Modeling the production of hard-to-recover oil reserves using thermal methods

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Abstract. This article presents the theoretical and numerical implementation of the possibility of heating a reservoir with hard-to-recover oil. In a radial one-dimensional formulation, the article proposes a solution to the problem of hard-to-recover oil filtration with an increased viscosity coefficient. The procedure is performed in a reservoir using the thermal method of exposure in a single horizontal channel. Hot steam or water flows are used as a heat carrier. Only one channel is used as a heated and production well, which operates alternately.

1. Introduction

A specific feature of the current development stage of the Russian oil industry is that oil reserves are being replaced by hard-to-recover ones [1-3]. The lack of scientific and methodological foundations for the development of deposits with hard-to-recover reserves makes it urgent to solve the problems of modeling various processes in order to increase the efficiency of oil reserves recovery [6–8].

Among the reservoirs with hard-to-recover reserves, a large group of fields contains high-viscosity oils. In this regard, the problem of modeling oil production processes using thermal methods is an urgent issue.

2. Materials and methods

Let us consider the problem where a single horizontal channel operates in the process of thermal impact on a formation rock with hard-to-recover oil (Figure 1). The system consisting of the equations of continuity and heat flow for an oil-saturated reservoir \((r_c < r < \infty)\) is as follows:

\[
\frac{\partial m \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r m \rho \nu \right) = 0,
\]

\[
\rho c \frac{\partial T}{\partial t} + \rho m c_i \nu \frac{\partial T}{\partial r} = \frac{\lambda}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right),
\]

where \(r\) is the radial coordinate, which is measured from the center of the well, \(\lambda\) is the thermal conductivity, \(\nu\) is the oil velocity, \(\rho c\) is the specific heat capacity of the rock, \(T\) is the temperature of the rock, \(r_c\) is the radius of the channel, \(m\) is the porosity, \(\rho\), and \(c_i\) are the density and heat capacity of oil.
3. Results and Discussion

Darcy’s law helps to determine the rate of oil filtration in a porous medium in the following form:

\[ m \nu = -\frac{k}{\mu(T)} \frac{\partial p}{\partial r}. \]  \hspace{1cm} (2)

Here \( p \) is the pressure, \( k \) is the permeability of the porous medium.

We write the equation of state for oil in the linear approximation \[8,12\]

\[ \rho_i = \rho_{i0} \left( 1 - \alpha^T (T - T_0) + \alpha^p (p - p_0) \right). \] \hspace{1cm} (3)

The subscripts 0, \( \alpha^T \) and \( \alpha^p \) correspond to the initial values of oil parameters - the coefficients of compressibility and thermal expansion of oil.

In this problem statement, the viscosity-temperature dependence of \( \mu(T) \) for heavy or bituminous oil is as follows:

\[ \mu(T) = \mu_0 e^{-\gamma(T - T_0)}, \] \hspace{1cm} (4)

where \( \mu_0 \) is the oil viscosity parameter at the initial temperature of the medium \( T_0 \), \( \gamma \) is the temperature coefficient.

From expressions (1), considering (2) and (3), we obtain new expressions for temperature and pressure:

\[ \frac{\partial p}{\partial t} = \frac{\alpha^T}{\alpha^p} \frac{\partial T}{\partial t} + \frac{k}{\mu(T)} \frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right), \]

\[ \frac{\partial T}{\partial t} = \frac{k \rho c_i}{\mu(T) \rho c} \frac{\partial}{\partial r} \left( \frac{\partial T}{\partial r} \right) + \frac{\nu}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right). \] \hspace{1cm} (5)

Here \( \nu = \lambda / (\rho c) \) is the thermal diffusivity of the formation. The resulting system of expressions (5) makes it possible to simulate changes in temperature and pressure in an oil-saturated reservoir, thus making it possible to describe the process of oil recovery with an increased viscosity index in detail.

Development of a field with hard-to-recover oil involves continuous thermal impact on the formation and horizontal drilling \[15\]. The production of traditional easily recoverable oil has large-scale costs for the construction of sites where the field is being developed \[10, 11\]. Heavy oil makes everything different: the initial investment may not be impressive, but the costs during the operation of the well will be substantial. Monitoring heat consumption and oil production is an integral part of the development of a field with high-viscosity oil under thermal influence.

We formulate the equation for the total heat flux from the well to the reservoir:
\[ q^{(T)} = 2\pi r_c \lambda \left( \frac{dT}{dr} \right)_{r_c}. \]  

(6)

The total spent heat will be determined from the expression:

\[ Q = \int_0^t q^{(T)} dt. \]  

(7)

In this work, we used the formula described in [13, 14]:

\[ \mu(T) = \mu_0 e^{\gamma(T-T_0)}, \]  

(8)

where \( \gamma \) is the temperature coefficient, \( \mu_0 \) is the oil viscosity at a temperature of \( T_0 \).

For the mass flow rate of oil from the well, considering Darcy's law, we write the equation

\[ q^{(o)} = -\frac{2\pi r_c \rho_o k}{\mu(T)} \left( \frac{\partial p}{\partial r} \right)_{r_c}. \]  

(9)

The total oil produced can be calculated from the expression

\[ M = \int_0^t q^{(o)} dt. \]  

(10)

Let us consider the 1st stage of thermal impact on the oil reservoir. At this stage of development, we can study the heating of oil-saturated rock \( (t < t_1) \), while the channel used is closed and oil withdrawal is not carried out. At the channel boundary \( (r = r_c) \), the pressure gradient is equal to zero \((\partial p/\partial r = 0)\) and a constant temperature is maintained at \( T_e \) far from the well \((r \to \infty) \). The pressure and temperature of the formation are equal to the initial values \( p_0, T_0 \). This condition means that the thickness of the oil-bearing layer is much greater than the area where filtration and temperature drops are observed for the time interval of interest to us. At the initial stage of development \((t = 0)\) the pressure and temperature are \( p_0, T_0 \) respectively.

The accepted system of expressions (5) under the given boundary conditions was solved using an explicit scheme using the finite difference method. For the numerical implementation of the numerical solution, a uniform grid was constructed in the coordinate \( r_i = r_c + (i-1) \cdot h \) \((i=1, 2...N)\) and in time \( \tau = n \cdot \tau \). After replacing the differential operators with their finite-difference analogs, we obtain a system of linear algebraic equations (5):

\[
\begin{align*}
p_i^{t,+1} &= p_i^t + \frac{\alpha^{(T)}}{\alpha^{(p)}} (T_{i,+1}^t - T_i^t) + \frac{k \cdot \tau}{m \alpha^{(p)} h^2} \left( \frac{r_{i+1}}{\mu(T_{i+1})} (p_{i+1}^t - p_i^t) - \frac{r_i}{\mu(T_i)} (p_i^t - p_{i-1}^t) \right), \\
T_i^{t,+1} &= T_i^t + \frac{k \rho_o c_i \tau}{\mu(T_i)^2 \rho c} \left( \frac{p_{i+1}^t - p_i^t}{h} + \frac{v_i \tau}{r h^2} \right), \\
\mu(T_i^{t,+1}) &= \mu_0 e^{-\gamma(T_i^t - T_e)}. 
\end{align*}
\]  

(11)

The boundary conditions will be:

\[ p_0^t = p_i^t; \quad p_N^t = p_0 T_i^t = T_e; \quad T_N^t = T_0. \]  

(12)

The boundary condition at \( r = \infty \) is shifted to the boundary of the grid \( r = r_\infty \).

The Courant condition determined the stability conditions for the difference scheme. For this, the following values were calculated, the smallest of which is taken as the step of integration over the time coordinate, i.e. \( \tau = \min\{\tau_1, \tau_2, \tau_3\} \).
The study performed numerical calculations for the following parameter values: $p_0 = 0.5 \text{ MPa}$, $T_c = 160^\circ \text{C}$, $r_c = 0.05 \text{ m}$, $\lambda = 1.28 \text{ W/}(\text{m} \cdot \text{K})$, $\rho_i = 980 \text{ kg}/\text{m}^3$, $c_i = 1400 \text{ J/}(\text{K} \cdot \text{kg})$, $\rho c = 2.5 \cdot 10^6 \text{ J}/(\text{K} \cdot \text{m}^3)$, $\nu = 10^{-6} \text{ m}^2/\text{s}, \alpha^{(T)} = 10^{-5} \text{ K}^{-1}$, $\alpha^{(p)} = 5 \cdot 10^{-9} \text{ Pa}^{-1}$, $k = 10^{-12} \text{ m}^2$, $m = 0.3$.

Figure 2 is a graphical illustration of the viscosity-temperature dependence for oil products at an initial value of the viscosity index $\mu_0 = 10 \text{ Pa} \cdot \text{s} \ (\gamma = 0.047\text{K}^{-1})$. It follows from the graph that a high rate of decrease in viscosity is observed at the initial stage of temperature increase. Furthermore, the viscosity slowly decreases along with further heat exposure.

\[
\tau_i = \frac{h^2}{2\nu}; \tau_2 = \frac{\mu h^2 \rho c}{2k \rho c_i}; \tau_3 = \frac{m \alpha^{(p)} \rho h^2}{2k}
\]  \ (13)

It should be noted that the quantitative dependences of viscosity on temperature are very different for different oils. However, qualitatively they are approximately the same. Assuming that the viscosity of liquefied oil in the temperature range under consideration is 10 times higher than the viscosity of water, the expression $\gamma$ is obtained for the coefficient $\gamma = 0.047\text{K}^{-1}$. The maximum rate of decrease in the viscosity parameter is observed at the initial stage of temperature increase; the intensity of viscosity decrease slows down with further heating.

Figure 3 shows a graphical illustration of the field of pressure dynamics (a), temperature (b) and viscosity (c) in a reservoir with high-viscosity oil at different periods of heating time $t_i = 10, 20, 30 \text{ days}$. At this stage of the thermal effect on high-viscosity oil, a certain area of several meters is located near the heating boundary, which leads to an increase in pressure in the reservoir, the maximum value of which is reached at the boundary. The pressure increase due to thermal expansion of oil will be insignificant (less than 0.1 MPa). As the temperature rises in the reservoir, the viscosity of the produced product decreases in the boundary region of the well. The thickness of the oil-saturated layer determines the time of thermal impact on the reservoir $t_i$. 

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{figure2.png}
\end{center}
\caption{The dependence of the viscosity of oil $\mu$ on temperature $T$}
\end{figure}
Figure 3. Distribution of pressure (a), temperature (b) and viscosity (c) along the coordinate r at different times of heating t = 10, 20 and 30 days

It is proposed to consider the holding stage, which can be proposed to increase oil recovery after the heating stage \( t_1 < t < t_2 \). At this stage of reservoir development, we perform shutdown until a uniform temperature distribution in the reservoir is achieved. At this stage of the thermal effect, we reduce the risk of destruction of the bottomhole region of the well during its development in the “overheated” state. Then the absence of heat flux \( \frac{\partial T}{\partial r} = 0 \) at \( r = r_c \) will be the boundary condition for the second equation from (5). The distributions of pressure \( p = p(r) \) and temperature \( T = T(r) \) obtained from the previous solution are the initial conditions at \( t = t_1 \).

In this case, we solve the standard system of linear algebraic equations (11) with the following boundary conditions:

\[
p^i = p_{i-1}^j; \quad p_N^i = p_0; \quad T_1^i = T_2^j; \quad T_N^i = T_0
\]  
(14).

It should be noted here that the values \( \tau_2 \) and \( \tau_j \) in formulas (13) are variables. Therefore, we use an uneven time grid in the numerical implementation of the problem for this stage, where the value \( \tau \) is recalculated at each time step. This approach allows you to increase the speed of the task counting.

Figure 4 shows an illustration of the evolution of the pressure field (a), temperature (b) and viscosity (c) after stopping heating of the oil-saturated reservoir at different time intervals \( t_2 = 10, 20 \) and 30 days.

At the stage of holding during the considered time, there is an alignment of the heated area in the formation and an increase in the heated area with a reduced viscosity parameter. Effective use of the thermal method of influencing the oil reservoir and increasing oil recovery is achieved by increasing the heated zone with a reduced viscosity parameter.
Let us consider the stage of channel functioning \((t > t_2)\), where near the boundary \(r = r_c\) there is a heated region with a reduced viscosity parameter, i.e. at the initial moment of time \((t = t_2)\) the distributions of pressure \(p = p(r)\) and temperature \(T = T(r)\) are taken from the previously obtained solutions for the heating and holding stage. At this stage of development, we will solve the system of equations for pressure and temperature \((5)\) with the following boundary conditions: at the boundary \(r = r_c\) the heat flux is absent \(\partial T / \partial r = 0\) and constant pressure \(p_c\) (\(p_c < p_0\)), is maintained; at the section \((r \to \infty)\) remote from the well, the initial parameters are temperature and pressure \(T_0, p_0\).

After passing to finite-difference analogs, the system \((11)\) is solved with the boundary conditions:
\[
p^j_1 = p^j_c; \quad p^j_N = p_0; \quad T^j_1 = T^j_c; \quad T^j_N = T_0.
\]

It also uses an uneven temporal grid.

Figure: 5 illustrates the results of calculations for the pressure field (a), temperature (b) and viscosity (c) at different filtration times of 2, 5, and 7 days. The well pressure takes the value \(p_c = 0.3\) MPA, the heating time of the oil reservoir is \(t_1 = 30\) days, and the holding time is \(t_2 = 30\) days. The dashed line corresponds to the case of the formation heating during the time \(t_1 = 30\) days.

The propagation of the filtration wave front is much deeper than the temperature differences. Later on, a noticeable decrease in temperature happens in the developed part of the formation near the studied channel and the viscosity value increases. As a result, there is a decrease the rate of oil filtration in the porous medium.

Without the stage of keeping the oil reservoir in a closed state, the rate of temperature decrease increases near the well. If there is a holding stage, then the temperature spreads deep into the formation; an intensive selection of accumulated heat from the oil-bearing formation happens during filtration. The stage of formation holding significantly reduces the threat of destruction of the well bottomhole zone due to severe overheating and can contribute to an increase in the filtration period of products with a reduced viscosity index.
Figure 5. Distribution of pressure (a), temperature (b) and viscosity (c) along the coordinate at different times of filtration of 2, 5, and 7 days. The dashed line corresponds to the case without reservoir holding.

4. Conclusion

The article discusses a numerical study of the filtration process of high-viscosity oil through one horizontal well, which is used first as a heating channel, and then as a production well. A system of differential equations for pressure and temperature is obtained for given boundary conditions. The system of equations is solved numerically by the finite difference method according to an explicit scheme. The task is solved in three stages. At the first stage, the oil reservoir is heated, which makes it possible to control the heating of the reservoir. The heating time depends on the thickness of an underlying rock. At the second stage, holding takes place in closed conditions to enhance oil recovery until the most uniform temperature distribution in the oil reservoir is achieved. At the third stage of the well operation, heated oil with a reduced viscosity index is filtered through the horizontal channel under study. The proposed method improves the efficiency of the development of an oil reservoir with hard-to-recover oil due to the possibility of uniform heating of the studied field area.

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