Research Article
Development and Application of Well-Test Model after Injection Biological Nanomaterials

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Received 16 January 2022; Revised 20 March 2022; Accepted 23 March 2022; Published 11 April 2022

Academic Editor: Keliu Wu

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Nanomaterials are gradually shining in the petroleum industry and have made great achievements in EOR, pipeline coating, fracturing, and other aspects. In practical application, they have the advantages of long validity period and more environmental friendliness. At the same time, due to the short effective period of conventional plugging removal measures such as acidizing and fracturing, which are not friendly to the environment, nanomaterials are gradually applied to reduce pressure and increase injection of injection wells, and good application results are obtained. In this study, a new biological nanomaterial with long-term injection enhancement characteristics was evaluated. To have a better understanding of the reservoir performance of water injection wells after pressure reduction and injection increase measures, it is necessary to establish the well test model after the step-down and injection increase measures of biological nanomaterials that are taken for water injection wells. In this paper, the influence of the injection amount of bionanomaterials on the permeability is studied, and the rule of the permeability around the injection well with the distance from the bottom of the well is analyzed. On this basis, the flow mathematical model of three zones (inner zone, transition zone, and outer zone) of bionanosolution is established. Then, using the basic principles of fluid mechanics and the Laplace transform principle, a mathematical model of the bottom hole pressure response of water injection wells in the third zone of the bionanosolution reservoir is obtained, and the influence of the key process parameters of the bionanosolution water injection on the bottom hole pressure is analyzed. The established well test interpretation model can be used to calculate the near wellbore permeability, reservoir skin factor, reservoir sweep radius, and reservoir resistance coefficient. Based on application examples, it was determined that the fitting results of the interpretation chart are in good agreement with the field test data, and the reservoir parameters obtained from the interpretation are reasonable and reliable. The findings of this study can help for better understanding of the dynamic change law of reservoir after injection of biological nanomaterials or similar plugging removal measures (the improvement effect varies with the distance from the bottom hole). To the best of our knowledge, it is the first paper on the application of biological nanomaterials in reducing pressure and increasing injection in injection wells.

1. Introduction

Water injection is a common means of secondary and tertiary oil recovery [1–4]. According to research and statistics, in the process of water injection in most of China’s oilfields, due to the low original permeability of the reservoir, sub-standard injection water quality, and high salinity, the pressure of the water injection wells generally increases with time, resulting in an excessive load on the water injection pump, a reduced water injection efficiency, and a high-pressure during injection [5–9]. At the same time, offshore oilfields are facing increasingly stringent environmental protection standards. To reduce pressure and increase injection without polluting the environment, some oilfields in China...
have developed a new type of bionanomaterial, which is environment-friendly and has a valid period exceeding that of ordinary pressure-reducing and injection-increasing materials. However, after multiple rounds of these measures, the amount of rock particles available for dissolution in the reservoir decreases, and the period of successful conventional plugging removal measures becomes shorter and shorter [10–13]. To improve the effective period of water injection well measures, a new nanomaterial with a long-term injection increase characteristic was studied, a field test was carried out, and good application results were obtained. However, at present, the reservoir performance after the depressurization and injection increase measures are implemented in the water injection well is still unclear. In addition, the seepage of the water injection well is more complex than producing well [14–18], which causes many difficulties and challenges in well tests after biological nano-measures are applied to water injection wells.

Many scholars have carried out relevant research on well test interpretation methods for various well conditions [16, 19–26]. Compared with previous scholars, Ju et al. increased the factors of permeability heterogeneity and established a mathematical model for well test interpretation of water injection wells in low permeability two-layer composite reservoirs, which considered the well test theory of water injection wells from another aspect [27]. Based on the law of conservation of mass and the principle of relative permeability normalization, Liu et al. established a function for the relationship between the water saturation and the relative permeability and then combined it with Darcy’s law of oil-water two-phase flow to establish a well test model of a water injection well, which simultaneously considered the influences of the formation and fluid properties [28]. Jiang et al. established the pressure drop well test model of water injection wells based on BL equation and studied the influence of crude oil viscosity on well test curve, which provided a certain basis for injection increasing measures of water injection wells [16, 17]. Wang et al. established a mathematical model of water injection well test considering the influence of WIF (waterflood-induced fracture), applied it in Changqing Oilfield, and achieved good interpretation results [29, 30].

At present, with the application of various nanomaterials in China’s oil fields, many articles explaining nanomaterials have been published, but most of them are limited to experimental tests, and there is no relevant seepage theory, especially the well test theory of water injection wells established after pressure reduction and injection increase measures. This study innovatively considers that the improvement effect caused by the adsorption of nanomaterials in the formation becomes worse with the distance from the bottom of the well, the nanomaterials need to reach the critical concentration in the formation to improve the effect, and when the concentration of nanomaterials exceeds a certain concentration, the improvement effect will not increase. The formation is divided into inner area (around the well, the concentration is high, which is the effective area of bionano materials), transition area (slightly away from the well, the concentration of bionanomaterials decreases rapidly, and the improvement effect also decreases with the distance), and outer area (farthest from the well, the concentration of bionanomaterials is too low to show improvement effect). The relationship between concentration and zoning is shown in Figure 1, where the depth of red indicates the concentration of biological nanomaterials. Then, based on the divided areas, the mathematical model of seepage is established, and the influence of the key process parameters of the bionanosolution water injection on the bottom hole pressure is analyzed. The model established on the application surface is reliable and can be applied to plugging removal measures (such as adsorption) reservoir performance analysis.

This paper is organized as follows: first, the mathematical model and solutions are presented. Then sensitivity about the reservoir's physical parameters and the fluid parameters are discussed, followed by an application example. The final chapter is the conclusion, summarizes the research results briefly, and puts forward the limitations of this article.

2. Development and Solution of the Model

2.1. Physical Model of the Biological Nanosolution Injection Stage. Before establishing the model, we used bionano to treat the core to explore the influence of bionano injection on reservoir physical properties. In the actual test process, PV number, a dimensionless number, was used instead of bionano injection to minimize the influence of the original formation physical properties on the experimental results.

In Figures 2 and 3, after increasing the injected PV number, we can easily find the relationship between the improvement degree of reservoir permeability and the amount of bionano injection; with the increase of bionano injection, the reservoir permeability will also increase rapidly, and there is a linear relationship between the permeability and the logarithm of injected PV number (corresponding transition zone), but after the amount of bionano injection reaches a certain level, its permeability increase is no longer obvious; that is, there is an upper limit to the increase in permeability caused by biological nanomaterials (Corresponding outer zone).
That is, within a certain PV number range, the following relationship is satisfied:

\[ k = A \log PV + B, \quad (1) \]

where \( k \) is the formation permeability \((10^{-3} \mu m^2)\), \( A \) is slope of the regression line, and \( B \) is intercept of the regression line.

This experiment can also be approximately regarded as the improvement of formation permeability around the injection well, and the injected PV number has a negative linear relationship with the distance from the formation to the bottom of the injection well. Therefore, it can be seen from the above figure that in the actual radial formation, the permeability improvement effect is obvious within a range from the wellhead. With the increase of the wellhead distance, the permeability shows a downward trend, and
then, after falling to a certain critical concentration, the biological nanoaction disappears.

\[ k = A \log R + B \tag{2} \]

where \( R \) is the distance from the formation to the bottom (m).

Therefore, after simple transformation, there is the following equation:

\[ (k/\mu)_2 = \frac{(k/\mu)_1}{M_{12}} \left( \frac{r_D}{R_1D} \right)^{-\theta_1}, \tag{3} \]

where \( \mu \) is the viscosity (mPa·s); \( R_{1D} \) is the dimensionless radius of the inner region, \( M_{12} \) is the mobility ratio at the interface between the inner zone and the transition zone, \( r_D \) is the dimensionless radius, \( \theta_1 \) is the mobility variation parameter, and it is related to the concentration of biological nanomaterials, \( 0 \leq \theta_1 \leq 2 \).

One of the mechanisms by which biological nanoparticles can increase permeability is to increase seepage channel and porosity. Therefore, considering the Kozeny model \([31]\), there is the following equation:

\[ \frac{\varphi}{\delta \tau} r_c^2 = A \log R + B, \tag{4} \]

where \( \varphi \) is the porosity (%), \( \tau \) is the tortuosity, and \( r_c \) is the capillary bundle radius.

Therefore, the well storage coefficient has the following equation:

\[ (\varphi C_t)_2 = \frac{(\varphi C_t)_1}{F_{12}} \left( \frac{r_D}{R_1D} \right)^{-\theta_2}, \tag{5} \]

where \( C_t \) is the comprehensive compression coefficient (mPa\(^{-1}\)), \( F_{12} \) is the storage capacity coefficient ratio at the interface between the inner zone and the transition zone, and \( \theta_2 \) is the change parameter of the storage coefficient; it is related to the concentration of biological nanomaterials, \( 0 \leq \theta_2 \leq 2 \).

In practical work, the effect of too low bionanomaterials is basically negligible; that is, the formation physical properties will not be affected by bionanomaterials after a certain distance from the bottom of the injection well (corresponding inner zone). Then, the change rule of mobility and storage coefficient can be shown in Figure 4:

In view of the above situation, the physical model after treatment with a biological nanosolution is shown in Figure 5 and makes the following assumptions. Its assumptions are as follows before establishing the model:

1. The formation is a three-zone radial composite reservoir with a horizontally consistent thickness
2. The gravity and capillary force in the formation can be ignored, and the fluid is a single-phase fluid
3. The fluid seepage in each area is isothermal seepage and conforms to Darcy’s plane radial seepage law
4. The water injection volume of the well is constant, and the water injection is carried out from \( t = 0 \). Before the water injection, the pressure balance in the formation is equal to \( p_i \)
5. There is additional resistance at the interface between each seepage area
6. The influences of the wellbore storage effect and the skin effect are considered

In this study, the three-zone radial composite reservoir model after nanoparticle adsorption only differs from the multi zone radial composite reservoir model in terms of the treatment methods of the formation and the fluid’s physical properties in the transition zone. The former is characterized by continuous change, while the latter is characterized by step-like changes.

2.2. Three-Zone Radial Composite Seepage Mathematical Model of a Biological Nanosolution Reservoir. According to the previously described physical models and assumptions and based on the theory of seepage mechanics, a well test
mathematical model of a three-zone radial composite reservoir with a biological nanosolution was established.

(1) The dimensionless seepage differential equations are as follows:

Inner region is as follows:

\[ \frac{1}{r_D} \frac{\partial}{\partial r_D} \left( r_D \frac{\partial p_{1D}}{\partial r_D} \right) = \frac{\partial p_{1D}}{\partial t_D} (1 \leq r_D \leq R_{1D}). \]  (6)

Transition region is as follows:

\[ \frac{1}{r_D} \frac{\partial}{\partial r_D} \left( r_D^{1-\theta} \frac{\partial p_{2D}}{\partial r_D} \right) = \eta_1 \left[ R_{1D}^{1-\theta} - r_D^{-\theta} \frac{\partial p_{2D}}{\partial r_D} \right], \]  (7)

\[ (R_{1D} \leq r_D \leq R_{2D}). \]

Outer region is as follows:

\[ \frac{1}{r_D} \frac{\partial}{\partial r_D} \left( r_D \frac{\partial p_{3D}}{\partial r_D} \right) = \eta_3 \frac{\partial p_{3D}}{\partial t_D} (R_{2D} \leq r_D \leq R_{30}). \]  (8)

In Eqs. (6)–(8), \( p_{1D} \) is the dimensionless pressure in the inner zone, \( p_{2D} \) is the dimensionless pressure in the transition zone, \( p_{3D} \) is the dimensionless pressure in the outer zone, \( t_D \) is the dimensionless time, \( \eta \) is the ratio of the pressure conductivity coefficients of the inner zone and transition zone, \( R_{1D} \) is the dimensionless inner radius, \( R_{2D} \) is the dimensionless transition radius, and \( R_{3D} \) is the dimensionless outer radius.

(2) The inner boundary conditions are calculated as follows:

Wellbore storage effect is as follows:

\[ C_D \left( \frac{dp_{1D}}{dt_D} - \frac{dp_{2D}}{dt_D} \right) - \left( \frac{\partial p_{1D}}{\partial r_D} \right)_{r_D=1} = 1. \]  (9)

Skin effect is as follows:

\[ p_{wfD} = \left( p_{1D} - S \frac{\partial p_{1D}}{\partial r_D} \right)_{r_D=1}. \]  (10)

In Eqs. (9) and (10), \( C_D \) is the dimensionless well storage coefficient, \( p_{wfD} \) is the dimensionless well bottom pressure, \( p_{wfD} \) is the dimensionless pressure of the formation near the wellbore, and \( S \) is the skin factor.

(3) The outer boundary conditions are calculated as follows:

Infinite outer boundary is as follows:

\[ p_{3D}(r_D \to \infty, t_D) = 0. \]  (11)

Circular constant pressure boundary is as follows:

\[ p_{3D}(r_D = R_{3D}, t_D) = 0. \]  (12)

Circular closed boundary is as follows:

\[ \frac{\partial p_{3D}}{\partial r_D} (r_D = R_{3D}, t_D) = 0. \]  (13)

(4) The interface continuity conditions are calculated as follows:

Equal interface pressure is as follows:

\[ p_{1D}(R_{1D}) = \left( p_{2D} - S_{1f} R_{1D} \frac{\partial p_{2D}}{\partial r_D} \right)_{r_D=R_{1D}}, \]  (14)

\[ p_{2D}(R_{2D}) = \left( p_{3D} - S_{2f} R_{2D} \frac{\partial p_{3D}}{\partial r_D} \right)_{r_D=R_{2D}}. \]  (15)

Equal interface velocity is as follows:

\[ \frac{\partial p_{1D}}{\partial r_D} (r_D = R_{1D}, t_D) = \frac{1}{M_{12}} \frac{\partial p_{2D}}{\partial r_D} (r_D = R_{1D}, t_D). \]  (16)

\[ \frac{\partial p_{2D}}{\partial r_D} (r_D = R_{2D}, t_D) = \frac{M_{12}}{M_{13}} \frac{\partial p_{3D}}{\partial r_D} (r_D = R_{2D}, t_D). \]  (17)

In Eqs. (14)–(17), \( S_{1f} \) is the inner skin coefficient, \( S_{2f} \) is the inner skin coefficient, and \( M_{13} \) is the mobility ratio of the inner zone to the outer zone.

(5) Initial conditions are as follows:

At the initial time, the pressure in the formation is equal:

\[ p_{1D}(r_D, t_D = 0) = p_{2D}(r_D, t_D = 0) = p_{3D}(r_D, t_D = 0) = 0. \]  (18)

2.3. Three-Zone Radial Composite Seepage Mathematical Model of a Biological Nanosolution Reservoir. For the dimensionless three-zone radial composite model, the Laplace
Iv
tively, second variants of the zero order Bessel functions, respectively, and the general solution of the seepage differential equation in Laplace space was obtained as follows:

\[ P_{1D} = A_1 I_0(r_D \sqrt{g}) + A_2 K_0(r_D \sqrt{g}), \]  

\[ P_{2D} = A_3 r_D^0 I_0(r_D \sqrt{g}) + A_4 r_D^0 K_0(r_D \sqrt{g}), \]  

\[ P_{3D} = A_5 I_0(r_D \sqrt{g}) + A_6 K_0(r_D \sqrt{g}). \]

In Eqs. (19)–(21), \( I_0(x) \) and \( K_0(x) \) are the first and second variants of the zero order Bessel functions, respectively, \( I_n(x) \) and \( K_n(x) \) are the first and second variants of the \( n \) order Bessel functions, respectively, and \( A_1 \)–\( A_6 \) are coefficients, which are determined by the internal and external boundary conditions and the interface connection conditions.

Dimensionless well bottom pressure calculation equation in the Laplace space is as follows:

\[ P_{w/D} = A_1 I_0(\sqrt{g}) - S \sqrt{g} I_1(\sqrt{g}) + A_2 K_0(\sqrt{g}) + S \sqrt{g} K_1(\sqrt{g}). \]

Eq. (22) gives the dimensionless well bottom pressure Laplace space solution of the three-zone composite reservoir with exponentially changing physical properties for the case of an infinite boundary, closed circular boundary, and circular supply boundary. Then, the Stehfest numerical inversion can be carried out to obtain the solution in the real space (there is a detailed solution process and information and code of Stehfest numerical inversion in the appendix).

3. Analysis of a Typical Well-Test Curve Chart

Figure 6 shows a typical dimensionless well bottom pressure curve for a three-zone composite reservoir with exponentially changing physical properties in the transition zone.

(a) In the pure wellbore storage stage, the pressure and pressure derivative curves are straight lines with slopes of 1

(b) The radial flow in the inner zone is reflected by the horizontal straight line with a pressure derivative curve of 0.5

(c) The reflection of the changes in the physical properties in the transition area is related to parameter \( \theta_1 \)

(d) The radial flow in the outer zone is reflected by the horizontal straight line with a pressure derivative curve of \( M_{13}/2 \)

(e) In the quasistable flow stage with a closed outer boundary, the pressure and derivative curves are straight lines with slopes of 1
The pressure derivative curve gradually decreases to 0 in the flow stage for a constant pressure boundary.

The transition stage from pure wellbore storage to radial flow in the inner zone.

The transitional flow stage between the transition and outer regions.

The dimensionless well bottom pressure response in a three-zone composite reservoir with exponentially changing physical properties in the transition zone is different from the conventional three-zone radial composite reservoir due to the influence of the parameter $\theta_2$, which is mainly reflected in flow stage (c). That is, the seepage in the transition zone, which is characterized by exponentially changing physical properties, is no longer a horizontal straight line on the derivative curve. For a conventional three-zone composite reservoir, if $R_{2D} - R_{1D}$ is large enough, the radial flow stage may occur in the transition zone, the derivative curve is a horizontal straight line segment, and there is a transition flow stage from the inner zone to the transition zone before the straight line segment.

4. Sensitivity Analysis of the Influence of a Biological Nanosolution

4.1. Sensitivity Analysis of the Reservoir’s Physical Parameters. Figure 7 shows the influence of the storage capacity parameter $\theta_2$ on the well bottom pressure performance. As can be seen from Figure 7, $\theta_2$ mainly affects flow stage (c) and the seepage in the transition zone. Although $\theta_2$ does not affect the start time and duration of flow phase (c), it does affect the shape of the pressure derivative curve. If $\theta_2$ is larger, the storage capacity coefficient at $r_D$ in the transition zone is smaller than that in the inner zone ($\phi C_1$). For a steeper pressure derivative curve, the slope of the curve will increase in the early stage of the flow period and then gradually decrease. Conversely, the smaller the pressure derivative $\theta_2$ is, the smoother the pressure derivative curve is.

Figure 8 shows the influence of the dimensionless inner radius $R_{1D}$ on the well bottom pressure performance. As can be seen from Figure 8, when the other parameters remain unchanged, the larger the radius $R_{1D}$ of the inner zone, the later the end time of radial flow (b) in the inner zone and the start time of flow stage (c) in the transition zone, and the earlier the start time of transition flow stage (h) from the transition zone to the outer zone. That is, the larger $R_{1D}$, the longer the duration of flow stages (b) and (h), and the shorter the duration of flow stage (c).

Figure 9 shows the influence of the transition zone radius $R_{2D}$ on the well bottom pressure performance. As can be seen from Figure 9, when the other parameters remain unchanged, the larger the transition zone radius $R_{2D}$, the longer the duration of transition zone flow stage (c), and the shorter the duration of transition flow stage (h) from the transition zone to the outer zone. Conversely, the smaller the transition zone radius $R_{2D}$, the shorter the duration of transition zone flow stage (c), and the longer the duration of transition flow stage (h) from the transition zone to the outer zone.

4.2. Sensitivity Analysis of the Fluid Parameters. Figure 10 shows the influence of the mobility change parameters in the transition zone $\theta_1$ on the well bottom pressure of the...
Figure 8: Influence of the radius of the inner zone of the three-zone homogeneous radial composite reservoir on the well bottom pressure performance.

Figure 9: Influence of the radius of the transition zone of the three-zone homogeneous radial composite reservoir on the well bottom pressure performance.
injection well. As can be seen from Figure 10, the influence of $\theta_1$ mainly affects flow stages (c) and (h), i.e., the seepage stage in the transition zone. That is, $\theta_1$ does not affect the start time of flow stage (c), but it affects the duration of the flow stage. In addition, $\theta_1$ affects the start time and duration of flow stage (h). The larger $\theta_1$ is, the greater the ratio of the
fluidity in the inner zone to that in the transition zone is, the greater the slope of the pressure derivative curve in flow stage (c) is, the longer the duration of the flow stage is, and the later the start time and the shorter the duration of flow stage (h) are. If $\theta_1 = 0$, $M_{12} = \eta_{12} = 1$. The model then degenerates into a conventional two-zone composite reservoir model. If $\theta_1 = 0$, $M_{12} = \eta_{12} \neq 1$, and the model degenerates into a conventional three-zone composite reservoir model.

Figure 11 shows the influence of the mobility ratio $M_{12}$ at the interface $R_{1D}$ between the inner zone and the transition zone on the well bottom pressure of the injection well. The change in $M_{12}$ affects the mobility ratio $M_{23}$ at the interface between the transition zone and the outer zone $R_{2D}$; so, flow stages (c) and (h) are mainly affected by $M_{12}$. If $M_{12} \neq 1$, then there is a sudden change in the mobility at the interface $R_{1D}$ between the inner and middle regions. As can be seen from the pressure response curve, there is a transition stage (i) before flow stage (c). The larger $M_{12}$ is, the greater the slope of the derivative curve and the longer the duration of transition stage (i) are, the later the start time and the shorter the duration of transition stage (h) are, and the higher the position of flow stage (c) is. However, the time reflecting the flow in the transition zone and the transition stage remains almost unchanged.

Figure 12 shows the relationship between the mobility ratio $M_{13}$ of the inner zone and the outer zone on the well bottom pressure performance. The smaller the mobility ratio is, the shorter the duration of transition stage (h) of the fluid seepage from the outer zone to the inner zone is, and the smaller the slope of the pressure derivative curve is; while the earlier the outer zone fluid radial flow stage (d) appears, the lower the position of the derivative curve is, and its value is $M_{13}/2$.

5. Application Examples

Well A1 is a water injection well in oilfield $W$, which was put into operation on March 1, 2016. The production horizon is E2s3UI + II + IV, the upper part of E2s3MI, the lower parts of oil formations I, and the parts of oil formations II, which are divided into four sand control sections. The vertical depth in the middle of the oil layer is 2567.35 m, the well completion depth is 2989 m, the completed vertical depth

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir thickness (m)</td>
<td>12.1</td>
</tr>
<tr>
<td>Crude oil volume coefficient</td>
<td>1.1</td>
</tr>
<tr>
<td>Water volume coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Crude oil viscosity (mPa·s)</td>
<td>125</td>
</tr>
<tr>
<td>Water viscosity (mPa·s)</td>
<td>0.5</td>
</tr>
<tr>
<td>Compressibility coefficient of crude oil (MPa$^{-1}$)</td>
<td>0.0045</td>
</tr>
<tr>
<td>Water compressibility coefficient (MPa$^{-1}$)</td>
<td>0.00035</td>
</tr>
<tr>
<td>Well radius (m)</td>
<td>0.27</td>
</tr>
<tr>
<td>Injection rate of biological nanomaterials (m$^3$/d)</td>
<td>5.595</td>
</tr>
<tr>
<td>Injection concentration of biological nanomaterials (ppm)</td>
<td>1200</td>
</tr>
<tr>
<td>Injection volume of biological nanomaterials (PV)</td>
<td>0.000292</td>
</tr>
</tbody>
</table>
is 2838.41 m, the elevation of the kelly bushing is 40.3 m, the oil compensation distance is 19.71 m, and the maximum well deviation is 21.49° at an inclined depth of 1474.63 m and a vertical depth of 1399.69 m. The casing has an outer diameter of 9-5/8″, and the entrance depth is 2983.12 m. The completion method is casing perforation and nonsand control completion. Table 1 presents the parameters of the water injection well and the reservoir.

Biological nanoplugging removal and injection increase measures were implemented in well A1 in July 2019. After these measures were implemented, the actual pressure data were measured and fitted to the results of the three-zone radial composite model described above. Firstly, wavelet transform and appropriate threshold are used to reduce the noise of well test data, and then particle swarm optimization is used to fit the well test data [32]. The near well zone permeability, reservoir skin factor, reservoir sweep radius, and reservoir resistance coefficient after the measures were taken were obtained (Figure 13 and Table 2). The fitting results of the interpretation chart are in good agreement with the field test data, and the reservoir parameters obtained from the interpretation are reasonable and reliable.

6. Summary and Conclusions

(1) Based on the dynamic characterization mathematical model of how a biological nanosolution changes the reservoir seepage resistance, seepage mathematical models of the biological nanosolution action area, the biological nanosolution action transition area, and the external nonaction area were established, the analytical solution was obtained in Laplace space, and the solution was obtained in real space using the Stehfest numerical inversion. The typical pressure performance curve for a three-zone homogeneous radial composite reservoir with exponentially changing physical properties in the transition zone was drawn, and we divide it into eight seepage stages.

(2) The dimensionless well bottom pressure response of a three-zone composite reservoir with exponentially changing physical properties in the transition zone is different from the conventional three-zone radial composite reservoir due to the influence of the parameter $\theta_1$. This is mainly reflected in the flow stage in the transition zone with the changing physical properties; that is, the seepage in the transition zone with exponentially changing physical properties is no longer a horizontal straight line on the derivative curve.

(3) The established well test interpretation model can be used to calculate the near well zone permeability, reservoir skin coefficient, reservoir sweep radius, and reservoir resistance coefficient. The fitting results of the interpretation chart are in good agreement with the field test data. The reservoir parameters obtained from the interpretation are reasonable and reliable. The results of this study have important guiding significance for the fine evaluation of the use of nanomaterials to improve the oil reservoir development effect.

(4) Of course, there are still some problems in this model. Although it has been developed by water injection for a period of time when bionano is
injected, the water saturation around the water injection well will still change after bionano is injected. This model does not take into account the change of water saturation of multiphase seepage around the water injection well, which can be improved in the follow-up work.

Appendix

A. Solution of the Well-Test Model in Laplace Space

For the dimensionless model of the three-zone radial composite model, Laplace transform about dimensionless time $t_D$ is carried out, and the mathematical model of well test analysis in Laplace space is obtained:

1. The dimensionless seepage differential equations are as follows:

   Inner region is as follows:

   $\frac{d^2 \tilde{p}_{1D}}{d r_D^2} + \frac{1}{r_D} \frac{d \tilde{p}_{1D}}{d r_D} = z \tilde{p}_{1D} (1 \leq r_D \leq R_{1D}). \quad (A.1)$

   Transition region is as follows:

   $\frac{\theta_1 - \theta_2}{r_D} \frac{d^2 \tilde{p}_{2D}}{d r_D^2} + (1 - \theta_1) \frac{r_D}{d r_D} \frac{d \tilde{p}_{2D}}{d r_D} = \eta_{12} \theta_2 - \theta_1 \tilde{p}_{1D} \tilde{p}_{2D}.$

   $(R_{1D} \leq r_D \leq R_{2D}). \quad (A.2)$

   Outer region is as follows:

   $\frac{d^2 \tilde{p}_{3D}}{d r_D^2} + \frac{1}{r_D} \frac{d \tilde{p}_{3D}}{d r_D} = \eta_{13} \tilde{p}_{3D} (R_{2D} \leq r_D \leq R_{3D}) \quad (A.3)$

   In Eqs. (A.1)–(A.3), $\tilde{p}_{1D}$ is the dimensionless pressure in the inner zone, $\tilde{p}_{2D}$ is the dimensionless pressure in the transition zone, $\tilde{p}_{3D}$ is the dimensionless pressure in the outer zone; $z$ is the Laplace variable, $\eta_{12}$ is the ratio of the pressure conductivity coefficients of the inner zone and transition zone, $\eta_{13}$ is the ratio of the pressure conductivity coefficients of the inner zone and outer zone, $R_{1D}$ is the dimensionless inner radius, $R_{2D}$ is the dimensionless transition radius, and $R_{3D}$ is the dimensionless outer radius.

2. The inner boundary conditions are calculated as follows:

   Wellbore storage effect is as follows:

   $C_D \tilde{p}_{wfD} - \left( r_D \frac{d \tilde{p}_{1D}}{d r_D} \right)_{t_D = 1} = \frac{1}{z}. \quad (A.4)$

   Skin effect is as follows:

   $\tilde{p}_{wfD} = \left( \tilde{p}_{1D} - S \frac{d \tilde{p}_{1D}}{d r_D} \right)_{t_D = 1}. \quad (A.5)$

   In Eqs. (A.4) and (A.5), $C_D$ is the dimensionless well storage coefficient; $\tilde{p}_{wfD}$ is the dimensionless well bottom pressure, and $S$ is the skin factor.

3. The outer boundary conditions are calculated as follows:

   Infinite outer boundary is as follows:

   $\tilde{p}_{3D}(r_D = \infty, z) = 0. \quad (A.6)$

   Circular constant pressure boundary is as follows:

   $\tilde{p}_{3D}(r_D = R_{3D}, z) = 0. \quad (A.7)$

   Circular closed boundary is as follows:

   $\frac{d \tilde{p}_{3D}}{d r_D} (r_D = R_{3D}, z) = 0. \quad (A.8)$

4. The interface continuity conditions are calculated as follows:

   Equal interface pressure is as follows:

   $\tilde{p}_{1D}(R_{1D}, z) = \tilde{p}_{2D}(R_{1D}, z). \quad (A.9)$

   $\tilde{p}_{2D}(R_{2D}, z) = \tilde{p}_{3D}(R_{2D}, z). \quad (A.10)$

   Equal interface velocity is as follows:

   $\frac{d \tilde{p}_{1D}}{d r_D} (R_{1D}, z) = \frac{1}{M_{12}} \frac{d \tilde{p}_{2D}}{d r_D} (R_{1D}, z). \quad (A.11)$

   $\frac{d \tilde{p}_{2D}}{d r_D} (R_{2D}, z) = \frac{M_{12}}{M_{13}} \frac{d \tilde{p}_{3D}}{d r_D} (R_{2D}, z). \quad (A.12)$

   In Eqs. ((A.9)–(A.12)), $S_{i}$ is the inner skin coefficient, $S_{i}^2$ is the inner skin coefficient, and $M_{ij}$ is the mobility ratio of the inner zone to the outer zone.

5. Initial conditions:

   At the initial time, the pressure in the formation is equal:

   $\tilde{p}_{1D}(r_D, t_D = 0) = \tilde{p}_{2D}(r_D, t_D = 0) = \tilde{p}_{3D}(r_D, t_D = 0) = 0. \quad (A.13)$

   At this point, define some variables:

   $\gamma = \frac{\theta_1}{2}. \quad (A.14)$
Then, the general solutions of seepage differential equations (A.1), (A.2), and (A.3) in Laplace space are obtained:

\[
\tilde{p}_{1D} = A_1 I_0 (r_D \sqrt{z}) + A_2 K_0 (r_D \sqrt{z}), \tag{A.18}
\]

\[
\tilde{p}_{2D} = A_3 r_D^\beta J_\beta (r_D^\alpha), + A_4 r_D^\beta K_\beta (r_D^\alpha), \tag{A.19}
\]

\[
\tilde{p}_{3D} = A_5 I_0 (r_D \sqrt{\eta_{13} z}) + A_6 K_0 (r_D \sqrt{\eta_{13} z}). \tag{A.20}
\]

In Eqs. (A.18)–(A.20), \(I_0 (x)\) and \(K_0 (x)\) are the first and second variants of the zero order Bessel functions, respectively, \(J_\beta (x)\) and \(K_\beta (x)\) are the first and second variants of the \(\nu\) order Bessel functions, respectively, \(A_1 - A_6\) are coefficients, which are determined by the internal and external boundary conditions and the interface connection conditions, and \(z\) is the Laplace variable.

The inner boundary conditions Eqs. ((A.4)) and ((A.5)) in Laplace space are

\[
C_D \xi^2 \tilde{p}_{1D} \bigg|_{r_D = 1} - (C_D \xi^2 S + z) \frac{d\tilde{p}_{1D}}{dr_D} \bigg|_{r_D = 1} = 1. \tag{A.21}
\]

Substituting Eq. (A.18) into Eq. (A.21) gives

\[
\alpha_{31} A_1 + \alpha_{32} A_2 = 1. \tag{A.22}
\]

Substituting Eqs. ((A.18)–(A.20)) into Eqs. ((A.9)–(A.12)) results in

\[
\begin{align*}
\alpha_{21} A_1 + \alpha_{22} A_2 + \alpha_{23} A_3 + \alpha_{24} A_4 & = 0, \\
\alpha_{33} A_3 + \alpha_{34} A_4 + \alpha_{35} A_5 + \alpha_{36} A_6 & = 0, \\
\alpha_{41} A_1 + \alpha_{42} A_2 + \alpha_{43} A_3 + \alpha_{44} A_4 & = 0, \\
\alpha_{53} A_3 + \alpha_{54} A_4 + \alpha_{55} A_5 + \alpha_{56} A_6 & = 0.
\end{align*} \tag{A.23}
\]

Substituting Eq. (A.20) into Eqs. (A.6)–(A.8) results in

\[
\alpha_{65} A_5 + \alpha_{66} A_6 = 0. \tag{A.24}
\]

In the equations,

\[
\begin{align*}
\alpha_{11} & = C_D \xi^2 I_0 (\sqrt{z}) - z \sqrt{z} (C_D \xi^2 S + 1) I_1 (\sqrt{z}), \\
\alpha_{12} & = C_D \xi^2 K_0 (\sqrt{z}) + z \sqrt{z} (C_D \xi^2 S + 1) K_1 (\sqrt{z}), \\
\alpha_{21} & = I_0 (R_{1D} \sqrt{z}), \alpha_{23} = K_0 (R_{1D} \sqrt{z}), \\
\alpha_{23} & = -R_{1D}^\xi I_\beta (R_{1D}^\alpha \delta), \alpha_{24} = -R_{1D}^\xi K_\beta (R_{1D}^\alpha \delta), \\
\alpha_{33} & = R_{2D}^\xi I_\beta (R_{2D}^\alpha \delta), \alpha_{34} = R_{2D}^\xi K_\beta (R_{2D}^\alpha \delta), \\
\alpha_{35} & = -I_0 (R_{2D} \sqrt{z}), \alpha_{36} = -K_0 (R_{2D} \sqrt{z}), \\
\alpha_{41} & = M_1 \sqrt{z} I_1 (R_{1D} \sqrt{z}), \alpha_{42} = -M_1 \sqrt{z} K_1 (R_{1D} \sqrt{z}), \\
\alpha_{43} & = -R_{1D}^\xi I_\beta (\delta R_{1D}^\alpha), \alpha_{44} = -R_{1D}^\xi K_\beta (\delta R_{1D}^\alpha), \\
\alpha_{53} & = R_{2D}^\xi I_\beta (\delta R_{2D}^\alpha), \alpha_{54} = R_{2D}^\xi K_\beta (\delta R_{2D}^\alpha), \\
\alpha_{55} & = -(M_{12} \sqrt{z}) (R_{2D} \sqrt{z}), \alpha_{66} = -K_0 (R_{2D} \sqrt{z}) \tag{A.25}
\end{align*}
\]

For infinite boundary,

\[
\alpha_{25} = \alpha_{35} = \alpha_{45} = \alpha_{55} = \alpha_{65} = \alpha_{66} = 0. \tag{A.26}
\]

For closed boundary,

\[
\alpha_{65} = I_0 (R_{zD} \sqrt{z}), \alpha_{66} = K_0 (R_{zD} \sqrt{z}). \tag{A.27}
\]

For supply boundary,

\[
\alpha_{65} = I_1 (R_{zD} \sqrt{z}), \alpha_{66} = -K_1 (R_{zD} \sqrt{z}) \tag{A.28}
\]

Solving Eqs. ((A.21)–(A.24)) by Cramer’s Law,

\[
D = \begin{vmatrix}
\alpha_{11} & \alpha_{12} & 0 & 0 & 0 & 0 \\
\alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} & 0 & 0 \\
0 & 0 & \alpha_{33} & \alpha_{34} & \alpha_{35} & \alpha_{36} \\
\alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & 0 & 0 \\
0 & 0 & \alpha_{53} & \alpha_{54} & \alpha_{55} & \alpha_{56} \\
0 & 0 & 0 & 0 & \alpha_{65} & \alpha_{66}
\end{vmatrix}
\]
Then, we can get

\[
A_1 = \frac{D_1}{D}, A_2 = \frac{D_2}{D}, A_3 = \frac{D_3}{D}, A_4 = \frac{D_4}{D}, A_5 = \frac{D_5}{D}, A_6 = \frac{D_6}{D}.
\]  

Substituting each coefficient into Eqs. (A.18)–(A.20) can obtain the dimensionless pressure calculation formula of Laplace space at any position.

Substituting Eq. (A.18) into (A.5) can obtain the dimensionless bottom hole pressure calculation formula of Laplace space:

Dimensionless well bottom pressure calculation equation in the Laplace space is as follows:

\[
\hat{p}_{wfd} = A_1 \left[ I_0(\sqrt{\hat{z}}) - S\sqrt{\hat{z}}L_1(\sqrt{\hat{z}}) \right] + A_2 \left[ K_0(\sqrt{\hat{z}}) + S\sqrt{\hat{z}}K_1(\sqrt{\hat{z}}) \right].
\]  

(B.31)

**B. Stehfest Numerical Inversion**

Given the transformation parameter \( \alpha_i \), take the value according to the following equation [33]:

\[
\alpha_i = \ln \frac{2}{l} i, i = 1, 2, \cdots, k,
\]  

(B.1)

where \( k \) is the even number.

Calculation of transformation parameters \( V_i \) is as follows

\[
V_i = (-1)^{k/2} \sum_{n=1}^{\lfloor k/2 \rfloor} \sum_{n=1}^{\lfloor k/2 \rfloor} \frac{n^{k/2} (2n)!}{(k/2 - n)! (n - 1)! (i - n)! (2n - i)!},
\]  

(B.2)

where \( \lfloor \cdot \rfloor \) is the Gaussian rounding symbol.

Calculate the original function of physical space, and the inversion equation is as follows,

\[
f(T) = \frac{\ln 2}{l} \sum_{i=1}^{k} V_i f \left( \frac{\ln 2}{l} i \right)
\]  

(B.3)

When we get the solution of Laplace space, we can get the solution of the original space through the above transformation. The following is the MATLAB code of Stehfest numerical inversion method in this study.
Data Availability

The data used to support the findings of this study are included within the article and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors are grateful for funding from the National Natural Science Foundation of China (Grant No. 51804048).

References


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\begin{algorithm}
\begin{verbatim}
function y=ILaplaceStehfest(fs,t,N)
    n=length(t);
    y=zeros(1,n);
    for j =1:n
        V=0;
        for i=1:N
            V=V+v
        end
        y(j) = log(2)/t(j)
    end
    fs=(-1)^((N/2)-k)/factorial(N/2-k)/factorial(2*k-i);
end
end
\end{verbatim}
\end{algorithm}


