oil reservoir.

The non-Darcy flow containing moving boundary conditions in low-permeability reservoirs is highly nonlinear, and it is hard to obtain its accurate analytical solution. Many scholars revealed the moving boundary of the water–oil interface using the finite difference method. Liu obtained the numerical solution of transient pressure of the model by the Douglas–Jones predictor-corrector method. Chen et al. established dual-porosity model and pressure distribution by the simulator. Li developed a fully coupled multidomain and multiphysics models which were solved by using the finite element method and verified against production data from the field. However, the numerical method is limited by the model and computing equipment. On the other hand, many scholars established a semianalytical model for predicting the productivity of fractured well. In view of characteristics of the unconventional reservoir, Zhu et al. developed a mathematical model to study pressure propagation by using steady-state replacement method and material balance law, which can describe the problem more accurately and grasp the essence of the problem better.

The above results provide the basis for the study of the dynamic pressure propagation in tight oil reservoirs. However, the formation pressure gradually decreased with the progress of production, which made tight sandstone show stress sensitivity characteristics by the overburden pressure, especially the different stress sensitivity characteristics in different regions; the above research results are not applicable. Therefore, a mathematical model is established to characterize the multiscale flow in the tight oil reservoir with stimulated reservoir volume fracturing, a calculation method of moving boundary which considers the stress sensitivity in each region is formed, and the law of dynamic pressure propagation is clarified, which provides a theoretical basis for producing reserve evaluation in tight reservoirs.

2. MULTISCALE FLOW CHARACTERISTICS

Tight oil flows through the reservoir matrix, microfractures, artificial fractures, and finally into the wellbore and lifts to the ground in tight oil reservoirs with stimulated reservoir volume development. The difference scales in the flow media formed the characteristics of multiscale flow. Among them, nanopores are widely distributed in tight sandstone reservoirs. The porosity of matrix is generally 4–10%, and the matrix permeability is generally less than 0.3 mD. Largescale complex fracture networks are formed by stimulated reservoir volume fracturing. The size of the matrix throat is between 50 nm and 1 μm. Microfractures derived from hydraulic fracturing range from tens to hundreds of microns. The width of artificial fractures can usually reach millimeter levels. Among them, the preparation and simulation of microfractures is the most difficult, and it is impossible to systematically carry out the multiscale flow experiments. Aiming at the technical limitation, our research group changed the original flat device into an arc-shaped device by changing the force method of Brazilian splitting, and we had made sure the linear load was changed to a surface load and applied to the tight sandstone core, so that the pressure was evenly distributed. The combined use of acoustic emission real-time monitoring technology

Figure 1. Preparation and analysis device of the core with microfractures.

ensures the integrity of the core shape of artificially produced microfractures and lays a solid foundation for studying matrix and matrix-fracture nonlinear flow characteristics.

The influence of the threshold pressure gradient and stress sensitivity on multiscale characteristics have been clarified through these system experiments. The characteristics of threshold pressure gradient and stress sensitivity in matrix and microfracture core are shown in Figures 2 and 3.

2.1. Threshold Pressure Gradient. The threshold pressure gradient is one of the main factors which affected the nonlinear flow characteristics in tight oil reservoirs, and predecessors have done a lot of research work. On the basis of previous research, the author studied the flow law of tight reservoir matrix cores and cores with microfractures and obtained the measured results of the threshold pressure gradient in tight oil reservoirs, as shown in Figure 2. It is shown that the matrix and fractures have nonlinear flow characteristics, and the threshold pressure gradient of the matrix is much
the matrix core and the fractured core are damaged as high as 79.66 and 91.5%, respectively. When the effective stress is simulated by constant back pressure and the confining pressure adjustment. The effective stress is adjusted in turn, and the test permeability is recorded after 1.5–2.5 h of constant pressure. As a result, the measured permeability of matrix cores and matrix-fracture cores were processed dimensionless. It is shown that as the effective stress rises to 15 MPa, the permeability of the matrix core and the fractured core are damaged as high as 79.66 and 91.5%, respectively.

2.2. Stress Sensitivity Characteristics. Stress sensitivity is a property of sandstone, which reflects the permeability damaged with the effective stress. The characteristics of effective stress are simulated by constant back pressure and the confining pressure adjustment. The effective stress is adjusted in turn, and the test permeability is recorded after 1.5–2.5 h of constant pressure. As a result, the measured permeability of matrix cores and matrix-fracture cores were processed dimensionless. It is shown that as the effective stress increases, the core permeability decreases significantly and the decline tends to be gentle. The stress sensitivity characteristic of the microfracture core is stronger than that of the matrix. When the effective stress rises to 15 MPa, the permeability of the matrix core and the fractured core are damaged as high as 79.66 and 91.5%, respectively.

3. MATHEMATICAL MODEL OF MULTIREGION COUPLING FLOW

Stimulated reservoir volume technology is an effective way for tight oil reservoir development, which promotes the expansion of natural microfractures, the shear slip of brittle rocks, and the formation of a staggered fracture network by natural fractures and artificial fractures. It greatly increases the production rate with the stimulated reservoir volume increasing. Therefore, the multiscale complex flow field structure of the reservoir matrix (nanometer level), fracture network (micron level), and hydraulic fracture (millimeter level) is formed. It is necessary to establish a mathematical model to characterize the multiscale nonlinear flow. Zhu et al. established the three region coupling flow model of main fracture, fracture network, and matrix in tight oil reservoirs with stimulated reservoir volume development, which characterized the multiscale flow. Each region corresponds to different scale porous media in the multiscale flow process. Region I is the main fracture which shows the characteristics of linear flow inside the fracture which approximated line confluence; region II is the fracture network; it is characterized by the elliptical flow field which focused on the tip of the main fracture, and taking into account the threshold pressure gradient related the permeability in the fracture network region; the third region is the matrix which has not been stimulated by stimulated reservoir volume; it is characterized by the elliptical flow field with the main fracture tip as the focus, and taking into account the threshold pressure gradient related the matrix permeability. The fracture network region and the matrix region are characterized as the nonlinear flow because of the threshold pressure gradient. More complex nonlinear flow will be shown in the multiregion coupling model.

3.1. Physical Model. The matrix-fracture interaction law and strong nonlinear flow characteristics appeared in tight reservoirs (Figure 4). Based on the equivalent medium model, Zhu et al. established the three region coupling flow model of main fracture, fracture network, and matrix in tight oil reservoirs with stimulated reservoir volume development, which characterized the multiscale flow. Each region corresponds to different scale porous media in the multiscale flow process. Region I is the main fracture which shows the characteristics of linear flow inside the fracture which approximated line confluence; region II is the fracture network; it is characterized by the elliptical flow field which focused on the tip of the main fracture, and taking into account the threshold pressure gradient related the permeability in the fracture network region; the third region is the matrix which has not been stimulated by stimulated reservoir volume; it is characterized by the elliptical flow field with the main fracture tip as the focus, and taking into account the threshold pressure gradient related the matrix permeability. The fracture network region and the matrix region are characterized as the nonlinear flow because of the threshold pressure gradient. More complex nonlinear flow will be shown in the multiregion coupling model.

3.2. Mathematical Model of Multiregion Coupling Nonlinear Flow. Based on the flow field structure divided by the physical model, a multiregion coupling flow mathematical model which considered the different characteristics of each region is established, and the assumptions are as follows: (1) The horizontal direction of the reservoir is an infinite stratum, and the vertical direction has closed boundaries at both ends. (2) Single-phase fluid flow and ignore the effects of gravity. (3) The fracture is assumed as finite conductivity and vertically throughout the reservoir. (4) Consider different threshold pressure gradients in the fracture network region and matrix region. (5) Ignore the effects of temperature.

3.2.1. Joukowski Transformation. In view of the complex boundary of the elliptical flow field structure, the conformal transformation method is one of the most effective ways for solving such complex boundaries formed in the tight oil reservoir with stimulated reservoir volume development. An analytic function is introduced which transforms from the elliptic domain to circular domain (Figure 5), and the original problem is solved by using the inverse transformation.

Figure 2. Characteristics of threshold pressure gradient in matrix and microfracture core.

Figure 3. Characteristics of stress sensitivity in matrix and microfracture core.

Figure 4. Physical model of multiregion coupling flow in tight oil reservoirs.
Introducing the Joukowski function\textsuperscript{35,46} defines the transform as follows
\[
z = \frac{x_f}{2} \left( \frac{w + 1}{w} \right)
\]
where \(z = x + iy\) and \(w = u + iv = M e^{i\theta}\), and based on Euler formula, we can get
\[
x + iy = \frac{x_f}{2} \left( M e^{i\theta} + \frac{1}{M} e^{-i\theta} \right) = \frac{x_f}{2} \left[ M \cos \theta + \left( M - \frac{1}{M} \right) \sin \theta \right]
\]
(2)

Defining \(a = \frac{x_f}{2} \left( M + \frac{1}{M} \right)\) and \(b = \frac{x_f}{2} \left( M - \frac{1}{M} \right)\), we can get
\[
x + iy = a \cos \theta + ib \sin \theta
\]
(3)

We transform the circular domain back to the elliptic domain by the Joukowski function. We can get its inverse transform function as follows
\[
w = \frac{z}{x_f} + \sqrt{z^2 - x_f^2} = \frac{a + b}{x_f}
\]
(4)

The above equation can be used to transform the elliptical flow field structure in the \(z\) plane to the circular radial flow field structure in the \(w\) plane, which simplifies the boundary conditions of complex flow field in the multiregion coupling model. In this way, the outer boundary of region I is transformed to the unit circle on the \(w\) plane, and the outer boundary of region II is transformed into a circle with radius \(r = (a_x + b_y)/x_0\) and the boundary of region III is transformed into a circle with radius \(r = (a_x + b_y)/x_f\) similarly.

### 3.2.2. Mathematical Model of Multiregion Coupling Flow.

The flow characteristics of each region are different, which made their mathematical model of each region different.\textsuperscript{34,33,34}

1. **Main fracture region**

   The main fracture region is the Darcy linear flow inside the artificial fracture. The motion equation and boundary condition are established as follows\textsuperscript{3,37}

   \[
   \begin{align*}
   \frac{v}{x} &= \frac{k_t d\rho}{\mu d\epsilon} \quad &r_n < x \leq x_f \\
   p_{|x=x_0} &= p_w \\
   p_{|x=x_f} &= p_i \tag{5}
   \end{align*}
   \]

   The solution of the pressure distribution in tight oil reservoirs can be expressed as

   \[
p(x) = p_w + \frac{p_i - p_w}{x_f - r_w} (x - r_w)
   \]

   (6)

   The flow rate in the main fracture region is

   \[
   q = \frac{p_i - p_w}{\rho(r_n - r_w)}
   \]

   (7)

2. **Fracture network region**

   The fracture network structure is formed by stimulated reservoir volume fracturing. The flow is characterized as an elliptical flow formed by the formation fluid in the fracture network to the main fracture.\textsuperscript{34} Both fractures and matrix are considered by using the continuous medium method.\textsuperscript{36} The equivalent permeability of the fracture network region is calculated according to the fracture spacing, matrix permeability, and fracture permeability. The threshold pressure gradient played an important role at the motion equation. The governing equation of fracture network region is\textsuperscript{33}

   \[
   \frac{1}{r^2} \int_{\theta_1}^{\theta_2} d\theta \left[ \frac{dp}{dr} - G_n'(k_n) \right] = 0 \quad r_t < r \leq r_n
   \]

   (8)

   where \(G_n'(k_n)\) is the threshold pressure gradient in the \(w\) plane; we assume that the oil near the hydraulic fractures flow along the \(y\)-axis; therefore, the operating range is the averaged minor axis length of the elliptic domain

   \[
   \overline{\rho_n} = \frac{2}{\pi} \int_{\theta_1}^{\theta_2} b_n \sin \theta d\theta = \frac{2b_n}{\pi}
   \]

   Based on the Joukowski transformation, the threshold pressure gradient of the fracture network in \(w\) plane is shown as follows

   \[
   G_n'(k_n) = \frac{\rho_n}{r_n - r_t} G_n(k_n) = \frac{2b_n}{\pi(r_n - r_t)} G_n(k_n) \tag{10}
   \]

   The solution of the pressure distribution in the fracture network region can be expressed as follows

   \[
   p(r) = p_i + G_n'(k_n)(r - r_t) + \frac{p_n - p_i - G_n'(k_n)(r_n - r_t)}{\ln \frac{r}{r_t}} \ln \frac{r}{r_t}
   \]

   (11)

   The flow rate in the fracture network region is as follows

   \[
   q_n = \frac{p_n - p_i - G_n'(k_n)(r_n - r_t)}{2k_n \ln \frac{r_n}{r_t}} \tag{12}
   \]

3. **Matrix region**

   The energy of the matrix region supplies the fracture network region when the pressure spreads to it. Similarly, the governing equation of the mathematical model in matrix area is as follows\textsuperscript{34}

   \[
   \frac{1}{r^2} \int_{\theta_1}^{\theta_2} d\theta \left[ \frac{dp}{dr} - G_n'(k_n) \right] = 0 \quad r_n < r \leq r_e
   \]

   (9)

   \[
   p_{|r=r_n} = p_n
   \]

   \[
   p_{|r=r_e} = p_e \tag{13}
   \]
where $G_m(k_m)$ is the threshold pressure gradient of matrix in the $w$ plane:

$$G_m(k_m) = \frac{r_m - r_n}{r_m - r_n} G_m(k_m) = \frac{2(h_m - h_n)}{\pi(r_m - r_n)} G_m(k_m)$$

(14)

The solution of the pressure distribution in matrix region can be expressed as follows:

$$p(r) = p_n + G_m(k_m) (r - r_n) + \frac{p_e - p_n - G_m(k_m)(r_n - r_n)}{\ln \frac{r_n}{r}} \ln \frac{r_n}{r}$$

(15)

The flow rate in the matrix region is as follows:

$$q_m = \frac{p_e - p_n - G_m(k_m)(r_n - r_n)}{\ln \frac{r_n}{r_n}}$$

(16)

3.3. Pressure Distribution. The stimulated reservoir volume development in tight reservoirs satisfies the flow conservation and the pressure conservation at the interface of each region. Equations 7, 12, and 16 can be used to derive the expression of pressure distribution:

$$p_e = p_l + G_m(k_m)(r_e - r_n) + \frac{p_e - p_n - G_m(k_m)(r_n - r_n)}{\ln \frac{r_n}{r_n}}$$

(17)

(18)

where $A$, $B$, and $C$ is the correlation coefficient:

$$A = k_i k_m \ln \frac{r_e}{r_n}$$

(19)

$$B = k_i k_m \ln \frac{r_n}{r_t}$$

(20)

$$C = k_i k_m \ln \frac{r_t}{r_n}$$

(21)

Substitute eqs 17 and 18 into 6, 11, and 15, we get the pressure distribution in the w plane. Furthermore, the solution of the pressure distribution in elliptical flow field can be obtained by the method of inverse transform.

4.4. Production Rate Prediction Equation. In view of the multiscale flow field by stimulated reservoir volume fracturing development, the pore structure system changed with the dynamic supply boundary. When the dynamic supply boundary has not reached the matrix region ($R_t < r_m$), it appeared as the coupling flow of the main fracture and fracture network; otherwise, it appeared as the coupling flow of main fracture, fracture network, and matrix. The pressure transmitted quickly in the main fracture and its time cost can be ignored. Based on the method of equivalent flow resistance, the multistage production prediction equation in the tight reservoir with stimulated reservoir volume fracturing development can be derived by eqs 7, 12, and 16.

$$Q_1 = \begin{cases} 
q_e + G_m(k_m)(r_e - r_n) & R_t < r_m \\
\frac{p_n - G_m(k_m)(r_n - r_t)}{\frac{\mu Q_f}{2k_m} + \frac{\mu Q_f}{2k_m} \ln \frac{r_n}{r_t}} & R_t \geq r_m 
\end{cases}$$

(22)

The pressure boundary spread quickly in the initial stage of production, which made its flow resistance increase significantly and the flow rate decrease rapidly. The velocity of pressure propagation slowed down when the dynamic supply boundary has reached the matrix region, and its flow resistance continued to increase, but the increase rate tended to be gentle, which made the production rate maintain stable basically. It can be seen that the volume fracturing in tight reservoirs is characterized by rapid declining in the initial stage and stable in the later stage, as shown in Figure 6.

Figure 6. Multistage production in tight oil reservoirs with stimulated reservoir volume.

4.2. Characterization of Stress Sensitivity. As the underground fluid is continuously produced during the development of the oil reservoir, the geostress is released, and the effective stress of the rock skeleton increases which promotes the elastic or plastic deformation of the rock. The flow characteristics change with the shrinkage of the matrix pore volume and the closure of fractures. Pedrosa et al. used an exponential equation to characterize the relationship between permeability and reservoir pressure:

$$k = k_1 e^{\alpha (q - q_0)}$$

(23)
According to the data in Figure 3, we obtained the alpha of each region by parameter matching. The alpha is 0.0961 MPa$^{-1}$ in the matrix and 0.1856 MPa$^{-1}$ in the fracture network and main fracture region.

The average reservoir pressure is calculated by area weighted average method

$$\bar{p} = \frac{1}{A} \int p(r) \cdot 2\pi r \, dr$$ \hspace{1cm} (24)

Similar to eqs 11 and 15, the general expression equation of reservoir pressure distribution which considers the threshold pressure gradient during radial flow is as follows

$$p(r) = \frac{p_{in}}{r_{in}} + G(r - r_{in}) + \frac{p_{out} - p_{in}}{\ln \frac{r_{out}}{r_{in}}} - \frac{G(r_{out} - r_{in})}{\ln \frac{r_{out}}{r_{in}}}$$ \hspace{1cm} (25)

With eqs 24 and 25, the average reservoir pressure in the target region can be obtained.

$$\bar{p} = \frac{p_{out}}{2} - \frac{p_{in}}{2} \cdot \ln \frac{r_{out}}{r_{in}} - \frac{1}{2} G \cdot \frac{r_{out}^2}{2} + \frac{r_{out}^2}{2} + \frac{r_{in}^2}{2} \ln \frac{r_{out}}{r_{in}}$$

$$\bar{p} = \frac{p_{out}}{2} - \frac{p_{in}}{2} \cdot \ln \frac{r_{out}}{r_{in}}$$ \hspace{1cm} (26)

When the inner boundary is the wellbore radius which is much smaller than the radius at outer boundary, a small amount can be omitted. The above equation can be simplified to the average reservoir pressure of the plane radial flow when the threshold pressure gradient is not considered, which verified the accuracy of eq 27.

$$\bar{p} = \frac{p_{out}}{2} - \frac{p_{in}}{2} \cdot \ln \frac{r_{out}}{r_{in}}$$ \hspace{1cm} (27)

4.3. Dynamic Pressure Propagation Law. The production rate at a certain time can be calculated by eq 22. However, the supply boundary transmits during the production process; it makes the characteristics of rapid decline in production with constant bottom-hole pressure. Without doubt, determining the effective supply boundary is crucial for the study of unsteady production prediction. The calculation method of dynamic pressure propagation in tight oil reservoirs is established. Based on the material balance method, the cumulative production rate is equal to the pore volume changed within the effective range of the tight reservoir

$$\sum_{i=1}^{n} Q_i = \int_{r_i}^{R_i} 2\pi r \cdot h \cdot [(\rho\phi)_i - (\rho\phi)] \, dr$$ \hspace{1cm} (28)

where $(\rho\phi)$ is the fluid mass per unit volume, kg/m$^3$.

Solving eq 28

$$\sum_{i=1}^{n} Q_i = \left\{ \begin{array}{ll}
\pi (R_i^2 - r_i^2) \cdot (p_i - p_{m}) \cdot h \cdot \phi \cdot C_t, & r_i \leq R_i < r_n \\
\pi (r_n^2 - r_i^2) \cdot (p_i - p_{m}) + \pi (R_i^2 - r_n^2) \cdot (p_i - p_{m}) \cdot h \cdot \phi \cdot C_t, & R_i \geq r_n
\end{array} \right.$$ \hspace{1cm} (29)

where $C_t$ is the reservoir total compressibility, MPa$^{-1}$. Substituting eqs 26 and 29 into 22, we can solve them to get the only unknown parameter $R_t$. Pay special attention at the first time step; the main fracture region provides the initial production rate.

In view of the nonlinear characteristics in the multiscale flow process, it is difficult to get the analytical solution. The steady-state sequential replacement method is good at solving this equation with the right assumptions. Based on the steady-state sequential replacement method, we considered that the unsteady flow process is the sequential substitution of several stable states, the difference of the stable state at each time step being supply radius. We hold that the solution is infinitely close to the real value when the time step is small enough. Accordingly, the law of dynamic pressure propagation under constant pressure condition is calculated. Specific steps are as follows:

Step 1: Based on the material balance method, eqs 22 and 29 can be used to calculate the dynamic supply radius $R_t$ and production rate $Q$ in the $\omega$ plane at time $t$.
5. RESULTS AND DISCUSSION

5.1. Model Verification. Based on the volume fracturing development case in the Ordos Basin, dynamic supply boundary prediction and its influencing factor analysis are performed.47 The basic parameters are shown in Table 2.

| Parameters                     | Data |
|-------------------------------|------|
| porosity                      | 0.1  |
| matrix permeability           | $3 \times 10^{-5} \mu m^2$ |
| effective thickness           | 10 m |
| tight oil viscosity           | 2.7 mPa·s |
| rock compressibility          | $7 \times 10^{-4} \frac{1}{MPa}$ |
| fluid compressibility         | $4.34 \times 10^{-3} \frac{1}{MPa}$ |

We input the value of all the basic parameters in our model and simulate natural energy development for 2000 days. In Figure 8, we compare the obtained prediction results and the actual oil rate. They are acceptable and have good matching with the field data. Meanwhile, it can be seen that the decreased curve agrees with the characteristic of multiscale flow in Figure 6.

5.2. Model Application. The dynamic supply boundary is predicted changing with time.33–36 It is shown that the dynamic supply boundary gradually increases with time and the increase rate decreases. The increase rate decreases significantly when the dynamic supply boundary reaches the matrix region. The dynamic supply boundary growth rate decreased significantly with the effect of threshold pressure gradient in matrix area on the 415th day (Figure 9).

Reservoir pressure distributions have been the output when simulated natural energy development was performed at the 20th day, the 200th day, and the 2000th day (Figure 10).

It is shown that the flow field of volume fracturing development in tight reservoirs is an elliptical flow field focused on the main fracture. The pressure dropped is mainly concentrated near the main fracture at the 20th day in Figure 11. Because the conductivity in the main fracture region is much greater than the fracture network region, the pressure at the fracture tip is close to the bottom-hole pressure in Figure 10. The pressure has not yet reached the matrix region by natural energy development at the 200th day in Figure 12. Obvious pressure drop is shown at both the direction of the main fracture and the direction of the vertical main fracture when the dynamic supply boundary gradually reaches to the matrix region at the 2000th day in Figure 13. The reservoir pressure has decreased significantly because of the low velocity flow in the matrix region and the pressure field distribution is no longer smooth. It is manifested as the knee at the junction of the matrix region and fracture network region in Figure 10. The pressure drop funnel shows the characteristics of two stages.

5.3. Sensitivity Analysis of Parameters. The pressure propagation law in tight oil reservoirs with stimulated reservoir volume development was revealed.39,40 We analyzed the effect of stress sensitivity, matrix permeability, and drawdown pressure on the dynamic supply boundary.35,36

5.3.1. Effect of Stress Sensitivity on Dynamic Supply Boundary. Natural microfractures often develop in tight oil reservoirs, and the stress sensitivity plays an important role during stimulated reservoir fracturing development, and it is accompanied by different stress sensitivity coefficients in various regions (Figure 3). The natural energy development simulation was performed for 2000 days, and the influence of stress sensitivity characteristics on the dynamic supply boundary was analyzed.

Figure 14 shows that the stress sensitivity has a significant effect on the distance at the dynamic supply boundary. At the 2000th day, the stress sensitivity reduces the pressure propagation distance by 6.27 m in the fracture direction, and the time transmission to the matrix region is delayed by 221 days in Figure 14a. Similarly, the stress sensitivity reduces the distance at the dynamic supply boundary by 17.76 m in the perpendicular fracture direction in Figure 14b.

The reservoir pressure gradually decreases during the depletion process, and its stress sensitivity is significant; it causes the permeability of the fracture network and the matrix to reduce with different degrees. The dynamic supply boundary is significantly reduced. When simulated to the 2000th day, the utilization area decreases from $5.76 \times 10^4$ to $4.42 \times 10^4 \text{m}^2$, and the overall utilization area decreased by 23.3%.

5.3.2. Effect of Matrix Permeability on Dynamic Supply Boundary. The matrix has the characteristics of poor physical properties and complex pore structure in tight oil reservoirs.
The matrix permeability is one of the factors that affect the dynamic supply boundary. We simulate the influence of matrix permeability (0.1, 0.15, 0.2, 0.25, and 0.3 mD) on the dynamic supply boundary during the natural energy development process over a time period of 2000 days. Figure 15 shows that the distances at the dynamic supply boundary are different under different matrix permeabilities. The equivalent permeability of the fracture network region increases with the matrix permeability increased. The time cost to reach the matrix region was shortened from 760 days to 415 days. At the 2000th day, the distance at the dynamic supply boundary extends from 209.3 to 210.8 m in the fracture direction; it extends from 61.7 to 66.7 m in the perpendicular fracture direction.

It can be seen that the dynamic supply boundary gradually increases with the increase of matrix permeability, but it is
mainly reflected by the difference velocity of pressure propagation in the fracture network region. When the dynamic supply boundary reaches the matrix region, the difference in the velocity of pressure propagation and the effective utilization area is insignificant.

5.3.3. Effect of Drawdown Pressure on Dynamic Supply Boundary. Increasing the drawdown pressure is the main way to overcome threshold pressure gradient. By adjusting bottom-hole pressures, we simulate the influence of drawdown pressure (2, 4, 6, 8, and 10 MPa) on the dynamic supply boundary during depletion process over a time period of 2000 days.

Figure 16 shows that the drawdown pressure has a great influence on the distance at the dynamic supply boundary. The
ability to overcome threshold pressure gradient increases with the drawdown pressure increased; it makes the distance at dynamic supply boundary extend from 200.9 to 210.8 m in the fracture direction when the drawdown pressure is greater than 6 MPa (Figure 16a). However, the stress sensitivity effect increased with the bottom-hole pressure decreased, which make the supply radius growth rate significantly reduced. Similarly, the distance at dynamic supply boundary extends from 19.5 to 66.7 m in the perpendicular fracture direction (Figure 16b). It is not enough to overcome the threshold pressure gradient at the fracture network region when the drawdown pressure is lower than 4 MPa, which appears that the dynamic supply boundary has not yet reached the matrix region. It can be seen that the distance at the dynamic supply boundary gradually increases with the drawdown pressure increased, but the growth rate gradually decreases. The reasonable drawdown pressure ranges from 6 to 8 MPa in the Ordos Basin.

6. CONCLUSIONS

In view of the complex flow field structure caused by stimulated reservoir volume fracturing development, a comprehensive and practical mathematical model is established to simulate the multiscale flow, and the pressure distribution equation is derived. The calculation method of dynamic supply boundary in tight reservoirs with stimulated reservoir volume fracturing development has been formed. Through systematical experiments, theoretical research, and numerical calculation, the pressure propagation law in tight reservoirs is clarified, and the influence of stress sensitivity characteristics, matrix permeability, and drawdown pressure on the distance at the dynamic supply boundary in tight oil reservoirs is revealed. The main realization gained is as follows:

1 Multiscale flow characteristics included the threshold pressure gradient, and the stress sensitivity has been revealed through the systematically experiments: the matrix and fractures have nonlinear flow characteristics, and the threshold pressure gradient of the matrix is much larger than that of the fractured core; the core permeability decreases significantly with the increase in the effective stress, and the stress sensitivity characteristic of the microfracture core is stronger than that of the matrix.

2 The three region coupling flow mathematical model of the matrix region, fracture network region, and main fracture region was established in tight oil reservoirs with stimulated reservoir volume fracturing development. It shows that the flow field is a confocal elliptical flow field, which can accurately describe the multiscale complex flow.

3A practical calculation method for the dynamic supply boundary in tight reservoirs with stimulated reservoir volume fracturing development was established. Multiscale flow, production rate decline, and stress sensitivity characteristics are comprehensively considered, and a rapid simulation of the pressure field is realized. It is shown that the dynamic supply boundary gradually increases with time, and the growth rate gradually decreases; the growth rate decreases significantly when it reaches the matrix region; at the same time, the reservoir pressure decreases significantly and the pressure drop funnel shows as the characteristics of two stages.

4 The stress sensitivity has a significant impact on dynamic supply boundary. The reservoir pressure gradually decreases with the development of production, and its stress sensitivity effect is significantly enhanced, which delays the time reached by the matrix region and significantly decreases the utilization area. The stress sensitivity reduces the utilization area by 23.3% at the 2000th day. The role of stress sensitivity cannot be ignored in the assessment of the producing reserves and the production prediction.

5 The matrix permeability has a certain effect on the dynamic supply boundary. The dynamic supply boundary gradually increases with the increase of matrix permeability, but it is mainly reflected by the difference velocities of pressure propagation in the fracture network region. The difference in the velocities of pressure propagation and the effective utilization regions are insignificant when the dynamic supply boundary reaches the matrix region.

6 The drawdown pressure has a great influence on the distance at the dynamic supply boundary. The dynamic supply radius gradually increases with the drawdown pressure increased, but the growth rate of distance at the dynamic supply boundary is significantly reduced. The rational drawdown pressure ranges from 6 to 8 MPa for the target block in Ordos Basin. Rational controlling the drawdown pressure is of great significance for the efficient development of tight oil reservoirs.

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Notes
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NOMENCLATURE

- a: the length of major axis in ellipse region, m
- b: the length of minor axis in ellipse region, m
- $a_2$: half-length of main fracture, m
- $G$: threshold pressure gradient, MPa/m
- $G'$: threshold pressure gradient transformed into w plane, MPa/m
- h: reservoir thickness, m
- M: the radius of circular domain which transformed from elliptic domain, dimensionless
- $\theta$: the angle of rotation during Joukowski transformation, fraction
- r: the equivalent radius in w plane, m
- $\nu$: velocity of porous flow, m/s
- k: permeability in main fracture region, m$^2$
- $\mu$: reservoir fluid viscosity, Pa·s
- $R_e$: the radius of dynamic supply boundary in w plane, m
- $\omega_i$: width of main fracture, m
- Q: production rate, m$^3$/d
- $\alpha$: stress sensitivity coefficient, MPa$^{-1}$
- $p$: pressure, MPa
- A: effective utilization area, m$^2$
- $\rho$: density, kg/m$^3$
- $\phi$: porosity, fraction

SUBSCRIPTS AND SUPERSCRIPTS

- f: fracture
- n: fracture network
- m: matrix
- in: inner boundary
- out: outer boundary
- w: wellbore
- i: initial
- t: time

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