New Gas Tracer Convection−Diffusion Model between Wells in Heavy Oil Reservoirs

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ABSTRACT: Different from conventional oil and gas, the storage and seepage space of heavy oil reservoirs are extremely complicated, thereby making it difficult to describe reservoirs in detail over the heavy oil production process. Acquiring development results accurately in real time is still a demanding task, and it is also a challenge to predict the average remaining heavy oil saturation during the production process. Tracers are mostly used to monitor steam flooding to obtain the real-time dynamics during heavy oil production in fields. However, the flow pattern of gas tracers in heavy oil is still unclear, with very rare investigations. In this work, a new one-dimensional gas tracer convection−diffusion model that considered the retention and oil phase migration velocity was established using the percolation law of gas tracers. The reservoir description coefficient was introduced to describe the relationship between the migration velocities of the oil and gas phases in the heavy oil reservoir. Subsequently, a new gas tracer well pattern flow model was also constructed based on the gas tracer linear flow model and verified simultaneously. The results revealed that at a larger partition coefficient, more amounts of gas tracers were distributed in the crude oil, the duration of stagnation was extended, and the start time of tracer production was moved backward. The injection velocity had a very minor effect on the tracer production performance. As the fluid injection rate increased, the duration of gas tracer production was extended; however, after the injection rate reached a certain level, the difference in the arrival time of the peak become minor. The effects of crude oil viscosity on the tracer production were reflected by the breakthrough time, production time, peak concentration, and peak arrival time of the tracer. The reservoir description coefficient mainly affects the peak concentration of tracer production and has very minor effects on the production time and other parameters. The outcomes of this work can be applied in the field of heavy oil development, in particular, for the heavy oil reservoir description and dynamic monitoring.

1. INTRODUCTION

The gas tracer interpretation method can be used to obtain a qualitative and quantitative evaluation of the reservoir formation to achieve the goals of finely characterizing the reservoir and calculating the average remaining oil saturation along the way. Tracers have been widely used as a major means in the actual on-site oil and gas reservoir development because they can precisely describe oil reservoirs and perform steam flooding and steam-assisted gravity drainage. However, there have been a few studies on the flow model of gas tracers, and numerical models have large limitations and cannot be applied to some types of reservoirs; they cannot consider the adsorption and retention of gas tracers in the reservoir and the distribution of the two phases of oil and gas. Each specific reservoir needs to be described separately and has no universal applicability. There is an urgent need for a theoretical gas tracer flow model between wells of heavy oil to describe the reservoir so as to realize the fast and accurate description of the gas missing agent between the heavy oil wells.

Brigham proposed and derived a method to predict the breakthrough time and peak concentration of the tracer in a water-flooding five-point well pattern based on the tracer flow characteristics. The established semianalytical model of the tracer has promoted research on the quantitative interpretation of the tracer flow. Subsequently, some researchers studied the gas tracer model and proposed that a tracer exists in the reservoir. Simultaneously, the dispersion and adsorption of the
tracer were considered in the established model. Although the gas tracer flow model is constantly improving, there is still no good calculation method for the preliminary prediction of the gas tracer; furthermore, there is still no suitable explanation method for the gas tracer retention and diffusion phenomenon and the multitracer situation. Therefore, Lou\textsuperscript{9} used the two-phase percolation mathematical model and the “semivariable tube” method under the condition that the ratio of miscible flooding solves the problem of tracer-front prediction. Combining the diffusion equation with the percolation equation, a mathematical model of gas tracer diffusion and seepage considering “gas tracer retention” in the miscible flooding of steam injection was established. This research provides a good explanation for the retention and diffusion of gas tracers in oil reservoirs and provides theoretical support for studying the flow laws of gas tracers in oil reservoirs.\textsuperscript{10–14}

By analyzing the influencing factors of the gas tracer distribution between phases, Huseby\textsuperscript{5} derived a formula that can be used to calculate the gas tracer in an actual reservoir, and a model for simulating the migration of the gas tracer is established; this model is also suitable for a heavy oil tracer used in development. Su\textsuperscript{3} created a multiphase and multitracer mathematical model that considers the diffusion, convection, and adsorption of the tracer based on the basic theory of tracer percolation. Although this research has perfected the gas tracer flow model and established a multiphase and multitracer flow model, it has neither considered the oil phase migration velocity in heavy oil reservoirs nor has it explained the gas tracer in the oil phase; thus, it does not match the actual reservoir conditions. Wang\textsuperscript{6} presented a mathematical model and a numerical approach to simulate the transport velocity and sweep efficiency of gas tracers. He aimed to evaluate the flow direction and sweep efficiency using our gas tracer model, and the results predicted by our model are used to optimize the production strategy. With the continuous injection of the gas tracer, its distribution in the gas–liquid two-phase flow is a crucial issue.

In 2018, Dejam\textsuperscript{9} evaluated the effect of hydraulic fracturing geometry with porous walls on the dispersion coefficient of tracers using rectangular, triangular, and elliptical models. Their results suggested that the average dispersion coefficient of the tracers in hydraulic fractures with porous walls was smaller than that of tracers in structures with nonporous walls. We herein described the distribution of gas tracers in pores and fractures but did not mention the distribution of gas tracers across both phases. This makes it impossible to accurately describe the distribution and flow law of the gas tracer in the formation, and with the continuous injection of the gas tracer, its distribution in the gas–liquid two-phase is a question worth discussing.

In 2020, Liu\textsuperscript{10} developed a technique to describe the tracer flowback behavior for a vertically fractured well in a tight formation by coupling fluid flow and geomechanical dynamics. He found that an increase in the matrix permeability increases the tracer flowback concentration and the tracer recovery factor (TRF). A larger tracer dispersion coefficient leads to an earlier arrival time for the tracer flowback concentration peak together with a lower TRF. This study can help us better understand the influence of parameters such as diffusion coefficient on the flow of gas tracers.\textsuperscript{11,13} Abdulaziz\textsuperscript{12} focused on the gas tracer’s interwell connectivity and dynamic fluid flow and proposed a tracer breakthrough model. The model was closely combined with the tracer breakthrough curve and was capable of describing reservoir properties well and improving the developmental parameters. Although the model can explain the flow law of the gas tracer in the gas phase, it does not provide a suitable calculation method for the distribution and retention of the gas tracer in the oil phase. When the gas tracer is distributed in the oil phase, its retention in the gas phase is weakened. Therefore, if only the distribution in the gas phase is considered, the results will be inconsistent with the actual situation. In the current research, scholars continue to improve the flow model, such as by considering the retention situation, partition coefficient, various influencing factors in the reservoir, among others. However, the flow law of gas tracers in heavy oil remains unclear. The current research does not consider the distribution and retention of gas tracers in the oil phase, and the change in the retention coefficient due to the distribution of gas tracers in the oil phase does not provide a reasonable explanation.\textsuperscript{14,15} The oil velocity is simply ignored, but the migration law of the gas tracer in an actual heavy oil reservoir is affected by the migration velocity of the oil phase.

Therefore, in this study, based on the gas tracer flow model considering the retention and diffusion phenomena, a linear tracer flow model that considers the oil phase migration velocity is established, and the reservoir description coefficient is used to quantitatively characterize the relation between the gas and oil phases in the reservoir. It considers the retention coefficient and obtains the retention coefficient considering the oil phase migration velocity. Subsequently, in accordance with the linear model of the gas tracer, the linear model is extended to the plane, and the gas tracer well pattern model considering the oil phase migration velocity was established. This research completes the flow model of gas tracers in heavy oil reservoirs: it can accurately describe the flow law of gas tracers between wells in heavy oil reservoirs and quickly predict the concentration and flow of gas tracers, as well as monitor and evaluate the development status for a long time to improve production and recovery efficiency.

2. RESULTS AND DISCUSSION

2.1. Linear Flow Model of Gas Tracers between Heavy Oil Wells. After analyzing the flow law of the gas tracer, a gas tracer linear model considering the retention and a model considering the oil phase velocity are established based on the gas tracer convection–diffusion equation. Meanwhile, we use the reservoir description coefficient to describe the migration velocities of the oil and gas phases where the gas tracer is located.

2.1.1. Model Hypothesis. Consider a one-dimensional linear flow pipe with a length $l$, cross-sectional area $A$, porosity $\phi$, and pore volume of $V_\phi = A l \phi$. When injecting the tracer into the pipe core full of gas and oil from point $x = 0$ and then replacing it with the injected gas, the tracer moves in the form of a slug flow, and the initial concentration is $C_0$. Figure 1 shows a schematic of the basic model. Based on the characteristics of heavy oil reservoirs and gas tracers, the following hypotheses are proposed for the establishment of a flow model of gas tracers between wells in heavy oil reservoirs:

(1) There are gas, oil, and water phases (the water phase does not participate in the flow) in the oil reservoir, and the fluid flows in a one-dimensional linear mode.
(2) The gas tracer distributed in the oil phase was assumed to not affect the oil viscosity, density, and other properties, and there exists the phenomenon of adsorption and retention.

(3) The oil-phase migration velocity is ignored.

(4) The gas tracer is transported in the gas phase as a segment plug flow.

(5) The gas tracer in the gas phase and the oil phase is constantly redistributed and can reach equilibrium at a faster rate.

(6) The oil reservoir is a homogeneous oil reservoir.

2.1.2. Gas Tracer Linear Model Considering Retention.

2.1.2.1. Mathematical Description of Retention. The concentration of the gas tracer injected at time \( t_0 \) decreases with the passage of time and the replacement of the injected gas owing to the presence of crude oil in the tube. The stagnation of the gas tracer manifests itself in a macroscopic reduction in the apparent velocity and a decreased movement velocity of the gas tracer segment plug flow owing to the distribution of the gas tracer in the oil phase.\(^{16-19}\)

\[
\nu = \frac{v_s S_g + KS_v}{S_g + KS_v} = \frac{1}{1 + \frac{K S_g}{S_v}} v_v = Z v_v
\]

where \( v_v \) denotes the migration velocity of the oil phase, \( v_s \) is the migration velocity of steam in the reservoir, \( K \) is the partition coefficient, \( S_g \) is the reservoir oil saturation, and \( S_v \) is the reservoir gas saturation.\(^{20}\)

where \( K = \frac{C_v}{C_g} \). As \( v_v \) is approximately equal to 0

\[
\nu = \frac{v_s S_g}{S_g + KS_v} = \frac{1}{1 + \frac{K S_g}{S_v}} v_v = Z v_v
\]

Thus, \( v_v \) can be represented as

\[
\nu_v = \frac{1}{Z} v
\]

where \( Z \) is the stagnation coefficient of the gas tracer, describing the degree of the decrease in apparent velocity caused by the stagnation of the gas tracer.

When the slug flow moves, the oil saturation and gas saturation are regarded as fixed values and so \( K \frac{S_g}{S_v} \) is constant, indicating that the stagnation coefficient \( Z \) is also unchanged.

2.1.2.2. One-Dimensional Convection–Diffusion Seepage Equation Considering Detention. Taking hysteresis into account, the equation for one-dimensional convective diffusive percolation in any microbody, including the oil and gas phases, must be rewritten as

\[
-Z v_g \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}
\]

Equation 4 is the one-dimensional convective-diffusion percolation equation for a gas tracer with hysteresis.\(^{20}\) If a gas tracer with a concentration of \( C_0 \) is continuously injected into an infinite stratum at \( x = 0 \), the definite solution condition is

\[
\begin{align*}
C &= C_0 \quad x = 0 \\
C &= 0 \quad x = \infty
\end{align*}
\]

We obtain

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - Z v_g t}{2 \sqrt{Dt}} \right) - \frac{1}{2} \text{erfc} \left( \frac{x + Z v_g t}{2 \sqrt{Dt}} \right)
\]

The exponential function is close to 0 when \( x \) is large, and the error of the bounded function is always less than 2. Besides, \( Z \) is a fixed value and so eq 5 can be simplified to

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - Z v_g t}{2 \sqrt{Dt}} \right)
\]

Under this condition, the length \( L \) of the mixing zone (concentration ranges from 0 to \( C_0 \)) is

\[ L = 8 \sqrt{Dt} \]

2.1.2.3. Retained Gas Tracer Slug Flow. As the gas tracer migrates in the gas phase in the form of slug flow, the concentration of the stagnant gas tracer slug flow at any position can be expressed as

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - Z v_g t - \Delta x}{2 \sqrt{Dt}} \right) - \frac{1}{2} \text{erfc} \left( \frac{x - Z v_g t + \Delta x}{2 \sqrt{Dt}} \right)
\]

Differentiating both ends of eq 7, we have

\[
\frac{C}{C_0} \frac{1}{\sqrt{\pi}} \exp \left[ -\left( \frac{x - Z v_g t - \Delta x}{2 \sqrt{Dt}} \right)^2 \right] = \frac{1}{2 \sqrt{Dt}}
\]

\[
+ \frac{1}{\sqrt{\pi}} \exp \left[ -\left( \frac{x - Z v_g t + \Delta x}{2 \sqrt{Dt}} \right)^2 \right] = \frac{1}{2 \sqrt{Dt}}
\]

As the slug length is relatively small compared to the injection–production well spacing, eq 8 can be simplified as follows

\[
\frac{C}{C_0} = \frac{\Delta x}{\sqrt{4 \pi Dt}} \exp \left[ -\left( \frac{x - Z v_g t}{2 \sqrt{Dt}} \right)^2 \right]
\]

2.1.3. Gas Tracer Linear Model Considering the Oil-Phase Velocity. In actual oil reservoirs, owing to the high viscosity and low fluidity of heavy oil and the occurrence of steam overlap during the production process, the injected gas tracer will not only exist in the gas phase but also will appear in the oil phase. Therefore, hypothesis (3) is revised assuming that the oil-phase migration velocity cannot be ignored, and the oil-phase migration velocity and the gas-phase migration velocity have the following proportional relationship: \( v_v = f v_v' \).
2.1.3.1. Gas-Phase Part. When only the gas-phase motion is considered, the mass flow rate \( u_g \) of the gas tracer in any micro-element of the gas phase can be expressed as

\[
    u_g = \frac{C_g S_g}{C_g S_g + C_o S_o} u
\]

(10)

We obtain

\[
    u_g = \frac{1}{1 + K \frac{S_o}{S_g}} u
\]

(11)

According to Fick’s law

\[
    u = -D \frac{\partial C}{\partial x}
\]

where \( u \) is the mass flow rate.

Because the oil-phase migration velocity cannot be ignored, it is assumed that there is a relationship between the oil-phase migration velocity and the steam migration velocity and we obtain

\[
    v_g = \frac{S_g + KS_o}{S_g + KS_o} v = Z'v
\]

(12)

where \( Z' \) is the gas tracer retention coefficient considering the oil-phase migration velocity, and \( f \) is the reservoir description coefficient that expresses the relation between the gas-phase migration velocity and oil-phase migration velocity during steam flooding in heavy oil reservoirs and ranges from 0 to 1.

For the two-phase characteristic velocity \( v \) in the entire model, the one-dimensional convective-diffusion seepage equation can be rewritten as

\[
    -\frac{v_g}{Z'} \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}
\]

(13)

If a gas tracer with a concentration of \( C_0 \) is continuously injected into an infinite stratum at \( x = 0 \), the definite solution condition is

\[
    \begin{cases}
    C = \frac{C_o S_g}{C_g S_g + C_o S_o}, C_0 = (1 - Z)C_0, x = 0 \\
    C = 0, x = \infty
    \end{cases}
\]

Simplifying it, we get

\[
    C = \frac{C_o S_g}{C_g S_g + C_o S_o} C_0 = (1 - Z)C_0, x = 0
\]

(14)

Under this condition, the length \( L \) of the mixing zone (concentration ranges from 0 to \( C_0 \)) is still \( L = 8\sqrt{D/t} \).

Based on the hypothesis (4), the concentration of the gas tracer segment plug flow available anywhere in the gas phase is expressed as follows

\[
    C = \frac{Z \Delta x}{\sqrt{4\pi D t}} \exp \left[ -\frac{x - Z g (1 - Z) t}{2 \sqrt{D t}} \right]
\]

(15)

According to eq 15, there is distribution stagnation, and the concentration of the gas tracer plug in the gas phase at position \( x \) and time \( t \), considering that the oil-phase velocity can be calculated.

2.1.3.2. Oil-Phase Part. When only the movement of the oil phase is discussed, the mass flow rate, \( u_o \), of the gas tracer in any micro-element of the oil phase can be expressed as

\[
    u_o = (1 - Z)u
\]

(16)

By extending the flow area of the gas tracer to the entire flow tube, eq 16 is rewritten as

\[
    u_o = (1 - Z)u - \frac{1}{1 - Z} = u
\]

(17)

According to \( u_o = f u_o = f Z v \), the one-dimensional convection-diffusion flow equation of the oil phase with the distribution stagnation considered is

\[
    -\frac{v_o}{Z'} \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}
\]

(18)

Assuming that the gas tracer with a concentration of \( C_0 \) is continuously injected into the infinite formation at \( x = 0 \), the solution conditions need to be changed according to hypothesis (6)

\[
    \begin{cases}
    C = \frac{C_o S_g}{C_g S_g + C_o S_o} C_0 = (1 - Z)C_0, x = 0 \\
    C = 0, x = \infty
    \end{cases}
\]

(19)

The concentration of the gas tracer slug flow at any point in the gas phase is expressed as

\[
    C \frac{C_o}{C_0} = \frac{1}{2 \sqrt{\pi D t}} \exp \left[ -\frac{x - Z g (1 - Z) t}{2 \sqrt{D t}} \right]
\]

(20)

According to eq 20, there is a distribution stagnation, and the concentration of the gas tracer slug in the oil phase at position \( x \) and time \( t \) in consideration of the oil phase velocity can be calculated.

2.2. Well Pattern Flow Model of Gas Tracers between Heavy Oil Wells. Based on the linear flow model of gas tracers between heavy oil wells, the well network model of gas tracers considering the stagnation and the model with oil-phase velocity is established in the integrated well network flow characteristics.

2.2.1. Gas Tracer Well Pattern Model Considering Retention. Considering eq 9

\[
    C \frac{C_o}{C_0} = \frac{\Delta x}{\sqrt{4\pi D t}} \exp \left[ -\frac{x - Z g (1 - Z) t}{2 \sqrt{D t}} \right]
\]

the dispersion coefficient of the gaseous substances is \( \alpha = D/v_g \).

As the lateral diffusion of molecules can be ignored with respect to the longitudinal diffusion, considering time \( t \)

\[
    t = v_g I
\]

(21)

where \( I = \int_{0}^{t} \frac{1}{\psi(s)} ds \). Substituting eq 21 into eq 9, we obtain
\[
\frac{C}{C_0} = \frac{V_t}{2aA\sqrt{\pi}} \exp \left[ -\left( \frac{V - ZV_t}{2aA} \right)^2 \right]
\]

where \( V_t \) is the tracer slug volume in the well pattern model.

According to Darcy’s law, the instantaneous unit pressure difference is transformed into the polar coordinate form

\[
\frac{C(\theta)}{C_0} = \frac{u_w V_t}{4\pi \omega h \sqrt{\pi}} \exp \left[ -u_w^2 \left( \frac{V - ZV_t}{4\pi \omega h \sqrt{\pi}} \right)^2 \right]
\]

The dimensionless equation is

\[
\frac{C(\theta)}{C_0} = \frac{u_w A \phi (1 - S_w) F_2}{4\pi \omega h \sqrt{\pi}} \exp \left[ -\mu^2 A^2 \phi^2 (1 - S_w)^2 \right]
\]

\[
\left( \frac{V_t(\theta) - V_{PD}}{4\pi \omega h \sqrt{\pi}} \right)^2
\]

where \( F_2 = \frac{V_t}{A \phi (1 - S_w)}, \quad V_{PD} = \frac{ZV_t - V_{PD}}{1 - V_{PD}}. \)

where \( V_t(\theta) \) is the dimensionless pore volume of the injected gas at streamline \( \theta \) during breakthrough, \( V_{PD} \) is the dimensionless pore volume of the gas injected at any time relative to the breakthrough pore volume of the well pattern, \( V_{PD} \) is the sweep coefficient of the injected gas breakthrough area, \( V_t \) is the injected gas volume at any time, \( A \) is the well pattern control area, \( h \) is the reservoir thickness, \( S_w \) is the reservoir water saturation, and \( F_2 \) is the dimensionless pore volume.

Substituting \( I(\theta) = \left( \frac{u_w \phi (1 - S_w)}{k_\theta} \right)^2 \times \frac{a^2}{4\pi k(m) k(m)^3} \times Y(\theta) \) into eq 24

\[
\frac{C(\theta)}{C} = \frac{\sqrt[k(m)]{k(m)} k(m) \sqrt{a / \alpha F_2}}{\pi \sqrt{\pi}} \exp \left[ -\frac{k(m)k(m)^3 a (V_t(\theta) - V_{PD})^2}{\pi^2 Y(\theta)} \right]
\]

where \( a \) and \( b \) are well pattern parameters, \( k(m) \) is the first type of complementary complete elliptic integral, \( k'(m) \) is the first type of complementary elliptic integral, and \( Y(\theta) \) can be calculated by the elliptic integral

\[
Y(\theta) = (1 + \eta)^{1.5} \int_0^{f(\theta)} \sqrt{t} dt / \sqrt{(t^2 - 2\beta t + 1)(t^2 + 2\beta t + \eta^2)(t^2 + \eta)}
\]

The term \( f(\theta) \) in the equation represents the upper limit of the integral of the elliptic function. The expressions for the other parameters are as follows

\[
\eta = \tan^2 \theta
\]

\[
\beta = 2m - 1
\]

As the tracer concentration of the production well in the well pattern model is the sum of the tracer concentrations of all flow tubes, for regular well patterns, we have

\[
\frac{C(\theta)}{C_0} = \frac{\pi}{4} \int_0^{\pi/4} \frac{q C(\theta)}{C_0} \cos \theta d\theta = \frac{\pi}{4} \int_0^{\pi/4} q C(\theta) \cos \theta d\theta
\]

where \( q \) is the fluid flow rate in the flow tube, and \( Q \) is the fluid flow rate in the well pattern.

The concentration of the dimensionless gas tracer is expressed as

\[
C_D = \frac{4\sqrt[k(m)]{k(m)} k(m) \sqrt{\pi}}{\pi} \int_0^{\pi/4} \exp \left[ -\frac{k(m)k(m)^3 a (V_t(\theta) - V_{PD})^2}{\pi^2 Y(\theta)} \right] \sqrt{Y(\theta)} d\theta
\]

2.3. Model Application. 2.3.1. Model Validation. To study the migration law of the gas tracer and verify the reliability of the gas tracer model between the heavy oil wells, we selected the \( Z \) well pair in the steam flooding test area of the Chunfeng Oilfield as the reference object. The Chunfeng Oilfield mainly uses steam flooding as its main development method. Table 1 lists the basic parameter table for the Chunfeng Oilfield. The data in the table were used to establish a CMG numerical conceptual model. To finely characterize the

| Table 1. Basic Parameters of the Chunfeng Oilfield |
|--------------------------------------------------|
| **item**                  | **value**               |
| permeability              | \( 1910 \times 10^{-5} \text{ m}^2 \) |
| effective reservoir thickness | 14 m                   |
| porosity                  | 0.35                    |
| oil viscosity (50 °C)     | 4000 mPa·s              |
| reservoir temperature     | 20 °C                   |
| reservoir pressure        | 16 MPa                  |
| oil saturation            | 0.3                     |
| gas saturation            | 0.32                    |
| diffusion coefficient     | 6.5                     |
| reservoir description coefficient | \( 1 \times 10^{-6} \) |
When the injection volume is 50,000 m³, the tracer output concentration is closer to the actual situation. At the same time, especially compared with the numerical model, the new model is closer to the actual situation. Owing to the fact that the numerical model cannot consider the distribution of the gas tracer in the two phases of gasoline and the phenomenon of adsorption and retention, the peak point of tracer production is higher than the new model. The output data graph and CMG model gas tracer output data graph are shown. The tracer concentration output diagrams of the three are observed to be basically the same, but the peak gas tracer output concentration of the new model can reach $82.5 \times 10^{-3}$ mg/L, when the actual oil field can only be $78.3 \times 10^{-3}$ mg/L. This is because, in actual mines, there are still some uncertain factors that affect the production of gas tracers, such as reservoir heterogeneity and formation heat loss, that lead to gas tracer production. The output concentration is not high and ultimately affects the reservoir development effect. However, compared with the numerical model, the new model is closer to the actual situation. At the same time, especially when the injection volume is 50,000–60,000, the new model is close to the actual field data, and the curve trend is the same but the numerical model is quite different from the actual situation. Owing to the fact that the numerical model cannot consider the distribution of the gas tracer in the two phases of gasoline and the phenomenon of adsorption and retention, the peak point of tracer production is higher than the new model and the actual field and so the new model is better than the numerical model.

2.3.2. Model Sensitivity Analysis. The sensitivity of the gas tracer well pattern model established herein was analyzed via MATLAB, and the influence of sensitive factors on the gas tracer flow between wells was analyzed to provide a reference for the application of the model to the field.

2.3.2.1. Partition Coefficient. To compare and calculate the influence of the partition coefficient on the gas tracer output, the partition coefficients were set to 0.1, 0.2, 0.4, and 0.8. Figure 3 shows the tracer output curve, and Figure 4 shows the partition coefficients.

As shown in Figure 3, the partition coefficient has a significant influence on the tracer output curve, including the output time, output duration, peak concentration, and peak arrival time. The larger the reasonable partition coefficient, the larger is the distribution of the tracer in the crude oil and the larger is the stagnation, and hence, the start time of the tracer production time moved backward. As the solubility of the tracer in the oil phase increases, the maximum concentration during production will be greatly reduced; as most tracers are produced with the production of crude oil, as seen in the output curve, when the partition coefficient is equal to 0.8, the output concentration of the tracer increased slightly and the output time of the gas tracer also increases; however, because the partition coefficient increases, the tracer is in the oil phase and there are many dissolution conditions and obvious retention phenomena, resulting in a decrease in the concentration of gas tracer and the maximum concentration of output. \cite{21,22}

2.3.2.2. Injection Rate. The influence of different injection velocities on the gas tracer output curve is shown in Figure 5. As the gas tracer injection velocity increased, the maximum output concentration of the tracer increased slightly and the maximum output concentration time shifted forward. The arrival time of the wave crest also moves forward, and when the injection velocity increases to a certain extent, the difference in the arrival time of the wave crest decreases. However, the production time and peak concentration are less sensitive to the injection rate. With an increase in the injection rate, the peak concentration slightly increases; this is because when the injection rate is faster, the contact between the displacement

![Figure 2. Tracer output concentrations of different models.](image1)

![Figure 3. Tracer production curves of different partition coefficients.](image2)
fluid and the oil phase and pores reduces. Time reduces the probability of dissolution and adsorption of the tracer in the oil phase and pore walls. However, the spreading area of the tracer with the displacement fluid is basically the same and so only the peak concentration increases slightly and the production time is long.2,23

Figure 6 shows the influence of injection velocity on tracer production. The influence of the injection velocity on the gas tracer concentration is relatively small and mainly affects the gas tracer production time. As the gas tracer injection velocity increased, the time for the tracer to reach the peak greatly reduced, especially when the injection velocity was 30–60 m³/day, and the peak arrival time decreased the most. This is because, compared with the initial injection velocity, a suitable increase in the injection velocity will considerably reduce the tracer. The phenomenon of retention and adsorption of the agent accelerates the output of the gas tracer; as the injection rate reaches a certain value, the retention of the tracer can no longer be reduced. This conclusion can be applied to the production of heavy oil steam flooding. With an increase in the
injection rate, the oil recovery increases; however, when the injection rate is too high, steam overlaps, and a high water cut will occur. Therefore, in the actual production, a suitable injection rate should be maintained to maximize the recovery factor.

2.3.2.3. Crude Oil Viscosity. On the one hand, the viscosity of crude oil can directly affect the partition coefficient of the gas tracer. On the other hand, it can also affect the apparent migration velocity of the fluid. This is a comprehensive factor. Figure 7 shows the effect of different crude oil viscosities on the tracer production curve under the condition that other variables remain unchanged.

The influence of crude oil viscosity on the tracer output curve is mainly reflected in four aspects: output time, output duration, peak concentration, and peak arrival time. When the crude oil viscosity was large, the output curve was slender on the left. The opposite is true for the right-side squat. This is because the smaller the crude oil viscosity, i.e., the smaller the relative molecular weight, the greater is the distribution of the tracer in the crude oil, which is reflected in the tracer output curve, indicating that the tracer output peak is small, at the specified test time. The total internal output is small. When the viscosity of crude oil is small and the same amount of heat is injected, the amount of flowable oil increases, the flow velocity of the oil phase is also greatly enhanced, the difference in seepage between the gas and oil phases is reduced, and the overall fluidity is enhanced. At this time, the gas tracer stagnation effect decreases and the tracer output time increases. When the viscosity of the crude oil is small, the difference in seepage velocity between the driving and driven phases is small. Under the action of the friction of the crude oil, the tracer as a gas-phase production time is delayed, and the curve is to the right.

Owing to the effect of the viscosity of oil on tracer production (Figure 8), the viscosity of crude oil is shown to have a significant influence on the production time of the tracer and the concentration of the tracer. As the viscosity of crude oil increases, although the gas tracer time required for the agent to reach its peak is greatly reduced, its output concentration is greatly reduced. The greater the viscosity of the crude oil, the less obvious is the distribution and retention of the gas tracer; consequently, the concentration distribution of the gas tracer in the reservoir will increase and the extraction time also increases. This conclusion can be applied to reservoir monitoring to ensure the efficient development of heavy oil.

Figure 7. Tracer production curves of different oil viscosities.

Figure 8. Effect of the viscosity of oil on tracer production.
2.3.2.4. Reservoir Description Coefficient. The reservoir description coefficient reflects the influence of the oil-phase velocity on the flow law of the gas tracer. Under the condition of controlling other variables unchanged, the reservoir description coefficient was set to 0.2, 0.4, 0.6, and 0.8, and numerical software was used to calculate the tracer production curve (Figure 9) and the influence of the reservoir description coefficient on tracer production (Figure 10).

As shown in Figure 9, the reservoir description coefficient has a small impact on the gas tracer production time and duration but has a greater impact on the peak concentration of the tracer production. This is because the smaller the reservoir description coefficient, the larger is the retention coefficient considering the oil-phase velocity, and the larger the tracer slug, which is equivalent to a larger tracer concentration in the gas phase, and a larger gas tracer. As the output concentration increases, the peak concentration increases, which is basically a linear inverse relation.

As the reservoir description coefficient has a small effect on the production time and duration of the gas tracer, it is temporarily not considered in the oil reservoir description on the tracer production impact map. Figure 10 shows that the reservoir description coefficient has an inverse relation with the maximum concentration of gas tracer production, and it has an inverse relation with the concentration of gas tracer production. This theory can be applied to the development of heavy oil. If the viscosity of the original heavy oil in the reservoir is greater, the oil-phase velocity will increase, indicating that the reservoir description coefficient will increase and will consume a significant amount of heat when steam heats the heavy oil. Simultaneously, there will be development problems, such as steam overriding and uneven coverage. At this time, the development method needs to be improved.

3. CONCLUSIONS

(1) Based on the seepage law of the gas tracer and the convection–diffusion equation, a linear flow model of the gas tracer between heavy oil wells considering the presence of retention was established, and the stagnant gas tracer slug flow was derived from the model
simultaneously. In addition, a gas tracer linear model considering the oil-phase migration velocity was constructed. The parameter $f$ is created to describe the oil-phase migration velocity and the gas-phase migration velocity in the gas tracer between wells in heavy oil reservoirs.

(2) A gas tracer well pattern flow model that considers the factors affecting retention and simulating molecular diffusion is derived from the established linear model. Meanwhile, another gas tracer well pattern model that considers the oil-phase migration velocity and the characteristics of actual heavy oil reservoirs was designed.

(3) The parameter $V_{f}(\theta)$ of the established gas tracer well pattern model between heavy oil wells is obtained, and the well pattern breakthrough curve is drawn. The curve provides a theoretical basis for accurately describing the flow of gas tracers in heavy oil reservoirs.

(4) By applying the established model and analyzing its sensitivity factors, a larger partition coefficient was observed that lead to greater tracer stagnation in the crude oil, and the start time of tracer production moved backward. Different injection rates had a relatively small impact on the tracer output curve. As the fluid injection rate increased, the tracer output curve moved forward. The viscosity of crude oil has a significant influence on the tracer output curve. When the viscosity of the crude oil is large, the output curve is slender on the left. However, the curve is squat on the right with a small crude oil viscosity. The reservoir description coefficient mainly affects the peak concentration of tracer production and has no significant influence on the production time and other parameters.

4. MATERIALS AND METHODS

The analysis and interpretation of gas tracers are based on the theory of convective mass transfer and diffusion. Therefore, understanding the theory of mass transfer, diffusion, and percolation of gas tracers as well as the particularity of tracer migration in oil reservoirs is a prerequisite for the establishment of a mathematical model suitable for gas tracers.

4.1. Mechanical Dispersion. The mechanical dispersion coefficient can represent the characteristics of tracer migration in porous media with water flow seepage. Owing to the uneven distribution and different geometric shapes of fractures and pores in the heavy oil reservoir, the gas tracer permeates in a tortuous manner. The local velocity of the moving seepage changes in direction and size, thereby increasing the range of solute diffusion in the medium. By studying the mechanical dispersion coefficient, we can obtain the relation between it and the seepage velocity of the water, and the distribution and flow law of gas tracers in porous media.

\[
D_{b} = \lambda^{2} \cdot \nu
\]  

(30)

where $\lambda^{2}$ represents the parameters related to the average particle size of the porous medium and its nonuniform characteristics. The mechanical dispersion coefficient is directly proportional to the flow velocity and is related to the distribution and size of particles in porous media.

4.2. Molecular Diffusion. According to the geometric distribution of pore throats and the state of the fluid in them, the diffusion of substances in porous media can be divided into three patterns:

(1) Volume diffusion: When the mean free path of the molecule is smaller than the diameter of the capillary channel, the molecule mainly collides with other molecules but less with the wall. The molecular diffusion of the fluid contained in it can still be expressed by Fick’s law, but the molecular diffusion coefficient calculated by it needs to be corrected. The diffusion coefficient at this time is

\[
D_{\text{ABp}} = D_{\text{AB}} \phi / \tau
\]  

(31)

where $\phi$ is the porosity (decimal) of porous media, and $\tau$ is the tortuosity factor that indicates the degree to which the diffusion distance is increased owing to the tortuous pores.

(2) Knudsen diffusion: If the diameter of the capillary channel is much smaller than the mean free path of gas molecules or if the pressure is very low, molecules are more likely to crash into molecules than into the wall. Under these conditions, the diffusion resistance along the porous medium depends on the collisions between the molecules and the wall. According to the motion theory of gas molecules, the diffusion resistance can be derived from the Knudsen diffusion coefficient

\[
D_{\text{kp}} = 97.0 \times r \sqrt{\frac{T}{m_{A}}}
\]  

(32)
where \( r \) denotes the average radius of the capillary channel, \( T \) is the absolute temperature, and \( m_A \) is the relative molecular weight of the tracer.

(3) Transition zone diffusion: This indicates material diffusion in the capillary pores between the Knudsen diffusion and volume diffusion. The coefficient can be expressed as

\[
D_p = \left( \frac{1}{D_{lp}} + \frac{1}{D_{kp}} \right)^{-1}
\]

(33)

For special reservoirs, the transition zone diffusion coefficient or Knudsen diffusion coefficient can be considered.

4.3. Gas Tracer Convection–Diffusion Equation.

4.3.1. Convection–Diffusion–Seepage Equation. Consider the micro-element cube shown in Figure 11 as an example. There is a diffuse substance \( i \) at point \( M \) in the middle of the micro-element body, and its mass flow rate is \( u_i \).

In the \( x \) direction, the mass flow rates of the substance \( i \) at points \( M' \) and \( M'' \) are

\[
u_{M'} = u_i - \frac{\partial u_i}{\partial x} \frac{dx}{2}
\]

(34)

\[
u_{M''} = u_i + \frac{\partial u_i}{\partial x} \frac{dx}{2}
\]

(35)

The mass flow of the substance \( i \) flowing through surfaces \( a' \) \( b' \) and \( a'' \) \( b'' \) in time \( dt \) is

\[
M_{i',b'} = \left( u_i - \frac{\partial u_i}{\partial x} \frac{dx}{2} \right) \phi dy dz dt
\]

(36)

\[
M_{i'',b''} = \left( u_i + \frac{\partial u_i}{\partial x} \frac{dx}{2} \right) \phi dy dz dt
\]

(37)

By subtracting eq 37 from eq 36, we have the difference between the mass inflow and mass outflow of the substance \( i \) in the \( x \) direction

\[
\Delta M_x = M_{i',b'} - M_{i'',b''} = -\frac{\partial u_i}{\partial x} \phi dx dy dz dt
\]

(38)

Similarly, the differences between the mass inflow and mass outflow of substance \( i \) in the \( y \) and \( z \) directions can be expressed as follows

\[
\Delta M_y = \frac{\partial u_i}{\partial y} \phi dx dy dz dt
\]

(39)

\[
\Delta M_z = \frac{\partial u_i}{\partial z} \phi dx dy dz dt
\]

(40)

Therefore, by adding eqs 39 and 40, we obtain the difference in the mass of substance \( i \) in the micro-element cube within time \( dt \)

\[
\Delta M = \Delta M_x + \Delta M_y + \Delta M_z
\]

(41)

As the substance \( i \) diffuses in all directions of the micro-element body (proportional to the flow velocity and the concentration gradient in all directions), the equation can be rewritten as

\[
-\frac{\partial C}{\partial x} = \nu_i \frac{\partial C}{\partial y} + \nu_i \frac{\partial C}{\partial z} - \frac{\partial u_i}{\partial y} - \frac{\partial u_i}{\partial z} - \frac{\partial u_i}{\partial t} = \frac{\partial C}{\partial t}
\]

(42)

Equation 42 is the three-dimensional convective-diffusion continuity equation for the tracer.

4.3.2. One-Dimensional Convection–Diffusion Equation. A one-dimensional convection–diffusion continuity equation can be derived from the convection–diffusion continuity equation

\[
-\frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}
\]

(43)

According to Fick's law, we can get

\[
-\frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}
\]

(44)

where \( D \) is the diffusion coefficient and \( C \) is the concentration of the diffusing substance.

where \( D = D_{lp} + D_{kp} \).

Assuming that a certain tracer with a concentration of \( C_0 \) is continuously injected into the infinite formation at \( x = 0 \), the definite solution condition is

\[
\begin{align*}
C &= C_0 & x &= 0 \\
C &= 0 & x &= \infty
\end{align*}
\]

The analytical solution to the above problem is

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - vt}{2\sqrt{Dt}} \right) + \frac{1}{2} \text{erfc} \left( \frac{vx}{2\sqrt{D}} \right)
\]

(45)

Generally, while studying the gas tracer between wells, the distance between the injection well and the production well is large. According to the above equation, the exponential function approaches 0 when \( x \) is large, and the error of the bounded function is always less than 2. Therefore, the second term on the right-hand side of eq 45 can be ignored when studying the concentration at the outlet of the production well.

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - vt}{2\sqrt{D}} \right)
\]

(46)

The length, \( L \), of the mixed zone (concentration ranges from 0 to \( C_0 \)) is

\[
L = 8/\sqrt{D}
\]

4.3.3. Slug Flow of Tracers in the Oil Layer. For the small slug flow in the oil layer, assuming that the edges of the preslug mixing zone and the postslug mixing zone are similar in shape and fit well with each other, the concentration at any point of the tracer slug flow can be calculated as

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - vt - \Delta x}{2\sqrt{D}} \right) - \frac{1}{2} \text{erfc} \left( \frac{x - vt}{2\sqrt{D}} \right)
\]

(47)

Differentiating both sides of eq 47, we have

\[
\frac{C}{C_0} = \frac{\Delta x}{4\sqrt{4\pi Dt}} \exp \left( \frac{(x - vt)^2}{2\sqrt{D}} \right)
\]

(48)
The authors declare no competing financial interest.

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NOMENCLATURE

\( v_m \): migration velocity of the oil phase, m/s
\( v_s \): migration velocity of steam in the reservoir, m/s
\( K \): porosity (decimal) of porous media
\( m_r \): relative molecular weight of the tracer
\( D \): diffusion coefficient
\( C_r \): concentration of the diffusing substance
\( r \): average radius of the capillary channel, m
\( T \): absolute temperature, °C
\( p \): reservoir pressure, MPa
\( r \): dimensionless pore volume of gas injected at any time during breakthrough, m
\( V \): dimensionless pore volume of the injected gas at breakthrough, m
\( V_{p,c} \): tracer slug volume in the well pattern model
\( Z \): gas tracer retention coefficient which considering the oil phase migration velocity
\( Z_c \): reservoir description coefficient
\( \theta \): stagnation coefficient of the gas tracer

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