Optimization of the slotted liners parameters during dual tubing steam injection process

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Abstract. To study the distribution of steam parameters along the wellbore and the influence of slotted liners parameters on the effect of reservoir uniform preheating during the dual tubing steam injection process. Based on the structural characteristics of screen pipe completion and the simultaneous steam injection technology of long and short tubing, a coupled numerical model of fluid flow and heat transfer in reservoir and wellbore was established, and the model was solved by full implicit finite difference method and iterative technique. The results show that when the density, width and length of the slotted liners increase from 350 to 550/m, 0.20 to 0.40 mm and 35 to 75 mm, respectively, the difference of steam quality at the two ends of steam convergence position in the annuli increases by 0.41%, 2.26% and 1.71%, and the reservoir heating uniformity decreases by 1.49%, 2.68% and 2.08%, respectively. Optimizing the slotted liners parameters and reducing the steam quality difference at the convergence position of annuli can improve the uniform heating degree of reservoir along the horizontal wellbore.

1. Introduction

Heavy oil is one of the most important energy resources, and it is mainly distributed in the United States, Canada, China and Venezuela. With the increasing difficulty in the development of conventional oil and gas resources, it is of great significance to develop heavy oil resources [1-4]. However, due to the reservoir heterogeneity and variable mass flow in horizontal wellbore, uneven reservoir heating is the main reason for low reservoir reserves utilization [5-10]. As the slotted liners parameters have an important influence on the distribution of steam parameters along horizontal wellbore and the uniformity of reservoir heating in the process of dual tubing steam injection process. Therefore, it is of great significance to explore the effect of slotted liners parameters during dual tubing steam injection process.

At present, dual tubing steam injection technology has been widely used in the development of heavy oil reservoirs. However, the relevant research on this technology is still lacked. In recent years, Wu et al. [11] and Sun et al. [12, 13] have established fluid flow and heat transfer models in dual tubing steam injection wellbore, and predicted the distribution of key parameters in the long tubing (LT) and annuli. However, these models are analytical models, and neglected the effect of changes of reservoir physical parameters with time and slotted liners parameters on reservoir heating.

In this paper, based on the structural characteristics of screen pipe completion and the simultaneous steam injection technology of long and short tubing, a new model of dual tubing steam injection...
process was established, and the model was solved by full implicit finite difference method and iterative technique. This study can provide a theoretical reference for optimizing the parameters of slotted liners and improving the uniformity of reservoir heating.

2. Reservoir governing equations

The mass conservation equation for each phase (oil, water, and steam) can be derived as follows:

\[
V \cdot \left( \frac{\alpha k_w}{\mu_w} \nabla (P_w - \rho_w g D) \right) + \rho_w q_w + m_w = \frac{\partial}{\partial t} (\rho_w S, \varphi) \tag{1}
\]

\[
V \cdot \left( \frac{\alpha k_o}{\mu_o} \nabla (P_o - \rho_o g D) \right) + \rho_o q_o + m_o = \frac{\partial}{\partial t} (\rho_o S, \varphi) \tag{2}
\]

\[
V \cdot \left( \frac{\alpha k_g}{\mu_g} \nabla (P_g - \rho_g g D) \right) + \rho_g q_g - m_g = \frac{\partial}{\partial t} (\rho_g S, \varphi) \tag{3}
\]

Considering the heat exchange between the wellbore and the reservoir, a modified energy conservation equation is developed as follow [5-7]:

\[
\nabla \cdot (\lambda \nabla T) + V \cdot \left( \sum_{i=1}^{3} \rho_i \mu_i \left( \nabla P_i \cdot \nabla g \rho_i g D \right) \right) - Q_{\text{well}} + Q_{\text{soil}} + Q_{\text{con}} = \frac{\partial}{\partial t} \left( S \rho_i U_i \right) \tag{4}
\]

To describe the equilibrium relationship between steam and water, the steam-water equilibrium equation is given as follow [14].

\[
T = T_s(P) \tag{5}
\]

Where \( \alpha \) is the unit conversion coefficient; \( P \) is the pressure, Pa; \( q \) is the unit volume flow rate, m\(^3\)/s; \( S \) is the saturation; \( k \) is the relative permeability, um\(^2\); \( \mu \) is the viscosity, Pa·s; \( \rho \) is the density, kg/m\(^3\); \( m \) is the condensate steam mass flow rate per unit volume, kg/(m\(^3\)/s); \( \varphi \) is the porosity of the reservoir; \( g \) is gravitational acceleration, m/s\(^2\); \( \lambda \) is the heat conductivity coefficient of rock, W/(m·°C); \( Q_{\text{conv}} \) is the heat loss rate to the boundary layer, J/s; \( Q_{\text{well}} \) is the heat loss rate from wellbore to the reservoir, J/s; \( U \) is the internal energy, J/kg; \( \rho_r \) is the rock density, kg/m\(^3\); \( H \) is the enthalpy, J/kg; \( T \) is the reservoir temperature, °C.

3. Wellbore governing equations

3.1. Steam flow model in the LT

The steam mass flow rate remains unchanged in the LT. According to the mass conservation principle, the mass conservation equation is given by:

\[
\frac{dm_{\text{steam}}}{dl} = \pi r_l^2 \frac{d(\rho_v v_i)}{dl} = 0 \tag{6}
\]

The momentum conservation equation for steam flow in the LT is derived as follow:

\[
\frac{dp_{\text{steam}}}{dl} + \frac{r_i}{\pi r_l^2} \frac{d(\rho_v v_i)}{dl} = -\frac{d(\rho_v v_i)}{dl} \tag{7}
\]

The energy conservation equation is developed as follow:

\[
\frac{dQ}{dl} = -\frac{d}{dl} \left[ m_i \left( H + \frac{v_i^2}{2} \right) \right] \tag{8}
\]

3.2. Steam flow model in the annuli

During dual tubing steam injection process, the steam mass flow rate in the annuli is not a constant, and the mass conservation equation for steam flow in the annuli can be written as:

\[
\frac{dm_{\text{steam}}}{dl} = -m_{\text{steam}} \tag{9}
\]

The momentum conservation equation for steam flow in the annuli is given as:

\[
\frac{dp_{\text{steam}}}{dl} + \frac{r_i}{\pi r_l^2} \frac{d(\rho_v v_i)}{dl} = -\frac{d(\rho_v v_i)}{dl} \tag{10}
\]
The energy conservation equation in the annuli is presented as follows:

\[
\frac{dQ_{\text{li}}}{dl} - \frac{dQ_{\text{ai}}}{dl} + m_{l} \left( h_{l} + \frac{v_{l}^2}{2} \right) = - \frac{d}{dl} \left[ m_{l} \left( h_{a} + \frac{v_{a}^2}{2} \right) \right]
\]  \hspace{1cm} (11)

Where \( m_{l} \) and \( m_{a} \) are the steam mass flow rate in the LT and annuli, respectively, kg/s; \( dl \) is the length of the microsegment, m; \( m_{sl} \) is the steam injection rate, kg/(m·s); \( r_{l} \) and \( r_{ai} \) are the equivalent radius of the LT and annuli, respectively, m; \( v_{l} \) and \( v_{a} \) are the steam flow velocity in the LT and annuli, respectively, m/s; \( \rho_{l} \) and \( \rho_{a} \) are the steam density in the LT and annuli, respectively, kg/m\(^3\); \( P_{l} \) and \( P_{a} \) are the steam pressure in the LT and annuli, respectively, Pa; \( \tau_{l} \) and \( \tau_{a} \) are the friction force in the LT and annuli, respectively, N; \( h_{l} \) and \( h_{a} \) are the steam enthalpy in the LT and annuli, respectively, J/kg; \( v_{ai} \) is the radial steam injection velocity, m/s; \( Q_{l} \) and \( Q_{a} \) are the heat exchange rate in the LT and annuli, respectively, J/s.

3.3. Coupled equations
The reservoir model and wellbore model can be coupled by steam injection rate from the annuli to the reservoir is presented as follow:

\[
m_{li} = \rho_{a} \cdot J \cdot (P_{a} - P) \cdot I_{s}
\]  \hspace{1cm} (12)

Where \( J \) is the well index; \( I_{s} \) is the steam absorption index; and \( P \) is the reservoir pressure, Pa.

4. Results analysis
With the developed new model, the profiles of steam quality and reservoir temperature along the horizontal wellbore are obtained as shown in Figure.1-6. The input parameters for simulation are listed in Table 1.

| Parameters                      | Values | Parameters                      | Values |
|---------------------------------|--------|---------------------------------|--------|
| Reservoir top depth /m          | 180    | Reservoir thickness /m          | 20     |
| Reservoir pressure /MPa         | 0.22   | Reservoir temperature /°C       | 10     |
| Porosity /%                     | 33     | Oil saturation /%               | 75     |
| Horizontal permeability /10\(^{-3}\)\,um\(^2\) | 2700   | Vertical permeability /10\(^{-3}\)\,um\(^2\) | 1890   |
| Length of horizontal wellbore /m | 850    | Reservoir thermal diffusivity /(m\(^2\)/h) | 0.004  |
| Steam pressure/(MPa)            | 2.0    | Steam quality                   | 0.95   |

4.1. Width of the slotted liners
As shown in Figure.1 and 2. It can be seen that with the increase of the slot width, the steam quality in the LT is almost unchanged, this is because the steam flow rate in the LT is a constant. However, the steam quality in the annuli decreases, because with the width of the slotted liners increasing, more steam is injected into the reservoir, which leads to more heat loss. When the width of the slotted liners increases from 0.20 to 0.40 mm, the difference of steam quality at the two ends of steam convergence position increases from 2.03% to 4.29%, increased by 2.26%. Influenced by the difference of steam enthalpy between two ends of steam convergence position, the ratio of maximum reservoir temperature to average reservoir temperature along wellbore increases from 1.007 to 1.034, increasing by 0.027, and the reservoir uniform heating degree decreases by 2.68%. Therefore, reducing the width of the slot and choosing suitable injected steam quality of short and long tubing can reduce the difference of steam quality at the two ends of annuli convergence position, which is conducive to the reservoir uniform heating along the horizontal wellbore.
4.2. Length of the slotted liners

As shown in Figure 3 and 4. It is found that with the increase of the slot length, the steam quality in the LT is almost unchanged, this is because the steam flow rate in the LT is a constant. However, the steam quality in the annuli decreases, because with the length of the slotted liners increasing, more steam is injected into the reservoir, which leads to more heat loss. When the length of the slotted liners increases from 35 to 75 mm, the difference of steam quality at the two ends of steam convergence position increases from 2.31% to 4.02%, increased by 1.71%. Influenced by the difference of steam enthalpy between two ends of steam convergence position, the ratio of maximum reservoir temperature to average reservoir temperature along wellbore increases from 1.008 to 1.029, increasing by 0.021, and the reservoir uniform heating degree decreases by 2.08%. Therefore, reducing the length of the slot and choosing suitable injected steam quality of short and long tubing can reduce the difference of steam quality at the two ends of annuli convergence position, which is conducive to the reservoir uniform heating along the horizontal wellbore.

4.3. Density of the slotted liners

As shown in Figure 5 and 6. It is observed that with the increase of the slot density, the steam quality in the LT is almost unchanged, due to the steam flow rate in the LT is a constant. However, the steam quality in the annuli decreases, because with the density of the slotted liners increasing, more steam is injected into the reservoir, which leads to more heat loss. When the density of the slotted liners increases from 350 to 550/m, the difference of steam quality at the two ends of steam convergence position increases from 3.18% to 3.59%, increased by 0.41%. Influenced by the difference of steam enthalpy between two ends of steam convergence position, the ratio of maximum reservoir temperature to average reservoir temperature along wellbore increases from 1.002 to 1.017, increasing
by 0.021, and the reservoir uniform heating degree decreases by 1.49%. Therefore, reducing the density of the slot and choosing suitable injected steam quality of short and long tubing can reduce the difference of steam quality at the two ends of annuli convergence position, which is conducive to the reservoir uniform heating along the horizontal wellbore.

![Figure 5. Distribution of steam quality along the wellbore with different slotted liners densities](image1)

![Figure 6. Distribution of reservoir temperature along the wellbore with different slotted liners densities](image2)

5. Conclusions
(1) The new coupled numerical model can predict the distribution of key thermal parameters of steam along the wellbore under different slotted liners parameters in the process of dual tubing steam injection.
(2) With the increase of slotted liners’ density, width and length, the difference of steam quality at both ends of steam convergence position in the annuli increases, while the uniformity of reservoir heating decreases gradually.
(3) During the dual tubing steam injection process, choosing appropriate steam injection parameters can reduce the steam quality difference at the annuli convergence position, which is beneficial to uniform reservoir heating.

In this paper, a numerical model for optimizing the slotted liners parameters during dual tubing steam injection process is developed for the first time. This study can provide some important suggestions for oilfield development. The authors’ following work will focus on: (1) the distribution of key parameters along the horizontal wellbore; (2) the optimization of the steam injection parameters, etc.

6. References
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