Pressure Transient Analysis for Hydraulically Fractured Wells with Changing Conductivity in Stratified Reservoirs: Case Study in Xinjiang Oilfield

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Abstract: The oil development has been oriented toward deep-layer reservoirs and the commingling production and the separate-layer fracturing are important development methods. Currently, limited attention is given to the pressure transient analysis (PTA) of the fractured wells located in a stratified reservoir. Moreover, the proppant is very difficult to move inside the hydraulic fracture in the deep-layer reservoir, leading to the uneven fracture conductivity along the hydraulic fracture and increasing the complexity of PTA. To fill this gap, this work presented a fully analytical well test model for hydraulically fractured wells with changing fracture conductivity in stratified reservoirs, which is convenient to be used for interpreting the recorded pressure data from the oilfield due to its analytical nature. The establishment of this model is based on the trilinear flow model, Duhamel theorem, and pressure superposition principle. A systematic verification is conducted to ensure the validity of the proposed model. Furthermore, we offer a sensitivity analysis to investigate the effect of crucial parameters on pressure and pressure derivative, including the fracture extension, fracture conductivity, transmissibility factor, and storativity factor. Finally, a field case of a four-layer fractured well from Xinjiang Oilfield in Junggar Basin is interpreted to demonstrate the practicability of the presented model.

1. INTRODUCTION

China has directed the petroleum exploration to deep-layer unconventional oil and gas reservoirs to meet the increasing demand for energy.1−9 In recent years, several largely deep-layer oil and gas reservoirs have been discovered in Western China, among which Xinjiang Oilfield Company achieved exploration breakthrough in the Nanyuan, Mahu, and Shawan districts of Junggar Basin and commercially developed deep-layer tight reservoirs.10−15

The deep-layer tight reservoirs contain multiple oil layers. Due to the huge investment costs needed for deep-layer drilling, the oilfield adopts commingling production for stratified reservoirs to reduce the number of drilling wells. Moreover, considering that the permeability of deep-layer reservoirs is extremely low, hydraulic fracturing stimulation is applied to each layer of stratified reservoirs to increase the production rate of oil well (separate-layer fracturing). Several papers have presented the pressure transient analysis (PTA) models of un-fractured multilayer systems where different situations are considered.16−19 However, limited attention was given to the fractured wells located in a stratified reservoir. Bennett et al.20 presented the analytical solutions for the response at a well intercepting a layered reservoir without interlayer communication. Osman21 developed a model of a well located in a multilayered infinite acting reservoir and crossed by a finite conductivity vertical fracture. Gao et al.22 presented the derivative responses of commingled systems with mixed inner and outer boundary conditions (BCs), including un-fractured and infinite-conductivity fractured wells. Osman and Abou-Kassem23 evaluated the effect of BCs on pressure behavior of finite-conductivity fractures in bounded stratified reservoirs. Manrique and Poe24 presented a unique methodology designed for the evaluation and optimization of multi-fractured wells in layered reservoirs using rate-transient analyses and historical production data. Ali et al.25 applied an analytical elliptical flow solution to analyze production data from hydraulically fractured vertical tight gas wells producing from multilayer reservoirs.

However, the issue of PTA for hydraulically fractured wells in deep-layer stratified reservoirs is more complicated. Proppant movement inside hydraulic fracture is always
restricted during the process of hydraulic fracturing, causing its accumulation near the wellbore segment and poorly propped at the tip of the hydraulic fracture.26 This problem is even worse in deep-layer reservoirs. Once the hydraulic fracturing completed and the oil wells are put into production, the width of poorly propped fracture segments would be rapidly decreased, causing that the conductivity at the fracture tip decreases sharply. Soliman27 analyzed the effect of changing conductivity on production based on the simplified bilinear flow assumptions for single-layer reservoir. Lolon et al.28 clearly pointed out that the effect of poorly propped segments should be considerable for making better interpretations. Gonzalez-Chavez and Cinco-Ley29 investigated the behavior of a well with variable finite-conductivity and skin fracture for a vertical fracture in an infinite slab reservoir. Wanjing and Changfu30 presented a semi-analytical model for a well with variable finite-conductivity fracture and non-Darcy effect in an infinite reservoir.

To the best of our knowledge, the well test model for hydraulically fractured wells with changing conductivity in stratified reservoirs has rarely been reported. For better matching the actual situations encountering in Xinjiang Oilfield and solving the Oilfield’s well test problems, this work considers investigating the pressure behavior of a well located in stratified reservoirs, which is intercepted by the finite-conductivity vertical fracture with changing conductivity. From the points of calculation efficiency and interpretation accuracy of field data, the mathematical model is developed based on the classical trilinear flow model presented by Lee and Brockenbrough.31 Following that, the model is validated to ensure its accuracy for general practice and the sensitivity analysis is conducted on crucial parameters, including the fracture extension, fracture conductivity, transmissibility factor, and storativity factor. Finally, a field case of hydraulically fractured well in the stratified reservoir from Xinjiang Oilfield is interpreted to demonstrate the practicability of the presented model.

2. METHODOLOGY

2.1. Physical Model. As shown in Figure 1, the stratified reservoir contains \( m \) oil layers, which are intercepted by hydraulic fractures. Every layer is homogeneous and isotropic, containing the single-phase, slightly compressible fluid with viscosity \( \mu \). The initial formation pressure is \( p_i \) and the porosity, permeability, thickness, total compressibility, wellbore storage, skin factor, and production contribution of the layer \( n \) are \( \varphi_n, k_n, h_n, c_n, C_n, S_n \) and \( q_n \) respectively. Considering the real situations of Xinjiang Oilfield, every layer is separated by interlayers with no communication. Other basic assumptions for facilitating the model establishment are also given as follows:

(a) The permeability of deep-layer reservoirs is extremely low. It is difficult to observe the pseudoradial flow regime during the real test duration. To achieve a high calculation efficiency, this work considers applying the trilinear flow model to present the flow behavior of finite-conductivity fractured wells.

(b) The hydraulic fracture is symmetrical along wellbore with permeability \( k_{f0} \) height \( h_{f0} \) half-length \( x_{f0} \) and width \( w_{f0} \). There is no flow at the fracture tip.

(c) The fracture conductivity along the hydraulic fracture is usually uneven due to the difficulty of proppant movement in deep-layer reservoirs. For the practical purpose, this work considers using two dimensionless fracture conductivities (i.e., \( F_{c1D} \) and \( F_{c2D} \) ) to characterize the propped and poorly propped fracture segments, as shown in Figure 1b.

(d) The fluid obeys Darcy’s flow and the gravity and capillary force are neglected in this work.

2.2. Mathematical Model. Following Lee and Brockenbrough’s work,31 only a quadrant of the flow domain in layer \( n \) will be considered due to the symmetry. We further divided the flow domain into regions I, II, and III. Region I represents the hydraulic fracture. The flow is dominated by the \( x \)-direction flow. It is worth to mention that region I contains two linear-flow regions due to the changing fracture conductivity, as shown in Figure 1b. If the fracture is regarded as a line sink, the flow in region II will be approximated by the \( y \)-direction flow and supply to region I. Similarly, the flow in region III is approximated by the \( x \)-direction flow for a short time period and supply to region II. This visualization of the flow behavior is reasonable for fluid flow before the pseudoradial flow period. Note that in our model, the fracture storage effect and fracture skin effect are not considered.

The diffusivity equation for linear flow is now formulated in terms of dimensionless variable in region I of layer \( n \). Note that we neglect the fluid compressibility inside the fracture because the hydraulic fracture volume is very small.32,33

\[
\begin{align*}
\text{For } 0 < x_D < R_{D0}, & \quad \frac{\partial^2 \Pi_{1Dn1}}{\partial x_n^2} + \frac{2}{\alpha_{F_{c1Dn1}}} \frac{\partial \Pi_{2Dn1}}{\partial y_n} \bigg|_{y_n=0} = 0 \\
\text{For } R_{D0} < x_D < \alpha_{c0}, & \quad \frac{\partial^2 \Pi_{1Dn2}}{\partial x_n^2} + \frac{2}{\alpha_{F_{c2Dn2}}} \frac{\partial \Pi_{2Dn2}}{\partial y_n} \bigg|_{y_n=0} = 0
\end{align*}
\]

\[\tag{1}\]
Table 1. Dimensionless Variable and Definition<sup>a</sup>

| dimensionless variable | definition | dimensionless variable | definition |
|------------------------|------------|------------------------|------------|
| dimensionless pressure | \( P_{3Dn} = \frac{\Omega (p_i - p_f)}{1.842 Q_{in}} \) | dimensionless time | \( t_d = \frac{3.6 \times 10^4 (\Omega t)_{D2}}{\phi B \mu B \pi_i} \) |
| dimensionless production contribution | \( q_{3Dn} = \frac{Q}{Q_{in}} \) | dimensionless fracture length | \( \alpha_n = \frac{x_n}{\pi_i} \) |
| dimensionless transmissibility factor | \( \lambda_n = \frac{(kh)_{n}}{B_f} \) | dimensionless storativity factor | \( \alpha_n = \frac{\phi (kh)}{\mu B} \) |
| dimensionless wellbore storage | \( C_D = \frac{C}{2 \pi n f \mu \pi_i} \) | dimensionless fracture conductivity | \( F_{3Dn} = \frac{k_n \omega_n}{k_{in} \pi_i} \) |
| dimensionless coordinates | \( x_0 = \frac{x}{\pi_i}, \ y_0 = \frac{y}{\pi_i} \) | dimensionless propped fracture length | \( R_{3Dn} = \frac{x_{Dn}}{\pi_i} \) |

<sup>a</sup>Note that the definitions \( \overline{kh} = \sum_{i=1}^{m} (kh)_i, \overline{\phi B} = \sum_{i=1}^{m} (\phi B)_i, \overline{\pi} = \sum_{i=1}^{m} (\pi_i) \) are used in Table 1.

The initial conditions (ICs) are
\[ P_{3Dn}(s \to \infty) = P_{3Dn}^{(s \to \infty)} = 0 \]  
(2)

The inner and outer BCs are
\[ \frac{\partial P_{3Dn}}{\partial x_D} \bigg|_{x_{D0}=0} = -\frac{\pi}{sF_{3Dn} \alpha_n \lambda_n} \]  
(3)
\[ \frac{\partial P_{3Dn}}{\partial x_D} \bigg|_{x_{D}=\alpha_n} = 0 \]  
(4)

The diffusivity equation for linear flow is formulated in terms of dimensionless variable in region II of layer \( n \) \( (0 < x_D < \alpha_n, 0 < y_D < \infty) \).

\[ \frac{\partial^2 P_{3Dn}}{\partial x_D^2} + \frac{1}{\alpha_n} \frac{\partial P_{3Dn}}{\partial x_D} \bigg|_{x_{D0}=0} = \frac{\alpha_n}{\lambda_n} F_{3Dn}^{\pi} \]  
(5)

The ICs are
\[ P_{3Dn}(s \to \infty) = 0 \]  
(6)

The inner and outer BCs are
\[ P_{3Dn}^{(s \to \infty)} = P_{3Dn}^{(s \to \infty)}(0 < x_D < R_{Dn}, \ y_D = 0) \]  
(7)
\[ P_{3Dn}^{(s \to \infty)} = P_{3Dn}^{(s \to \infty)}(R_{Dn} < x_D < \alpha_n, \ y_D = 0) \]  
(8)

The diffusivity equation for linear flow is formulated in terms of dimensionless variable in region III of layer \( n \) \( (\alpha_n < x_D < \infty, 0 < y_D < \infty) \).

\[ \frac{\partial^2 P_{3Dn}}{\partial x_D^2} = \frac{\alpha_n}{\lambda_n} F_{3Dn}^{\pi} \]  
(9)

with ICs
\[ P_{3Dn}(s \to \infty) = 0 \]  
(10)

and BCs
\[ P_{3Dn} = P_{3Dn}^{(s \to \infty)}(x_D = \alpha_n) \]  
(11)
\[ P_{3Dn}(x_D = \infty) = 0 \]  
(12)

The dimensionless definitions in equation system, eq 1 through eq 12, are listed in Table 1.

We solve the partial-difference equation system from the start of region III. The pressure solution is obtained with the auxiliary ICs and BCs, given by

\[ P_{3Dn} = \sum_{i=1}^{m} (\pi_i) \]  
(13)

Making the derivation of eq 13 and substituting it into eq 5, the pressure solution is obtained with the auxiliary ICs and BCs in region II, given by

\[ P_{3Dn} = P_{3Dn}^{(s \to \infty)}(0 < x_D < R_{Dn}) \]  
(14)

where \( A \) is defined by

\[ A = \sqrt{\frac{\alpha_n}{\lambda_n} s / \alpha_n + \frac{\alpha_n}{\lambda_n}} \]  
(15)

Making the derivation of eq 14 and substituting it into eq 1, we can obtain the following equations with the auxiliary ICs and BCs in region I, given by

\[ C_B_1 - C_B_1 = \frac{\pi}{sF_{3Dn} \alpha_n \lambda_n} \]  
(16)

where \( B_1 \) and \( B_2 \) are defined by

\[ B_1 = \sqrt{\frac{2A}{\alpha_n F_{3Dn}}}, \quad B_2 = \frac{2A}{\alpha_n F_{3Dn}} \]  
(17)

Equation 16 can be written as a matrix form, given by

\[ \begin{bmatrix} C_B_{11} - C_B_{12} \end{bmatrix} = \frac{\pi}{sF_{3Dn} \alpha_n \lambda_n} \]  
(18)

\[ \begin{bmatrix} C_B_{11} e^{R_{B_{11}}} + C_B_{12} e^{R_{B_{12}}} \end{bmatrix} = D_{11} e^{R_{B_{11}}} + D_{12} e^{R_{B_{12}}} \]  
(19)

\[ \begin{bmatrix} F_{3Dn}(C_B_{11} e^{R_{B_{11}}} - C_B_{12} e^{R_{B_{12}}}) \end{bmatrix} = F_{3Dn}^{(s \to \infty)}(D_{11} B_1 e^{R_{B_{11}}} - D_{12} B_2 e^{R_{B_{12}}}) \]  
(20)

\[ D_1 B_1 e^{R_{B_{11}}} - D_2 B_2 e^{R_{B_{12}}} = 0 \]  
(21)

where \( B_1 \) and \( B_2 \) are defined by

\[ B_1 = \sqrt{\frac{2A}{\alpha_n F_{3Dn}}}, \quad B_2 = \frac{2A}{\alpha_n F_{3Dn}} \]  
(22)
model match well with that of the trilinear flow model, indicating the correctness of the proposed model.

3.2. Sensitivity Analysis. Taking two-layer reservoir as an illustration, this subsection conducts sensitivity analysis on several crucial parameters that are focused by oil engineers, including the transmissibility factor, storativity factor, fracture extension (\( r_f = x_{fr}/x_{1} \)), and fracture conductivity. The wellbore storage and skin effect are not considered in the sensitivity analysis.

3.2.1. Transmissibility Factor. Three cases are designed to investigate the effect of the transmissibility factor on pressure and pressure derivative. The results are presented in Figure 3.

Although the transmissibility factor has an evident effect on production contribution of single layer as has been recognized by many literature, \(^{18,23}\) it did not show an evident effect on pressure behavior. Nevertheless, with the difference of \( \lambda_t \) and \( \lambda_2 \) increasing, one can find that the pressure and pressure derivative increase slightly. We can further conclude from the results of Figure 3 that the stronger heterogeneity due to a change in transmissibility leads to more increase of the pressure and pressure derivative.

3.2.2. Storativity Factor. The effect of the storativity factor on pressure and pressure derivative is also investigated. Three cases are designed in this subsection. The results are presented in Figure 4. With the difference of \( \omega_1 \) and \( \omega_2 \) increasing, one can find that the pressure and pressure derivative increase slightly. We can further conclude from the results of Figure 4 that the stronger heterogeneity due to a change in storativity leads to more increase of the pressure and pressure derivative.

Figure 2. Comparison of the proposed model and Lee and Brockenbrough's model under different dimensionless fracture conductivity. (a) Pressure results, (b) pressure derivative results.

Figure 3. Effect of the transmissibility factor on pressure and derivative.

Figure 4. Effect of the storativity factor on pressure and derivative.

\[
\begin{align*}
B_i = & -B_i & 0 & 0 & C_1 \\
& e^{B_{DS}} & 0 & -e^{B_{DS}} & C_2 \\
F_{D1} & B_1 & e^{B_{PS}} & 0 & e^{B_{PS}} \\
& 0 & 0 & 0 & 0 \\
& 0 & 0 & 0 & 0
\end{align*}
\]

Solving eq 18, we can obtain the values of \( C_1, C_2, D_1, \) and \( D_2 \). Eventually, the pressure function \( F_{D1} \) in the Laplace domain can be written as

\[
F_{D1} = C_1 + C_2
\]

If the wellbore storage and skin effect are considered (here, we consider that every layer has different wellbore storage coefficients and skin factors), we obtain the following equation based on the Duhamel theorem and pressure superposition principle, given by \(^{34}\)

\[
F_{Dn} = \frac{1 + C_{D}^2 \sum_{i=1}^{m} F_{1D1} \frac{S_{i}}{\lambda_i}}{s F_{1D1} + \frac{S_{i}}{\lambda_i}}
\]

Finally, the bottom-hole pressure is obtained with the flowrate condition \( \sum_{n=1}^{m} F_{D1} = 1/s \) in the Laplace domain, given by

\[
F_{Dn} = \frac{1}{s} \left( \sum_{n=1}^{m} \frac{1 + C_{D}^2 \sum_{i=1}^{m} F_{1D1} \frac{S_{i}}{\lambda_i}}{s F_{1D1} + \frac{S_{i}}{\lambda_i}} \right)^{-1}
\]

and Stehfest numerical inversion method is used to obtain \( F_{Dn} \) in the time domain. \(^{35}\) It deserves to clarify that total wellbore storage should be \( C_D = \sum_{n=1}^{m} C_{Dn} \) in this work.
3.2.3. Fracture Extension. We designed three different cases \((r_2 = 1, r_2 = 10, r_2 = 30)\) to investigate the effect of the fracture extension on pressure and derivative, as shown in Figure 5. The fracture extension affects the lasting time of bilinear and linear flow. The bilinear and linear flow would last longer with a larger fracture extension.

3.2.4. Poorly Propped Fracture Conductivity. We designed three different cases \((F_{cD^2} = 160, F_{cD^2} = 60, F_{cD^2} = 10)\) to investigate the effect of the poorly propped fracture conductivity on pressure and derivative, as shown in Figure 6. The poorly propped fracture conductivity affects the lasting time of bilinear flow. The bilinear flow would last longer with a lower poorly propped fracture conductivity. Moreover, the pressure and derivative increase with the decrease of the poorly propped fracture conductivity, while this effect becomes nil after linear flow.

4. CASE STUDY

In recent years, Xinjiang Oilfield companies have advanced the exploration to deep-layer unconventional reservoirs. Several reservoirs with complex geological structures, and complex fluids have been discovered in Junggar Basin, which will increase the oil and gas production rate in the future. We choose the Mahu-district reservoir as the study area to verify the applicability of the developed model. The Mahu-district reservoir is a deep-layer reservoir with buried depth more than 4 km. The permeability of the rock matrix is very low, and hence, a large number of oil wells is stimulated by separate-layer fracturing. In this subsection, we will use the proposed model to interpret the recorded buildup pressure data of well P1.

As shown in Figure 7, well P1 intercepted a four oil layers. Four oil layers are all fractured after two rounds of hydraulic fracturing operations. The first fracturing operation is conducted on two oil layers ranging from 4056 to 4059 and 4066.5 to 4068.5 m. The second fracturing operation is conducted on remaining two oil layers ranging from 4082 to 4085 and 4087 to 4090 m. The production rate of well P1 is 17 S m\(^{-3}\)/d. The other basic parameters of reservoir and oil well are given in Table 2. We apply the proposed model to interpret the pressure data of well P1. It can be seen clearly from Figure 8 that the theoretical curves match the recorded transient pressure and derivative data. The interpretation results are given in Table 3. The average fracture half-length is 68.1 m, indicating that the effect of hydraulic fracturing stimulation is good. The average reservoir permeability is ~0.35 mD.

5. CONCLUSIONS

The deep-layer reservoirs generally adopt the separate-layer fracturing and commingling production. However, the proppant is usually difficult to move inside the hydraulic fracture in the deep-layer reservoir during the hydraulic fracturing operation, leading to the decrease of fracture conductivity at the fracture extreme. For giving the suitable PTA method to solve the well test problem encountered in Xinjiang Deep-Layer Oilfield, this work presented an analytical well test model of hydraulically fractured wells with changing conductivity in stratified reservoirs. The contributions and conclusions of this work can be summarized as follows.

- An analytical well test model for hydraulically fractured wells with changing conductivity in stratified reservoirs has been presented. The model is fully analytical and hence it is convenient to be applied to solve the well test problem of deep-layer reservoirs.
- The solution is simple and reliable for short-time analysis. When the test pressure data exhibit the radial flow regime, the proposed model is not applicable.
- The heterogeneity among layers will lead to an increase of the pressure drop and pressure derivative. The stronger heterogeneity can lead to more increase of the pressure drop and pressure derivative.
- The poorly propped fracture conductivity affects the lasting time of bilinear flow. The bilinear flow would last longer with a lower poorly propped fracture conductivity. Moreover, the pressure and derivative increase with the decrease of the poorly propped fracture conductivity.
conductivity, while this effect becomes nil after linear flow.

- A case study of hydraulically fractured well in stratified reservoir is conducted in the Xinjiang Oilfield of Junggar Basin, which indicates that the proposed model is feasible to analyze the formation parameters of stratified reservoirs.

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**Notes**

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**NOMENCLATURE**

- \( w_{nf} \): hydraulic fracture width of layer \( n \), m
- \( k_{nf} \): hydraulic fracture permeability of layer \( n \), \( 10^{-3} \) \( \mu \)m²
- \( h_{nf} \): hydraulic fracture half-length of layer \( n \), m
- \( h_{nf} \): hydraulic fracture height of layer \( n \), m

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**Table 2. Reservoir and Well P1 Parameters**

| parameters                | unit   | layer 1 | layer 2 | layer 3 | layer 4 |
|---------------------------|--------|---------|---------|---------|---------|
| oil viscosity             | cP     | 1.2     | 1.2     | 1.2     | 1.2     |
| reservoir thickness       | m      | 3       | 3       | 2       | 3       |
| oil compressibility       | MPa⁻¹  | 0.001   | 0.001   | 0.001   | 0.001   |
| reservoir porosity        | %      | 7.2     | 7.2     | 7.2     | 7.2     |
| oil volume factor         |        | 1.128   | 1.128   | 1.128   | 1.128   |

**Table 3. Interpretations Results of Well P1**

| parameters                | unit   | layer 1 | layer 2 | layer 3 | layer 4 |
|---------------------------|--------|---------|---------|---------|---------|
| wellbore storage coefficient | m³/MPa | 0.53    |         |         |         |
| skin factor               |        | 0       | 0       | 0       | 0       |
| reservoir permeability    | \( 10^{-3} \) \( \mu \)m² | 0.41    | 0.37    | 0.31    | 0.25    |
| fracture half-length      | m      | 79.6    | 69.3    | 63.6    | 59.9    |
| fracture conductivity (\( D \)) |     | 113.6   | 97.8    | 101.6   | 88.6    |
| poorly propped half-length | m      | 9.4     | 13.2    | 15.0    | 13.6    |
| poorly propped conductivity (\( D \)) | | 62.9    | 58.3    | 52.6    | 46.7    |
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