Research Article

Rate Transient Analysis for Multistage Fractured Horizontal Well in Tight Oil Reservoirs considering Stimulated Reservoir Volume

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A mathematical model of multistage fractured horizontal well (MsFHW) considering stimulated reservoir volume (SRV) was presented for tight oil reservoirs. Both inner and outer regions were assumed as single porosity media but had different formation parameters. Laplace transformation method, point source function integration method, superposition principle, Stehfest numerical algorithm, and Duhamel’s theorem were used comprehensively to obtain the semianalytical solution. Different flow regimes were divided based on pressure transient analysis (PTA) curves. According to rate transient analysis (RTA), the effects of related parameters such as SRV radius, storativity ratio, mobility ratio, fracture number, fracture half-length, and fracture spacing were analyzed. The presented model and obtained results in this paper enrich the performance analysis models of MsFHW considering SRV.

1. Introduction

Development of unconventional gas and oil has accelerated in recent years as conventional reservoirs have become increasingly difficult to find and produce [1–3]. Unconventional resources mainly include shale gas and oil, coal bed methane, tight gas and oil, and heavy oil. As one part of “unconventionals,” tight oil has garnered a lot of attention both in North American and Asia. Some of the noteworthy tight oil plays in North America include the Barnett, Haynesville, Marcellus, Eagle Ford, and Bakken. In China, tight oil also distributes widely such as in Ordos, Junggar, Songliao, Sichuan, and Qaidam Basin. The amount of reserves is about (80–100) × 10⁶ t [4–7]. To economically produce these hydrocarbons, unconventional methods are required. As an effective technique, multistage fractured horizontal well (MsFHW) has been widely used due to its advantages, such as creating high flow channels for liquids to flow into the well and increasing drainage area.

The creation of large complex fracture networks by hydraulic fracturing is imperative in many unconventional reservoirs by microseismic mapping observation. These networks are defined as stimulated reservoir volume (SRV) [8, 9]. The fracture networks can happen when the differences between the principle stresses are small. SRV benefits oil or gas production because of its high conductivity [10, 11]. Some tight oil or gas reservoirs such as Eagle ford, Sulige, and Barnett have obtained high production by applying MsFHW with SRV [12–15].

To study flow mechanisms of MsFHW with SRV, both analytical and numerical methods are used. (1) Analytical method: Ozkan’ research group [16–19] proposed the “trilinear” model to study MsFHW performance. Pressure transient analysis was obtained in unconventional gas reservoirs. Stalgorova and Mattar [20, 21] improved the trilinear flow model. Five regions were defined to simulate the stimulated reservoir volume. In their model, SRV was simplified into a simulated region of limited width. Both “trilinear” model
and “five regions” models are based on the assumption that flow obeys “linear flow” in different regions. This assumption may ignore some flow regimes for MsFHW. Then, Ketineni and Ertekin [22] used equivalent flow model to describe SRV. In their model, reservoir was approximated as composite naturally fractured. The mathieu modified functions were used to solve the elliptical flow problem and some key factors were analyzed, such as mobility ratio, diffusivity ratio, storativity ratio, and interporosity flow coefficient ratios. Similar to this model, Zhao et al. [23] used a circular region to characterize the SRV in tight gas reservoir and the pressure transient response was given considering the effect of SRV. (2) Numerical simulation method: Mayerhofer et al. [8, 15] used numerical simulator to characterize SRV explicitly. Impacts of fracture network properties including fracture network size, network density, fracture conductivity, matrix permeability, and gaps in the network on well performance were studied. Meyer and Bazan [24] provided the foundation for predicting the behavior of discrete fracture networks. Wang et al. [25] used numerical simulator to study flow regimes considering SRV. Five regimes were divided and the characteristics in each regime were given.

All above work is meaningful to understand MsFHW performance with SRV. To our best knowledge, there are few models which can successfully calculate the performance behavior including pressure transient analysis (PTA) and rate transient analysis (RTA) for MsFHW with SRV in tight oil reservoirs. We try to solve this problem using the composite reservoir model. Lots of work has been done on RTA or PTA for composite reservoirs [26–29]. These studies mainly focused on vertical well or horizontal well and few are related to multistage fractured horizontal well. In our paper, we extended the composite model to MsFHW with SRV in tight oil reservoirs. We assumed the inner region was a single porosity medium to characterize SRV by equivalent continuum model [30, 31]. Another contribution in our work is that we try to obtain the solution with point function. Line source function was obtained by point function integration. Compared with the line source solution proposed by Zhao et al. [23] which can only be used to fully penetrating fracture, point function is more practical for partially penetrating fracture or planar/bending fracture. Besides, we try to give the flow regimes for MsFHW and parameters effect analysis which is meaningful for well performance diagnosis. This paper is organized as follows: in Section 2, we established the composite model to describe the SRV for tight oil reservoirs; in Section 3, the point source function was obtained and used for semianalytical solution of the proposed model; in Section 4, the pressure transient analysis (PTA) and rate transient analysis (RTA) curves for MsFHW were discussed and the effects of related parameters were analyzed as well.

2. System Description

2.1. Physical Model. The schematic diagram for MsFHW with SRV is shown in Figure 1. The reservoir has two regions: inner and outer region, which have different reservoir properties. The inner region is a medium including matrix and induced fracture. The equivalent continuum model concept is used to describe the inner region as a single porosity medium which has high flow capacity. The outer region is another single porosity medium which is not influenced by hydraulic fracturing. The model assumptions are as follows: (1) the outer region of a circular reservoir is infinite and the inner region radius is \( r_1 \); (2) the reservoir is horizontal with uniform thickness of \( h \) and original pressure \( p_i \); (3) for the inner region, the horizontal permeability is \( K_{h1} \), the vertical permeability is \( K_{h2} \), the compressibility is \( C_{21} \), and the porosity is \( \phi_{1} \); while for the outer region, they are \( K_{h2}, K_{h2}, C_{21}, \) and \( \phi_{2} \). (4) The influence of gravity and capillary forces are ignored; (5) Wellbore storage effect and formation damage are taken into account. The purpose of hydraulic fracturing is to create high conductivity around the wellbore that means inner region conductivity is higher than outer region conductivity. The left picture of Figure 1 shows the geology schematic after hydraulic fracturing. After hydraulic fracturing, permeability near the fractures will increase because the high flow channels (region in the green circle) form near the multistage fractured horizontal well. The outer region (region out of the green circle) is not affected by hydraulic fracturing. Thus the flow capacity is lower than the inner region. This analysis suggests the scenario that the MsFHW completely in the inner region should be considered (Figure 1). The proposed model is effective when conductivity capacity around the well improves greatly after hydraulic fracturing. It is worth noting that this paper assumes the inner region is a circle which is used to characterize the SRV. In fact, the SRV is rather complex and has no regular shape in tight oil reservoirs. On the other hand, the inner region is assumed as an equivalent continuum single porosity model which has high conductivity, so the induced fracture cannot be characterized explicitly. It is necessary to conduct some further researches considering the above issues. These are some limitations of the model.

2.2. Mathematical Model. With radial cylindrical coordinate system, the flow equation can be expressed as follows.

Flow equation in inner region is

\[
1 \frac{1}{r} \frac{\partial}{\partial r} \left( k_{h1} \mu \frac{\partial p_1}{\partial r} \right) + \frac{1}{r^2} \frac{k_{h1}}{\mu} \frac{\partial^2 p_1}{\partial \theta^2} + \frac{k_{h1}}{\mu} \frac{\partial^2 p_1}{\partial z^2} = \phi_{1} \frac{\partial p_1}{\partial t} \quad (0 < r \leq r_1).
\]

Flow equation in outer region is

\[
1 \frac{1}{r} \frac{\partial}{\partial r} \left( k_{h2} \mu \frac{\partial p_2}{\partial r} \right) + \frac{1}{r^2} \frac{k_{h2}}{\mu} \frac{\partial^2 p_2}{\partial \theta^2} + \frac{k_{h2}}{\mu} \frac{\partial^2 p_2}{\partial z^2} = \phi_{2} \frac{\partial p_2}{\partial t} \quad (r_1 < r < \infty).
\]

Inner boundary condition is

\[
\lim_{r \to 0} \frac{4\pi \sqrt{k_{h1} k_{h2}}}{\mu} r^2 \frac{\partial p_1}{\partial r} = -\bar{q} \quad \text{point source in inner region.}
\]
Using the dimensionless variables and Laplace transformation to (1)–(5), the following equations can be derived:

\[
\frac{1}{r_D^2} \frac{\partial}{\partial r_D} \left( r_D \frac{\partial \overline{p}_{D1}}{\partial r_D} \right) + \frac{1}{r_D^2} \frac{\partial^2 \overline{p}_{D1}}{\partial z^2_{1D}} + \frac{\partial^2 \overline{p}_{D1}}{\partial z^2_{1D}} = \eta u \overline{p}_{D1} \tag{6}
\]

\[
(0 \leq r_D \leq r_{1D}),
\]

\[
\frac{1}{r_D^2} \frac{\partial}{\partial r_D} \left( r_D \frac{\partial \overline{p}_{D2}}{\partial r_D} \right) + \frac{1}{r_D^2} \frac{\partial^2 \overline{p}_{D2}}{\partial z^2_{2D}} + \frac{\partial^2 \overline{p}_{D2}}{\partial z^2_{2D}} = u \overline{p}_{D2} \tag{7}
\]

\[
(r_{1D} \leq r_D \leq \infty).
\]

Inner boundary is

\[
\lim_{r_D \to 0} \frac{2M}{r_D^3} \frac{\partial \overline{p}_{D1}}{\partial z_{1D}} = -\frac{\overline{q}}{q_\infty} \text{ point source in inner region.} \tag{8}
\]

Outer boundary is

\[
\frac{\partial \overline{p}_{D1}}{\partial z_{1D}} = \frac{\partial \overline{p}_{D2}}{\partial z_{2D}} = 0, \quad z_{1D} = 0 \text{ or } h_D,
\]

\[
\overline{p}_{D2} = 0, \quad r_D = \infty. \tag{9}
\]

Interface condition is

\[
\frac{\partial \overline{p}_{D1}}{\partial r_D} = \frac{1}{M} \frac{\partial \overline{p}_{D2}}{\partial r_D}, \quad r_D = r_{1D},
\]

\[
\tag{10}
\]

where \(\overline{q}\) is the point source, \(m^3/s\).

3. Model Solution

3.1. Solution Method. From the characteristics of the Bessel functions and the point source functions in pure medium
described previously [32, 33], pressure distribution in the inner region can be expressed as follows when the point source is in the inner region:

\[ p_{NI} = \frac{\tilde{q}_\mu}{2\pi k_{th} h} \]

\[ \times \left[ \sum_{k=\infty}^{+\infty} I_k (\sqrt{\eta} \mu r_D') K_k (\sqrt{\eta} \mu r_D) \right. \]

\[ \times \cos (\theta - \theta') + 2 \sum_{n=1}^{+\infty} \cos n\pi \frac{z_{1D}}{h_{1D}} \cos n\pi \frac{z_{1D}'}{h_{1D}} \]

\[ \left. \times \sum_{k=\infty}^{+\infty} I_k (\xi \nu r_D') K_k (\xi \nu r_D) \cos (\theta - \theta') \right], \]

(11)

where

\[ \xi = -C_{kn} I_k (\xi \nu r_D'), \]

\[ C_{kn} = \frac{M \xi K'_k (\xi \nu r_D') K_k (\xi \nu r_D) - \xi K'_k (\xi \nu r_D') K_k (\xi \nu r_D)}{M \xi l'_k (\xi \nu r_D') K_k (\xi \nu r_D) - \xi l'_k (\xi \nu r_D') K'_k (\xi \nu r_D')}, \]

(12)

where \((r_D, \theta, z_{1D})\) is the pressure observation point and \((r_D', \theta', z_{1D}')\) is the point source position.

3.2. Continuous Point Sources in Tight Oil Reservoirs considering SRV. By integrating of the point source function with respect to \(z_{1D}\) over the interval 0 to \(h_{1D}\), we can obtain the pressure distribution for a line source function:

\[ \tilde{p}_{NI} = \frac{\tilde{q}_\mu}{2\pi k_{th} h} \]

\[ \times \left[ K_0 (\sqrt{\eta} \mu r_D) \right. \]

\[ + \left( \left( M \sqrt{\eta} \mu K_1 (\sqrt{\eta} \mu r_D) K_0 (\sqrt{\eta} r_D) \right. \right. \]

\[ \left. \left. - \sqrt{\eta} K_0 (\sqrt{\eta} r_D) K_1 (\sqrt{\eta} r_D) \right) \right. \]

\[ \times \left( M \sqrt{\eta} u I_1 (\sqrt{\eta} u r_D) K_0 (\sqrt{\eta} u r_D) \right. \]

\[ + \sqrt{\eta} I_0 (\sqrt{\eta} u r_D) K_1 (\sqrt{\eta} u r_D)^{-1} \right) \]

\[ \times L_0 (\sqrt{\eta} \mu R_D) \right], \]

(13)

where \(\tilde{q}_\mu\) is the line source, \(m^3/s\) and \(R_D\) is the distance between the line source and pressure observation point in horizontal direction.

3.3. Pressure Behaviors for MsFHW in Tight Oil Reservoir considering SRV. To obtain the pressure or rate behaviors for MsFHW, the assumptions are made as follows [34–36]: the wellbore is intersected by \(N\) fractures and all fractures are transverse to the wellbore as shown in Figure 2; flow from the reservoir to the wellbore is negligible compared to the flow from the hydraulic fractures; the well is assumed to produce at a constant wellbore pressure or at a constant production rate and the horizontal well is treated as infinite conductivity one.

The fracture is discretized to make the solution possible as shown in Figure 3. Each fracture includes \(2n\) units. Each unit can be taken as a line source. For the \(j\)th discrete unit of the \(i\)th fracture, the pressure distribution caused by the line source is

\[ \tilde{p}_{Nij}^{(j)} = \int_{x_{i,j}}^{x_{i,j+1}} \frac{\tilde{q}_{Lij} L}{2nk_{th} h} \]

\[ \times \left[ K_0 \left( \sqrt{\eta} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{Dh})^2} \right) \right. \]

\[ + \left( \left( M \sqrt{\eta} u K_1 \left( \sqrt{\eta} u r_D \right) K_0 \left( \sqrt{\eta} u r_D \right) \right. \right. \]

\[ \left. - \sqrt{\eta} u K_0 \left( \sqrt{\eta} u r_D \right) K_1 \left( \sqrt{\eta} u r_D \right) \right) \]

\[ \times \left( M \sqrt{\eta} u I_1 \left( \sqrt{\eta} u r_D \right) K_0 \left( \sqrt{\eta} u r_D \right) \right. \]

\[ + \sqrt{\eta} u I_0 \left( \sqrt{\eta} u r_D \right) K_1 \left( \sqrt{\eta} u r_D \right)^{-1} \right) \]

\[ \times L_0 \left( \sqrt{\eta} \mu R_D \right) \right] \] \(dx_w.\)

(14)

Define

\[ x_{Di,j} = \frac{x_{i,j}}{L}, \quad x_{Di,j+1} = \frac{x_{i,j+1}}{L}, \]

\[ q_{Di,j} (t) = \frac{\tilde{q}_{Lij} L}{q_{ic}}, \quad \tilde{q}_{Di,j} (u) = \frac{\tilde{q}_{Lij} (u) L}{q_{ic}}. \]

(15)
Equation (14) becomes

\[
\frac{\Delta p_{N1D}}{\Delta x_{D,k,j}} = \tilde{q}_{D,k,j} \int_{x_{D,k,j}}^{x_{D,k,j+1}} \left[ \frac{K_0 \left( \sqrt{u} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2} \right)}{M} \right.
\]

\[
+ \frac{\sqrt{u} K_1 \left( \sqrt{u} r_{1D} \right) K_0 \left( \sqrt{u} r_{1D} \right) - \sqrt{u} \eta_0 \left( \sqrt{u} r_{1D} \right) K_1 \left( \sqrt{u} r_{1D} \right)}{M \sqrt{u} (\sqrt{u} r_{1D}) K_0 \left( \sqrt{u} r_{1D} \right) + \sqrt{u} \eta_0 \left( \sqrt{u} r_{1D} \right) K_1 \left( \sqrt{u} r_{1D} \right)}
\]

\[
\times I_0 \left( \sqrt{u} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2} \right) \right] \, dx_{wD}.
\]

By applying the principle of superposition, the pressure response for \( N \times 2n \) discrete segments can be obtained as follows:

\[
\frac{\Delta p_{N1D}}{\Delta x_{D,y}} = \sum_{i=1}^{2n} \sum_{j=1}^{N} \Delta p_{N1D}^{(i,j)}(x_{D,y}) ,
\]

(17)

Thus, the pressure response at the discrete segment \((k, v)\) can be obtained:

\[
\frac{\Delta p_{N1D}}{\Delta x_{D,v}} = \sum_{i=1}^{2n} \sum_{j=1}^{N} \Delta p_{N1D}^{(i,j)}(x_{D,v}) ,
\]

(18)

where \( (x_{D,v}, y_{D,v}) \) is the center coordinate of the \( j \)th discrete unit in the \( i \)th fracture. The assumptions of infinite conductivity wellbore and fractures result in that the pressure at each point within the fractures and the horizontal wellbore is identical to bottomhole pressure, \( p_{wD} \). Thus, the wellbore pressure drop may be expressed as

\[
\Delta p_{wD} = \sum_{i=1}^{2n} \sum_{j=1}^{N} \Delta p_{N1D}^{(i,j)}(x_{D,v}, y_{D,v}) .
\]

(19)

The assumption of constant flow rate gives the following condition that must hold at any time:

\[
\sum_{i=1}^{2n} \sum_{j=1}^{N} \Delta p_{D,v}^{(i,j)}(u) \left( x_{D,j+1} - x_{D,j} \right) = \frac{1}{u}.
\]

(20)

There are \( 2n \times (N + 1) \) equations which can solve the \( 2n \times (N + 1) \) unknowns of \( p_{wD}, q_{D1}, q_{D2}, \ldots, q_{D2N} \). A system of equations which is formed by (19) and (20) is now obtained and solution of such a system produces values for bottomhole pressure distribution as well as flux distribution for each fracture in Laplace domain.

The solution can be inverted back into real time domain using Stehfest algorithm. The Gauss elimination method was used to solve the system of equations. Then the Stehfest numerical inversion algorithm [37] was chosen to calculate the dimensionless bottomhole pressure as well as the dimensionless production rate distribution in real time space. For the numerical integration, Gauss-Legendre method was used [38].
4.2. Effect of Different Parameters

4.2.1. Effect of SRV Radius. Figure 8 shows effect of SRV radius on rate transient curves when the well produces at a constant wellbore pressure. The values of relevant parameters are listed as follows: $C_D = 10000$, $S = 0.02$, $L_f = 100$ m, $N = 3$, $M = 15$, $L = 0.1$ m, $DL = 300$ m, $\eta = 15$, $r_1 = 350$ m, 550 m, 750 m, 950 m. It can be seen the SRV radius has significant effect on the production rate during the practical life of the well when all other parameters remain constant. As the SRV radius becomes larger, there will be a greater production rate. For the tight oil reservoirs, because of the extremely low permeability, flow resistance is high for oil. SRV is where the induced fractures exist and these fractures make the oil flow capacity increase to obtain economic development. Large SRV radius leads to large “high permeable” area and thus decreases the flow resistance. Therefore, in the development of tight oil reservoir it is desirable to obtain a large SRV radius to obtain a high production rate.

4.2.2. Effect of Storativity Ratio. Figure 9 shows effect of storativity ratio on rate transient curves when the well produces at a constant wellbore pressure. The values of relevant parameters are listed as follows: $C_D = 10000$, $S = 0.02$, $L_f = 100$ m, $N = 3$, $M = 15$, $L = 0.1$ m, $DL = 300$ m, $r_1 = 350$ m, $\omega = 0.2, 0.5, 1, 2, 5$. Large storativity ratio leads to large production rate. Large storativity ratio means that the compressibility of the inner region is large. The production rate will become high under the same pressure difference.

4.2.3. Effect of Mobility Ratio. Figure 10 shows effect of mobility ratio on rate transient curves when the well produces at a constant wellbore pressure. The values of relevant parameters are listed as follows: $C_D = 10000$, $S = 0.02$, $L_f = 100$ m, $N = 3$, $L = 0.1$ m, $DL = 300$ m, $r_1 = 350$ m, $\omega = 1$, $M = 1, 5, 10, 15$. As can be seen, when the mobility ratio is bigger than one, the production rate increases greatly. The blue line is rate transient curve when the mobility ratio is equal to one which means the reservoir is homogenous and there is no SRV near the well. The production rate is very low for the homogenous reservoir which indicates the necessity of the SRV. Another conclusion can be drawn from Figure 10 is that larger mobility ratio leads to larger production rate. Large mobility ratio represents large inner permeability and thus decreases flow resistance. So production rate increases effectively. When developing tight oil reservoirs, we hope to improve the inner region permeability as possible as we can to obtain high production rate.

4.2.4. Effect of Fracture Number. Figure 11 shows effect of fracture number on rate transient curves when the well produces at a constant wellbore pressure. The values of
relevant parameters are listed as follows: $C_D = 10000$, $S = 0.02$, $L_f = 100$ m, $L = 0.1$ m, $DL = 80$ m, $r_1 = 350$ m, $\omega = 1$, $N = 3, 5, 7, 9$. The fractures are assumed to be equally spaced and the properties of the fractures are identical in this case. As shown in Figure 11, increasing the number of fractures mainly influences the early production rate. Increasing the number of hydraulic fractures will improve the permeability around the wellbore. Flow resistance in the vicinity of the wellbore will be small. At the same time, more fractures increase the contact area with the formation for well and thus high production rate can be obtained.

4.2.5. Effect of Fracture Half-Length. Figure 12 shows effect of fracture half-length on rate transient curves when the well produces at a constant wellbore pressure. The values of

relevant parameters are listed as follows: $C_D = 10000$, $S = 0.02$, $N = 3, M = 15, L = 0.1$ m, $DL = 300$ m, $r_1 = 350$ m, $\omega = 1$, $L_f = 20$ m, 50 m, 80 m, 120 m. The fractures are assumed to be equally spaced and the properties of the fractures are identical in this case. As shown in Figure 12, fracture half-length significantly influences the early production rate. Increasing fracture half-length can increase the contact area between the MsFHW and formation which is beneficial for the oil production.

4.2.6. Effect of Fracture Spacing. Figure 13 shows effect of fracture spacing on rate transient curves when the well produces at a constant wellbore pressure. The values of

4.2.6. Effect of Fracture Spacing. Figure 13 shows effect of fracture spacing on rate transient curves when the well produces at a constant wellbore pressure. The values of
\[ \omega = 1, DL = 50 \text{ m}, 100 \text{ m}, 200 \text{ m}, 300 \text{ m}. \] The properties of the fractures are identical in this case. The well production performance indicates that large fracture spacing increases the production rate in early time. The reason is that when fracture number remains unchanged, larger fracture spacing leads to larger drainage area, and oil production rate will increase.

5. Conclusions

In this paper, a new model was presented for multistage fractured horizontal well considering simulated reservoir volume in tight oil reservoirs. The solution was obtained with point function. Pressure transient responses and rate transient responses were discussed. The following conclusions can be drawn.

1. Oil flow in tight reservoir is a comprehensive result coupling the MsFHW and formation. The mathematical model is verified to describe the flow in both MsFHW and formation. Specifically, the SRV is taken into consideration compared to the existing PTA and RTA methods in tight oil reservoirs. Nine flow regimes are identified from the transient pressure curves. These regimes may not be complete when the formation properties and hydraulic fracture parameters change.

2. The SRV has significant effect on rate transient curves. Large SRV radius leads to high production rate. That means a large SRV should be created for hydraulic fracture treatment in development of tight oil reservoirs. Permeability in the SRV region affects not only the early production rate, but also the production rate in later flow period. If mobility ratio is larger than 1, the rate is much bigger than that of the homogenous model. Large storativity ratio leads to large compressibility of inner region and high production rate can be obtained.

3. The hydraulic fracture properties have significant effect on well early production rate. But the late-time behaviors are not affected. Increasing fracture number, fracture half-length, fracture spacing will increase the drainage area and improve the permeability around the wellbore. So if high early production rate is needed, the hydraulic fracture properties should be considered.
Figure 12: Effect of fracture half-length on well production performance.

Figure 13: Effect of fracture spacing on well production performance.

Nomenclature

- \( M \): Mobility ratio, fraction
- \( k \): Permeability, \( \text{m}^2 \)
- \( \omega \): Storativity ratio, fraction
- \( \mu \): Fluid viscosity, \( \text{Pa} \cdot \text{s} \)
- \( \eta \): Diffusivity ratio, fraction
- \( u \): Laplace space variable with respect to \( t_D \)
- \( h \): Reservoir thickness, \( \text{m} \)
- \( L \): Reference length, \( \text{m} \)
- \( I_k(x) \): The modified Bessel function of first kind
- \( K_n(x) \): The modified Bessel function of second kind
- \( q_{sc} \): Production rate, \( \text{m}^3/\text{s} \)
- \( C \): Wellbore storage, \( \text{m}^3/\text{Pa} \)
- \( S \): Skin factor, dimensionless
- \( L_f \): Fracture half-length, \( \text{m} \)
- \( t \): Time, \( \text{s} \)
- \( N \): Fracture number
- \( DL \): Fracturing spacing, \( \text{m} \)
- \( r, \theta, z \): Cylindrical coordinate system
- \( \varphi \): Radius in spherical coordinate system

Subscripts and Superscripts

- \( D \): Dimensionless
- \( i \): Initial
- \( h \): Horizontal direction
- \( v \): Vertical direction
- \( - \): Laplace domain
- \( 1 \): Inner region
- \( 2 \): Outer region

Conflict of Interests

Ruizhong Jiang, Jianchun Xu, Zhaobo Sun, Chaohua Guo and Yulong Zhao declare that there is no conflict of interests regarding the publication of this paper.

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