Transient Pressure Analysis of Volume-Fractured Horizontal Wells Considering Complex Fracture Networks and Stress Sensitivity in Tight Reservoirs

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ABSTRACT: Tight reservoirs, as an important alternative for conventional energy resources, have been successfully exploited with the aid of hydraulic fracturing technologies. Because of the inherent ultralow permeability and porosity, tight oil reservoirs generally suffer from the effects of stress sensitivity. Both hydraulic fractures with complex geometries and a high-permeability area known as stimulated reservoir volume (SRV) may be generated by the massive hydraulic fracturing operations. All these bring huge challenges in transient pressure analysis of tight reservoirs. Up till now, although many research studies have been carried out on the transient pressure analysis of volume-fractured horizontal wells in tight reservoirs, unfortunately, there is still a lack of research studies that have taken stress sensitivity, complex fracture networks, and the SRV into consideration, simultaneously. To fill up this gap, this paper first idealizes the reservoir after hydraulic fracturing as two radial composite regions, that is, the unstimulated outer region and the inner SRV. The stress sensitivity is characterized by the variable permeability depending on the pore pressure. A linear source with consideration of the stress sensitivity in the composite reservoir is obtained by the perturbation technique, Laplace transformation, and the flow coupling of two regions. Second, the complex fracture networks are discretized into segments to capture their geometries. A semi-analytical model is finally established and validated by the comparison with previous models. On the basis of our model, six flow stages of volume-fractured horizontal well are identified and special features of each regime are analyzed. The stress sensitivity has a great impact on the later stage of production. The mobility ratio and the SRV radius mainly affect SRV pseudo-steady-state flow period and interporosity flow period in the outer region. Fracture number mainly affects the linear flow in the SRV. Fracture geometries mainly affect linear flow and interporosity flow in the SRV. This study has some significance for well test interpretation and production performance analysis of tight reservoirs.

1. INTRODUCTION

During the oil production, the decrease of formation pressure can result in an increase of effective stress and the reduction of reservoir properties, especially the permeability. This phenomenon known as stress sensitivity will be more obvious in the tight reservoirs. Massive hydraulic fracturing along with the horizontal well drilling is an effective way to exploit the tight reservoirs, which not only can form highly flowing channels but also can generate stimulated reservoir volume (SRV).1 Because of the complex in situ stress and fracturing operations, it can be observed from the microseismogram that hydraulic fractures might be in arbitrary direction and there might be an approximately circular stimulated region in vicinity of the well as illustrated in Figure 1.

So far, lots of experimental techniques and theoretical methods on the stress-sensitive media have been presented, given out important parameters and models to describe the stress-sensitive effect.2−11 Fatt and Davis,6 Fatt,7 and Gray and Fatt8 studied the effect of stress sensitivity on permeability and porosity via experimental study for typical rocks under tri-axial
stresses and found that porosity is less sensitive to pressure drop compared to permeability under reservoir conditions. Vairogs and Rhoades performed more detailed stress-sensitive experiments on rock samples with different initial permeability and concluded that there is a greater degree of permeability reduction under low-permeability conditions. Pedrosa introduced the permeability modulus to establish an equation about the relationship between the permeability and the pressure drop. Kilmer et al.1 and Han et al.2 carried out research studies on stress sensitivity in tight reservoirs by using indoor experimental measures and provided the relational expression for the various permeabilities and the effective pressure. All above fundamental research results provided powerful tools to study the effect of stress sensitivity on transient pressure response and rate performance of fractured horizontal well in tight reservoirs.

There has been a lot of attention to transient pressure response and rate performance of fractured horizontal well in tight reservoirs. Considering the fact that the withdrawal of fluids is mainly from stimulated region, Ozkan et al. proposed a “trilinear flow” model to study the transient pressure behaviors of multistage fractured horizontal wells, with consideration of a limited SRV region around the main fractures. Stalgorova and Matta extended the “trilinear flow” model into a “five-zone” linear model, taking both the SRV and unstimulated outer region into account. With considering the SRV and stress sensitivity, Ji et al. and Wu et al. established multilinear models to study the flow characteristics of fractured horizontal wells in tight reservoirs. However, both the “trilinear flow” and “five region” models rooted in an assumption that the fractures are either perpendicular or parallel to the horizontal wellbore, which indicates that the complex fracture geometry cannot be reflected. Furthermore, in order to obtain the analytical solutions, the flow in different regions is always assumed to be linear, some important flow stages, especially, the radial flow regimes, cannot be observed using these models.

To address these weaknesses, many semi-analytical models without such simplifications have been proposed by treating the reservoirs after hydraulic fracturing as radial composite region. Zhao et al. simplified the SRV into a circular high-permeability area and used the radial composite model to study the pressure-transient response of fractured wells in unconventional reservoirs. Many useful point source and linear source functions in radial composite regions with different boundary conditions were first proposed in their work. Although the flow forms of the fluids were no longer limited to be linear, only transient pressure behaviors of the horizontal well with fractures perpendicular to the wellbore was discussed. On the basis of the source functions proposed in Zhao et al., Jiang et al. further conducted transient rate and pressure analysis for multistage fractured horizontal well in tight oil reservoirs considering SRV, unfortunately, the fractures were still limited to be perpendicular with the wellbore and stress sensitivity was neglected as well in their work. Moreover, Zhao et al., Xu et al. combined the linear source function method and the perturbation technique to take stress sensitivity into consideration when they studied the transient pressure behaviors of horizontal wells, but the complexity of the fracture networks was ignored. Jia et al. presented a comprehensive model combining finite-difference and boundary-element method for the flow behaviors of the volume-fractured horizontal well. Although the irregular geometry of the complex fracture networks and internal and external boundaries were captured in their model, the stress sensitivity was still neglected and the modeling process was complex because of a coupling of various mathematical methods. Considering the stress sensitivity of hydraulic fractures and the reservoirs, Wang et al. proposed semi-analytical models for transient flow behaviors of the fractured horizontal well with complex fracture networks in homogeneous tight reservoirs, while ignoring the property difference between the inner SRV and the outer unstimulated region.

By the combination of the linear source function, perturbation transformation, and Laplace transformation with the discrete fracture model, the semi-analytical model proposed by this paper extends previous work by a simultaneous consideration of the existence of SRV, complex fracture networks after massive hydraulic fracturing, and the stress sensitivity in the tight reservoirs. What is more, this paper discusses the influence of relevant parameters on the transient response of fractured horizontal wells in stress-sensitive tight reservoirs, including stress sensitivity, mobility ratio of the SRV and the outer region, SRV radius, storage coefficient and interporosity factor, fracture number, and fracture geometries. Corresponding solutions can be useful for fracturing design and test interpretation in field practice.

2. MATHEMATICAL MODEL AND SEMI-ANALYTICAL SOLUTION

2.1. Model Descriptions. Microseismic data of a volume-fractured horizontal well with SRV is shown in Figure 1, and the corresponding simplified physical model is shown in Figure 2. The whole reservoir after massive fracturing can be divided into two circle zones with different properties. Specially, the inner zone is the SRV, while the outer zone is the unstimulated region. Other basic assumptions are as follows:

(1) Inner SRV is idealized as dual porosity media to consider the small-scale fractures included the induced fractures and the pre-existing natural fractures. The outer region is treated as dual porosity media because tight oil reservoirs generally contain a certain number of natural fractures.

(2) The complex fracture networks in the SRV consist of hydraulic fractures in arbitrary direction.

(3) Only the stress sensitivity of permeability in the SRV and outer region is taken into consideration, while the porosity is assumed to be constant during the production.
The fluid in the whole reservoirs is simplified to be a single phase and micro compressible, and the seepage of the fluid follows Darcy’s Law.

All hydraulic fractures are vertical and fully penetrate the formation, so the flow pattern in this work is simplified into plane radial flow, ignoring the influence of gravity and capillary force.

Hydraulic fractures and the wellbore have infinite conductivity, and the well is produced at a constant rate and the fluid in the whole reservoirs is simplified to be a single phase and micro compressible, and the seepage of the fluid follows Darcy’s Law.

2.2. Mathematical Model for the Radial Composite System. According to Pedrosa, the pressure-dependent permeability could be expressed as an exponential function of pore pressure, which has

$$k_i(p) = k_0 e^{-\gamma(p_i - \bar{p}_i)}$$  \hspace{1cm} (1)

When the stress sensitivity of natural fractures is considered, the uniform governing equations of natural fractures and matrix can be obtained as follows

$$\frac{1}{r} \frac{\partial}{\partial r} \left( k_0 e^{-\gamma(p_i - \bar{p}_i)} \frac{\partial p_i}{\partial r} \right) - (1 - \omega) \frac{\partial p_m}{\partial t} + \omega \frac{\partial p_i}{\partial t} = \lambda (p_m - p_i)$$

$$= (1 - \omega) \frac{\partial p_m}{\partial t} \hspace{1cm} (2)$$

In eq 1, $k_0$ is the initial permeability of the fracture system in the reservoir, $m^2$; $\gamma$ is the permeability modulus, which is determined by the property of rock geomechanics and always in the range of $10^{-5}$ to $10^{-4}$ Pa$^{-1}$; $p_i$ is the initial reservoir pressure, Pa.

For the convenience and simplicity of formula deducing, some dimensionless parameters are introduced first.

$$P_{m1D} = \frac{2\pi k_h r (p_i - \bar{p}_i); P_{m2D} = \frac{2\pi k_h h}{\mu} (p_i - \bar{p}_i);$$

$$P_{f1D} = \frac{2\pi k_h h}{\mu} (p_i - \bar{p}_i); P_{f2D} = \frac{2\pi k_h h}{\mu} (p_i - \bar{p}_i);$$

$$r_D = r/L; \gamma_D = \frac{q \gamma_D^2}{2\pi k_h h}; t_D = \frac{x_D}{\sqrt{x_D^2 + y_D^2}};$$

$$R_{m1D} = \frac{R_i}{L}; \omega_1 = \frac{\phi_{m1} r_{m1} + \phi_{f1} r_{f1} \gamma_D}{x_D} = x/L;$$

$$\omega_2 = \frac{\phi_{m2} r_{m2} + \phi_{f2} r_{f2} \gamma_D}{y_D} = y/L; t_D = \sqrt{x_D^2 + y_D^2};$$

$$L_{Df} = L_f/L; \omega_{21} = \frac{\phi_{m2} r_{m2} + \phi_{f2} r_{f2} \gamma_D}{x_D}; M_{12} = \frac{k_{m1}}{\mu};$$

$$q_D = \frac{2\pi k_h h (p_i - \bar{p}_i)}{2\pi k_h h (p_i - \bar{p}_i)}; q_{f1} = \frac{\mu}{q}$$

Based on the above dimensionless variables, the transient flow equation for the outer region can be expressed as follows.

$$\frac{\partial^2 p_{2D}}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial}{\partial r_D} \left( \gamma_D \frac{\partial p_{f2D}}{\partial r_D} \right) = \omega_2 M_{12} e^{\gamma_D t} \frac{\partial p_{m2D}}{\partial t} + (1 - \omega_2) \frac{\partial p_{m2D}}{\partial t} = 0 \hspace{1cm} (3)$$

The corresponding outer boundary condition in dimensionless form is

$$P_{2D}\ |_{r_D = 0} = 0 \hspace{1cm} (4)$$

The corresponding initial condition for the outer region in dimensionless form is

$$P_{2D}\ (r_D, 0) = 0 \hspace{1cm} (5)$$

Transient flow equation for the inner SRV can be expressed in dimensionless form as follows

$$\frac{\partial^2 p_{1D}}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial}{\partial r_D} \left( \gamma_D \frac{\partial p_{f1D}}{\partial r_D} \right) = e^{\gamma_D t} \left[ \omega_1 \frac{\partial p_{m1D}}{\partial t} + (1 - \omega_1) \frac{\partial p_{m1D}}{\partial t} \right]$$

$$\lambda_D (p_{m1D} - p_{f1D}) + (1 - \omega_1) \omega_2 \frac{\partial p_{m1D}}{\partial t} = 0 \hspace{1cm} (6)$$

The corresponding initial condition for the SRV in dimensionless form is

$$P_{1D}\ (r_D, 0) = 0 \hspace{1cm} (7)$$

The continuity condition on the interface between the outer region and the SRV in dimensionless form can be expressed as

$$P_{f1D}\ |_{r_D = R_{m1D}} = P_{f2D}\ |_{r_D = R_{m1D}}$$

$$\frac{\partial p_{f1D}}{\partial r_D} |_{r_D = R_{m1D}} = \frac{1}{M_{12}} \frac{\partial p_{f2D}}{\partial r_D} |_{r_D = R_{m1D}} \hspace{1cm} (8)$$

The source function methods can be used to solve the abovementioned partial differential equations. It is assumed.
that there is a linear source fully penetrating the formation with a radius of almost zero in the SRV, the withdrawal of the fluid for the linear source is $q(t)$. The schematic diagram of the linear source in radial composite reservoir is shown in Figure 3.

Figure 3. Schematic diagram of the linear source in the composite reservoir.

According to the characteristic of the Dirac delta function $\delta(t)$, the internal boundary condition of the instantaneous linear source can be expressed as follows

$$\lim_{\epsilon \to 0} 2\pi \eta c \frac{k_1}{\mu_1} \int_0^1 r \frac{\partial p}{\partial r} \bigg|_{r=\epsilon} = -\bar{q} \delta(t)$$

Equation 9 can be simplified as

$$\lim_{\epsilon \to 0} \frac{-\eta c}{\epsilon} \int_0^1 r \frac{\partial p}{\partial r} \bigg|_{r=\epsilon} = -\bar{q} \delta(t)$$

Equations 3 and 6 are strongly nonlinear partial differential equations, which are not convenient to be solved analytically. A perturbation transformation proposed by Pedrosa\textsuperscript{10} can be used to eliminate the nonlinearity. New dimensionless variables $\eta ID$ related to the dimensionless pressure are introduced as follows

$$p_{ID} = \frac{1}{\gamma_D} \ln(1 - \eta ID), \quad j = 1, 2$$

It can be induced that $\eta ID$ and $\eta ID D$ satisfy the following partial differential equations

$$\frac{\partial^2 \eta ID}{\partial r^2} + \frac{1}{r} \frac{\partial \eta ID}{\partial r} + \frac{\partial \eta ID}{\partial t} = \frac{\omega_2}{\gamma_D} \frac{\partial \eta ID}{\partial t} + \frac{\omega_1}{\gamma_D} \frac{\partial \eta ID}{\partial t} + \frac{1}{\gamma_D} \frac{\partial \eta ID}{\partial t} + (1 - \omega_1) \frac{\partial \eta ID}{\partial t}$$

$$\lambda_1 p_{mID} + \frac{1}{\gamma_D} \ln(1 - \eta ID) + (1 - \omega_2) \omega_2 M_1 \frac{\partial \eta ID}{\partial t} = 0$$

$$\frac{\partial^2 \eta ID D}{\partial r^2} + \frac{1}{r} \frac{\partial \eta ID D}{\partial r} + \frac{\partial \eta ID D}{\partial t} = \frac{\omega_1}{\gamma_D} \frac{\partial \eta ID D}{\partial t} + (1 - \omega_1) \frac{\partial \eta ID D}{\partial t}$$

$$\lambda_1 p_{mID} + \frac{1}{\gamma_D} \ln(1 - \eta ID) + (1 - \omega_1) \frac{\partial \eta ID D}{\partial t} = 0$$

Subjecting to the boundary and the initial conditions, respectively, we can get

$$\eta ID(r_D, 0) = 0$$

$$\lim_{\epsilon \to 0} \frac{\partial \eta ID}{\partial t} \bigg|_{r=\epsilon} = -\bar{q} \delta(t)$$

Equation 9 can be simpliﬁed as

$$\eta 2D I = \eta 2DD I_{\gamma = R_{ID}}$$

$$\left. \frac{\partial \eta ID}{\partial t} \right|_{r_0 = R_{ID}} = \frac{1}{M_{12}} \left. \frac{\partial \eta ID D}{\partial t} \right|_{r_0 = R_{ID}}$$

$$\lim_{r_0 \to \infty} \eta 2D I = 0$$

According to the simpliﬁed method proposed by Pedrosa,\textsuperscript{10} because the dimensionless permeability modulus $\gamma_D$ is usually a small value, $\eta ID$ can be expanded as a power series in the parameter $\gamma_D$.

$$\eta ID = \eta ID 0 + \gamma_D \eta ID D + (\gamma_D)^2 \eta ID 2 + (\gamma_D)^3 \eta ID 3 + \ldots$$

$$\frac{1}{1 - \gamma_D} = 1 + \gamma_D \eta ID D + (\gamma_D)^2 (\eta ID 2) + (\gamma_D)^3 (\eta ID 3) + \ldots$$

By substituting eqs 19 and 20 into eqs 12 and 13, we can get a sequence of linear problems that can be solved for $\eta ID 0, \eta ID D$, and so on. According to Yeung et al.,\textsuperscript{25} the zero-order approximation $\eta ID 0$ was accurate enough for pressure analysis.

Following the previous works of Wang et al.,\textsuperscript{21} Liu et al.,\textsuperscript{26} the zero-order perturbation solutions for eqs 12 and 13 can be expressed as

$$\begin{cases}
\frac{\partial^2 \eta ID 0}{\partial r^2} + \frac{1}{r} \frac{\partial \eta ID 0}{\partial r} + \frac{\partial \eta ID 0}{\partial t} = \omega_1 \omega_2 \frac{\partial \eta ID 0}{\partial t} + (1 - \omega_1) \frac{\partial \eta ID 0}{\partial t} \\
\lambda_1 p_{mID} - \eta ID 0 = 0 \\
\lambda_1 \left. \frac{\partial \eta ID 0}{\partial t} \right|_{r_0 = R_{ID}} = 0 \\
\lim_{r_0 \to \infty} \eta ID 0 = 0
\end{cases}$$

Accordingly, the boundary and the initial conditions become

$$\lim_{r_0 \to R_{ID}} \frac{\partial \eta ID 0}{\partial t} \bigg|_{r_0 = R_{ID}} = -\bar{q}_D \delta(t)$$

$$\eta ID 0(r_D, 0) = \eta ID 0(r_D, 0)$$

$$\left. \frac{\partial \eta ID 0}{\partial t} \right|_{r_0 = R_{ID}} = \frac{1}{M_{12}} \left. \frac{\partial \eta ID 0}{\partial t} \right|_{r_0 = R_{ID}}$$

The general solutions of partial differential eqs 21 and 22 can be obtained by Laplace transformation.

$$\eta ID 0 = A_1 \bar{q}_D \left( r_D, \sqrt{\frac{2}{s_1}}(s) \right) + B_1 K_0 \left( r_D, \sqrt{\frac{2}{s_1}}(s) \right)$$

$$\eta ID 0 = A_2 \bar{q}_D \left( r_D, \sqrt{\frac{2}{s_2}}(s) \right) + B_2 K_0 \left( r_D, \sqrt{\frac{2}{s_2}}(s) \right)$$
Here, \( s \) is the Laplace variables, \( I_\nu(x), K_\nu(x) \), \( \nu = 0, 1 \) are the \( \nu \)-order first and second modified Bessel functions, respectively; \( A_I, B_I, A_J, B_J \) are the constant coefficients of the general solution determined by the internal and outer boundary conditions.

Taking Laplace transformation of the internal boundary condition 23, we can get

\[
\lim_{\epsilon \to 0} \left. \frac{\partial \tilde{f}_i}{\partial \tilde{D}} \right|_{\tilde{r}_0} \tilde{q}_0 = -\tilde{q}_0
\]

As \( \lim_{\tilde{r}_0 \to 0} \tilde{f}_i(s)[A_I\tilde{r}_0\tilde{f}_i(s)] = 0 \), then \( B_1 = \tilde{q}_D \). With boundary condition given in eq 26, we can get

\[
\lim_{\tilde{r}_0 \to \infty} \tilde{\eta}_{D0} = \lim_{\tilde{r}_0 \to \infty} \left. \{A_I\tilde{r}_0\tilde{f}_i(s) + B_I K_0(\tilde{r}_0 \tilde{f}_i(s)) \} \right|_{\tilde{r}_0} = 0
\]

, as \( \lim_{\tilde{r}_0 \to \infty} \tilde{f}_i(s) \to \infty \), then \( A_2 = 0 \).

With the continuity conditions on the interface between the outer region and the SRV, that is, eq 24 and 25, we can get

\[
A_I K_0(\tilde{r}_0 \tilde{f}_i(s)) + B_I K_0(\tilde{r}_0 \tilde{f}_i(s)) \]

\[
= B_2 K_0(\tilde{r}_0 \tilde{f}_i(s))
\]

\[
M_{i2}[A_I \tilde{r}_0 \tilde{f}_i(s) I_1(\tilde{r}_0 \tilde{f}_i(s)) - B_1 \tilde{f}_i(s) K_0(\tilde{r}_0 \tilde{f}_i(s))]
\]

\[
= -B_2 \tilde{f}_i(s) K_0(\tilde{r}_0 \tilde{f}_i(s))
\]

As \( B_1 = \tilde{q}_D \), then the only unknowns of eqs 31 and 32 are \( A_I \) and \( B_2 \). As \( B_1 = \tilde{q}_D \), then the only unknowns of eqs 31 and 32 are \( A_1 \) and \( B_2 \), and we can solve the linear equation system represented by eqs 31 and 32 to obtain \( A_I \) and \( B_2 \) simultaneously.

We first take ratios of the two sides of eqs 31 and 32 to eliminate \( B_2 \):

\[
\frac{A_I K_0(\tilde{r}_0 \tilde{f}_i(s)) + \tilde{q}_D K_0(\tilde{r}_0 \tilde{f}_i(s))}{M_{i2}[A_I \tilde{r}_0 \tilde{f}_i(s) I_1(\tilde{r}_0 \tilde{f}_i(s)) - \tilde{q}_D \tilde{f}_i(s) K_0(\tilde{r}_0 \tilde{f}_i(s))]} \]

\[
= -B_2 \tilde{f}_i(s) K_0(\tilde{r}_0 \tilde{f}_i(s))
\]

Then we can get

\[
A_I = \{\tilde{q}_D M_{i2} \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)} ) K_0(\tilde{r}_0 \sqrt{f_i(s)} ) \}
\]

\[
- \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)} ) K_0(\tilde{r}_0 \sqrt{f_i(s)} ) \}
\]

\[
/\{M_{i2} \sqrt{f_i(s)} I_1(\tilde{r}_0 \sqrt{f_i(s)} ) K_0(\tilde{r}_0 \sqrt{f_i(s)} ) \}
\]

\[
+ \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)} ) I_0(\tilde{r}_0 \sqrt{f_i(s)} ) \}
\]

(34)

Finally, by substituting eq 34 into eq 27, we can get

\[
\tilde{\eta}_{D0} = \tilde{q}_D [K_0(\tilde{r}_0 \sqrt{f_i(s)}) + a I_0(\tilde{r}_0 \sqrt{f_i(s)})]
\]

(36)

\[
\alpha = \{M_{i2} \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)}) K_0(\tilde{r}_0 \sqrt{f_i(s)}) \}
\]

\[
- \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)}) K_0(\tilde{r}_0 \sqrt{f_i(s)}) \}
\]

\[
/\{M_{i2} \sqrt{f_i(s)} I_1(\tilde{r}_0 \sqrt{f_i(s)}) K_0(\tilde{r}_0 \sqrt{f_i(s)}) \}
\]

\[
+ \sqrt{f_i(s)} K_0(\tilde{r}_0 \sqrt{f_i(s)}) I_0(\tilde{r}_0 \sqrt{f_i(s)}) \}
\]

(35)

Equation 37 is a 3D linear source solution for the two-zone composite reservoir considering the stress-sensitive effects of the reservoir.

2.3. Solutions for the Complex Fracture Networks.

The 3D linear source fully penetrating the formation can be simplified as the point source in the \( X-Y \) plane. Assuming that the dimensionless coordinate of the point source location is \((x_d, y_d)\) in the \( X-Y \) plane, then the dimensionless pressure at the dimensionless coordinate point \((x_d, y_d)\) caused by the point source can be written in a more general form

\[
\tilde{\eta}_{id} \approx \tilde{q}_D \tilde{\eta}_{D0} = \tilde{q}_D \tilde{\eta}_{D0} = \tilde{q}_D [K_0(\tilde{r}_0 \tilde{f}_i(s)) + a I_0(\tilde{r}_0 \tilde{f}_i(s))]
\]

(37)

Following the methods proposed by Jia et al., for complex fracture networks in the homogeneous reservoirs, in order to capture the complex geometries of fractures. The complex fracture networks should first be divided into segments in different directions as shown in Figure 4. Each segment can be treated as a uniform flux plane source with the arbitrary angle as shown in Figure 5. As the fractures fully penetrate the formation, according to Jia et al., the 3D flow problems in the formation can be simplified into 2D problems as shown in Figure 6.
that all hydraulic fractures are divided into pressure response caused by each fracture segment. We assume networks can be calculated by utilizing the superposition of pressure response in the reservoir caused by the fracture networks satisfy the superposition principle, which indicates that the dimensionless pressure drop at the midpoint of fracture segments is the same and all equal to the zero-order perturbation solution of the bottom hole pressure drop \( \eta_{\text{wD}} \).

\[
\eta_{\text{wD},j} = \sum_{i=1}^{N} q_{Dj} / \eta_{\text{ID},i,j} \tag{40}
\]

Because of the assumption that the hydraulic fractures and the wellbore have infinite conductivity, the pressure drop of the fracture segments is the same and all equal to the dimensionless wellbore pressure drop \( \eta_{\text{wD}} \).

\[
\sum_{j=1}^{N} \eta_{\text{ID},i,j} - \eta_{\text{wD}} = 0 \tag{41}
\]

The constant production rate boundary condition is given in the Laplace domain

\[
\sum_{j=1}^{N} q_{Dj} = 1 / s \tag{42}
\]

Applying eq 41 to all the segments of the complex fracture networks, we can get \( N \) equations correlating \( q_{D1}, q_{D2}, q_{D3}, \ldots, q_{D2N} \). Combined with the constant production rate condition given in eq 42, a total of \( N + 1 \) equations are obtained, and the associated matrix form can be written as

\[
\begin{bmatrix}
\eta_{\text{ID},1,1} & \eta_{\text{ID},1,2} & \eta_{\text{ID},1,3} & \ldots & \eta_{\text{ID},1,N} - 1 & q_{D1} \\
\eta_{\text{ID},2,1} & \eta_{\text{ID},2,2} & \eta_{\text{ID},2,3} & \ldots & \eta_{\text{ID},2,N} - 1 & q_{D2} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
\eta_{\text{ID},N,1} & \eta_{\text{ID},N,2} & \eta_{\text{ID},N,3} & \ldots & \ldots & q_{D2N} \\
1 & 1 & 1 & \ldots & 1 & 0
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
\ddots \\
\ddots \\
0 \\
1 / s
\end{bmatrix}
\tag{43}
\]

The zero-order perturbation solution of the bottom hole pressure and dimensionless flux of each fracture segment in the Laplace space can be obtained by solving the eq 43. Then, following the methods proposed by Van Everdingen and Hurst,28 and Mukherjee and Economides,29 the zero-order perturbation solution of the bottom hole pressure in the Laplace space considering the wellbore storage \( C_D \) and the skin factor \( S \) is obtained

\[
\eta_{\text{wD}}(S, C_D) = \frac{s\eta_{\text{wD}} + S}{s + C_D^{-2}[s\eta_{\text{wD}} + S]} \tag{44}
\]

Finally, by using the numerical inversion methods proposed by Stehfest,30 the zero-order perturbation solution of the bottom hole pressure in real space is obtained, and the real dimensionless bottom hole pressure \( p_{\text{wD}} \) can be obtained by eq 11.

### 3. MODEL VERIFICATION

As mentioned above, previous models have not taken the stress sensitivity, complex fracture networks, and the SRV into consideration, simultaneously, so some simplifications need to be imposed in order to validate our model with the previous ones.

Zongxiao et al.31 have established a pressure analysis model for multiple fractured horizontal wells (MFHWs) in homogeneous and stress-sensitive reservoirs. Further analysis of the proposed model in this work reveals that if we make the inner SRV has the same physical properties with the outer region, the solution for MFHWs in homogeneous and stress-sensitive reservoirs can be obtained. To verify the correctness of our...
model, comparison is made with the model proposed by Zongxiao et al.31 The case is a fractured horizontal well with 5 fractures perpendicular to wellbore in stress-sensitive tight oil reservoirs as shown in Figure 7. The other parameters used for simulation are listed in Table 1.

Another case presented here for model verification is for MFHWs in tight gas reservoirs with SRV (Figure 8). Zhao et al.1 proposed a semi-analytical model for MFHWs in unconventional gas reservoirs with SRV based on radial composite assumption. If the intersection angle between wellbore and hydraulic fractures is set as 90° and the stress sensitivity is neglected in this paper, the dimensionless pressure solutions presented in this work will be the same with dimensionless pseudo-pressure solutions for MFHWs in unconventional gas reservoirs obtained by Zhao et al.1 The values of parameters used for comparison can be found in the Table 1 of Zhao et al.1

As shown in Figures 7 and 8, there is a good agreement of transient pressure response between our model and these two models, which indicates the correctness of our model.

4. RESULTS AND DISCUSSIONS

4.1. Transient Pressure Behavior Analysis. Typical pressure response curves of a volume-fractured horizontal well with complex fracture networks considering the influence of the SRV and the stress sensitivity are shown in Figure 8. The fracture distribution and geometry of the complex fracture networks can be seen in Figure 2. We take the reference length \( L = 100 \) m. The values of the relevant parameters used in our model are as follows: \( M_1 = 4, \omega_0 = 0.2, \omega_1 = 0.1, \omega_{11} = 0.5, R_D = 10, \gamma_D = 0.05, C_D = 0.001, S = 0.1 \). By analyzing the log-log graphs of dimensionless wellbore hole pressure (\( p_{wD} \)) and its derivative (\( \frac{dp_{wD}}{d\ln(t_D/C_D)} \)) versus dimensionless times, we find that approximately six flow stages can be identified.

Stage I: wellbore storage and skin effect flow. This is a relatively common flow stage. The wellbore storage coefficient and the skin representing the flow choking between the hydraulic fractures and the wellbore can be obtained by analyzing the characteristic of pressure and pressure derivative curves in this stage. The detailed explanation of this stage can be found in Chen et al.,22 Agarwal et al.,32 and Kuchuk et al.33

Stage II: the formation linear flow in the inner SRV. In this flow regime, because of the high permeability of the complex fracture networks, hydraulic fractures can be treated as linear sinks, and liquid enters the hydraulic fractures in the directions perpendicular to the fracture faces. The typical feature of this flow behavior is that a 1/2-slope straight line (Figure 9) occurs on the dimensionless derivative pressure curve.1

Stage III: inter-porosity flow between the fracture system and the matrix system due to the dual porosity assumption in the SRV. In this stage, fluid in the matrix system flows into the fracture system. The fluid supply of the matrix system slows down the pressure depletion evidently. The typical characteristic is that there is a “recess” on the pressure derivative curves.

Stage IV: pseudo-steady flow in the SRV. The stress sensitivity begins to take effects in this regime; the pressure wave reaches the boundary of the SRV. However, because of

![Figure 7. Comparison between the model in this paper and that in Zongxiao et al.](image)

![Figure 8. Comparison between the proposed model and that in Zhao et al.](image)

![Figure 9. Typical curves of pressure response for volume-fractured horizontal well in stress-sensitivity formation.](image)
the lower permeability of the unstimulated region, there is not enough fluid supply in the outer region. The flow characteristic in this stage is essentially reflective of boundary-dominated flow.  

This is mainly because of the pressure interference between the fracture networks and the property difference between the SRV and the outer region. The fracture networks and boundary of the SRV dominates the pressure responses. The similar flow stage is also discussed by Song and Economides, when they studied transient pressure behavior trends. 

Stage V: inter-porosity flow between the fracture system and the matrix system in the outer region. Because of the pre-existing natural fractures in the tight oil reservoirs, when the pressure waves reach the outer region, there are fluids fed from the matrix to the natural fracture in the outer region. This stage is marked by a “concave” on the pressure derivative curve. The effects of stress sensitivity on the transient pressure response become evident in this stage.

Stage VI: pseudo-radial flow in the entire system. In this period, fluid in outer region flows into SRV in the radial direction, the outer-zone dominates the system. The stress sensitivity has strongly affected the fluid flow in this flow regime. According to Zhao et al. and Jiang et al., the pressure derivative response will exhibit a horizontal line with a value of $M_{12}/2$ in the two-zone composite reservoirs without stress sensitivity. However, because of the stress sensitivity, the value of the dimensionless pressure derivative in this stage is greater than $M_{12}/2$.

It should be noted that characteristics of the above flow stages can be affected by various factors, such as the physical properties of the SRV and the outer region, the stress sensitivity, the hydraulic fracture distribution, and geometry in the SRV. In practice, not all flow periods would appear on type curves in a single situation. Therefore, effects of key variables on the typical curves need to be further studied.

### 4.2. Sensitivity Analysis

In order to further study the transient pressure behaviors of the volume-fractured horizontal wells with complex fracture networks in stress-sensitive tight reservoirs, sensitivity analysis is conducted in this section to analyze the effect of important parameters on the typical pressure response curves.

#### 4.2.1. Effect of Stress Sensitivity

Figure 10 shows the effects of stress sensitivity on the pressure derivative curves. The values of relevant parameters are listed as follows: $L = 100$ m, $M_{12} = 4$, $\omega_1 = 0.5$, $R_{1D} = 12$, $N = 36$, $\omega_2 = 0.2$, $\omega_3 = 0.1$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.01$, $S = 0.1$. Three cases were studied in which the dimensionless permeability modulus $\gamma_D$ is equal to 0.03, 0.05, and 0.08, respectively (seen from Figure 10). It can be seen from Figure 10 that as the dimensionless permeability modulus increases, the dimensionless pressure and its derivative curves rise gradually, and the stress sensitivity mainly affects the flow behaviors at the middle and later stages. In stress-sensitive reservoirs, as the fluid is produced, the gradual reduction of formation pressure will result in a decrease of the permeability of the fracture system while a growing of pressure depletion. When the dimensionless permeability modulus increases to a certain value, the pressure derivative curve rises up significantly in later periods, showing the characteristic of the closed boundary.

#### 4.2.2. Effect of the Mobility Ratio of the SRV and the Outer Region

Figure 11 illustrates the effects of mobility ratio of the SRV and the outer region on pressure and derivative curves. The values of relevant parameters are listed as follows: $L = 100$ m, $\gamma_D = 0.03$, $\omega_1 = 0.5$, $R_{1D} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.01$, $S = 0.1$, while the mobility ratio of the SRV and the outer region, $M_{12}$ is 2, 4, 8, individually. It can be seen from Figure 11 that the initial mobility ratio, $M_{12}$, has great influence on the flow behaviors of the middle to later time, including pseudo-steady-state flow in the SRV, outer-region interporosity flow, and pseudo-radial flow periods. As $M_{12}$ decreases, the duration of SRV pseudo-steady-state flow period will be shortened and the starting time of the interporosity flow period in the outer region will be advanced. It is mainly because the mobility ratio determines flow capacity contrast of the SRV and outer zone. A larger $M_{12}$ indicates a lower flow capacity of the outer zone and a larger flow capacity contrast between the SRV and the outer region. Therefore, the pressure and derivative response-associated outer zone will surely enlarge; the curves of the transient response will rise in interporosity flow and pseudo-radial flow periods in the outer zone.

#### 4.2.3. Effect of SRV Radius

Figure 12 illustrates the effect of SRV radius on the transient behaviors. The values of relevant parameters are listed as follows: $L = 100$ m, $M_{12} = 4$, $\omega_1 = 0.5$, $\gamma_D = 0.05$, $R_{1D} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.01$, $S = 0.1$, and the dimensionless SRV radius $R_{1D}$ is 8, 12, and 15, respectively (Figure 12). It can be seen from Figure 12 that the radius of the SRV can affect all the flow stages after the interporosity flow periods. The larger SRV radius has (1) a later end of interporosity flow in the SRV; (2) a postponed beginning of pseudo-steady flow in the SRV; and (3) the lower
values of dimensionless pressure and its derivatives in outer-zone pseudo-radial flow periods. All these phenomena might provide useful information to identify the sizes of SRV after massive hydraulic fracturing. Figure 12 also shows that the larger the SRV radius, the smaller the dimensionless pressure and its derivatives. Smaller dimensionless pressure indicates lower pressure depletion in the formation, which is beneficial to obtain a high production rate.

4.2.4. Effect of Storage Ratio and InterPorosity Factor. Figures 13 and 14 show the effect of storage ratio $\omega_1$ and interporosity $\lambda_1$ of the SRV on the transient behavior. The values of the parameters related to the Figure 13 are listed as follows: $L = 100$ m, $M_{12} = 2$, $\omega_{21} = 0.5$, $\gamma_D = 0.05$, $R_{ID} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-4}$, $C_D = 0.001$, $S = 0.1$, and the values of $\lambda_1$ for comparison are $10^{-3}$, $10^{-2}$, and $10^{-1}$ individually. Figures 13 and 14 show that $\omega_1$ and $\lambda_1$ mainly affect the degree and time of interporosity flow from matrix to induced fractures system in the SRV, respectively. Smaller $\omega_1$ indicates greater contrast of the storage capacity between induced fractures system and matrix, the “concave” which reflects the interporosity flow becomes more obvious. $\lambda_1$ reflects the ability of the fluid to flow from the matrix to the induced fractures system in the SRV. The larger the $\lambda_1$ is, the earlier the interporosity flow will happen. The larger $\omega_1$ and $\lambda_1$ usually means better degree of hydraulic fracturing, which is beneficial to the production.

Figures 15 and 16 show the effects of storage ratio $\omega_2$ and interporosity $\lambda_2$ of the outer region on the transient behavior. The values of the parameters related to the Figure 15 are listed as follows: $L = 100$ m, $M_{12} = 2$, $\omega_{21} = 0.5$, $\gamma_D = 0.03$, $R_{ID} = 12$, $\omega_1 = 0.2$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.001$, $S = 0.1$, the values of $\omega_2$ for comparison are 0.01, 0.05, and 0.1, individually. The values of the parameters associated with Figure 16 are listed as follows: $L = 100$ m, $M_{12} = 2$, $\omega_{21} = 0.5$, $\gamma_D = 0.03$, $R_{ID} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-2}$, $C_D = 0.001$, $S = 0.1$, the values of $\lambda_2$ for comparison are $10^{-3}$, $10^{-4}$, and $10^{-5}$, individually. Figure 15 shows storage ratio $\omega_2$ in the outer region, which mainly affects the interporosity flow and pseudo-radial flow periods in the outer region, as the increase of $\omega_2$, dimensionless pressure and its derivatives will be lower, the depth of the “recess” on the...
pressure derivative curves will be shallower. Figure 15 shows that the interporosity flow factor $\lambda_2$ mainly affects beginning time of interporosity flow from natural fracture system to matrix system in the outer region, the larger the $\lambda_2$, the faster the transition flow (mass exchange) between matrix system and the natural fracture system, the earlier the interporosity flow stage shows up.

4.2.5. Effect of Fracture Number. Three cases with different number of hydraulic fractures shown in Figure 17 are studied in this section to identify the effect of fracture number on the transient behaviors. The values of relevant parameters are listed as follows: $L = 100 m$, $M_{12} = 4$, $R_{1D} = 10$, $\omega_{21} = 0.5$, $\gamma_{D} = 0.05$, $R_{1D} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.001$, $S = 0.1$. As shown in Figure 17, fracture number mainly affects the linear flow in the SRV, with the increasing of the fracture numbers, the dimensionless pressure and its derivatives will be lower because of the interference of adjacent fractures. More hydraulic fractures mean higher permeability around the wellbore and more contact area with the formation for well, as a result, the flow resistance in the vicinity of the wellbore will be smaller, which is beneficial to obtain high production rate.36,37

4.2.6. Effect of Fracture Geometry of the Complex Fracture Networks. Because of the irregular geological processes and uncertainties caused by hydraulic fracturing operation, the geometries of fracture networks are usually complex.25 Here, we also study the effect of fracture geometry on the transient behaviors. Two cases with different fracture geometries, that is, the orthogonal fracture networks and nonorthogonal fracture ones, are studied in this subsection. The configurations of the two complex fracture networks and the transient pressure and derivative curves are illustrated in Figure 18. Both of two fracture networks have the same total fracture length and fracture numbers. The values of relevant parameters are listed as follows: $L = 100 m$, $M_{12} = 4$, $R_{1D} = 10$, $\omega_{21} = 0.5$, $\gamma_{D} = 0.05$, $R_{1D} = 12$, $\omega_1 = 0.2$, $\omega_2 = 0.1$, $\lambda_1 = 10^{-2}$, $\lambda_2 = 10^{-4}$, $C_D = 0.001$, $S = 0.1$.

As seen in Figure 18, the fracture geometry mainly affects linear flow and interporosity flow in the SRV. The non-orthogonal fracture networks have a smaller dimensionless pressure than that of the orthogonal one in this stage, illustrating that complex fracture geometry is beneficial for fluid production. When other parameters are determined, the volume fractured well with the nonorthogonal fracture network has a shorter linear flow and an earlier beginning of the interporosity in the SRV, which indicates an earlier pressure interference between the fractures. These phenomena might be useful when we need to distinguish the nonorthogonal fracture network from the orthogonal one.

5. CONCLUSIONS

A semi-analytical model is proposed for volume-fractured horizontal wells with SRV and complex fracture networks in tight oil reservoirs. The transient pressure and pressure derivative curves are also established. The principal contributions in this work are summarized as follows:

[1]. By using the perturbation technique and Laplace transformation, a linear source with consideration of stress sensitivity and SRV is obtained. The fracture networks are divided into fracture segments to capture the complex geometries, meanwhile, the pressure drop caused by the fracture segment in arbitrary direction can be calculated by integrating the linear source along these segments. The solution of transient pressure behaviors for the volume-fractured horizontal well with SRV and complex fracture networks in stress-sensitive tight reservoirs is finally obtained by the principle of superposition.

[2]. Approximately, six transient behaviors can be identified on the basis of the calculation results of our model: the wellbore storage and skin effect flow, the formation linear flow in the inner SRV, interporosity flow in the SRV, Pseudo-steady flow in the SRV. Interporosity flow from the matrix to the natural fracture in the outer region and the pseudo-radial flow in the entire system. The stress sensitivity has a great impact on the later stage of production, specifically pseudo-steady flow in the SRV, interporosity flow in the outer region and the pseudo-radial flow in the entire system.

[3]. The mobility ratio of the SRV and the outer region mainly affect the duration of SRV pseudo-steady-state flow period and the starting time of the interporosity flow period in the outer region. The SRV radius can influence the ending time of interporosity flow in the SRV, the beginning time of pseudo-steady flow in the SRV and the values of dimensionless pressure and its derivatives in outer-zone pseudo-radial flow periods.

[4]. Storage ratio and interporosity factor of the SRV mainly affect the degree and time of interporosity flow from the
matrix system to induced fractures system in the SRV, respectively. The larger storage ratio and interporosity factor of the SRV usually means better degree of hydraulic fracturing, which is beneficial to the production. Storage ratio and interporosity of the outer region mainly influence the interporosity flow and pseudo-radial periods in the outer region.

Fracture number mainly affects the linear flow in the SRV. Fracture geometries mainly affect linear flow and interporosity flow in the SRV. The nonorthogonal fracture networks yield a smaller dimensionless pressure than the orthogonal one in these stages. The volume-fractured well with nonorthogonal fracture networks results a shorter linear flow and an earlier beginning of the interporosity in the SRV, which might be useful when we need to distinguish the nonorthogonal fracture network from the orthogonal one.

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NOMENCLATURE

c_{m,2} matrix compressibility of the SRV, Pa\(^{-1}\)
c_{m,2} outer zone matrix compressibility, Pa\(^{-1}\)
c_{f,1} fracture compressibility of the SRV, Pa\(^{-1}\)
c_{f,2} outer zone matrix compressibility, Pa\(^{-1}\)
c_{D,1} dimensionless wellbore-storage coefficient
h\(_i\) Formation thickness, m
k_{f,1} initial fracture permeability of the SRV, m\(^2\)
k_{f,2} initial fracture permeability of the outer region, m\(^2\)
k_{m,1} matrix permeability of the SRV, m\(^2\)
k_{m,2} outer zone matrix permeability, m\(^2\)
M_{12} initial mobility ratio between the SRV and outer zones
N\(_i\) number of discrete fracture segment
p_{m,1} matrix pressure of the SRV, Pa
p_{f,1} fracture pressure of the SRV, Pa
p_{m,2} matrix pressure of the outer region, Pa
p_{f,2} fracture pressure of the outer region, Pa
p_{m,1D}, p_{f,1D} dimensionless matrix pressure of the SRV
p_{m,2D}, p_{f,2D} dimensionless fracture pressure of the SRV
p_{m,2D} initial formation pressure, Pa
p_{wD} Wellbore pressure, Pa
p_{wD} wellbore pressure
q\(_f\) flow flux of the linear source, m\(^3\)/s
q\(_{fD}\) flow rate of the fracture segment j, m\(^3\)/s
q\(_{fD}\) dimensionless flow rate of the linear source

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