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Numerical Modeling Of Heavy Oil Displacement By Hot Water

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Abstract- Within the terms of considerable depletion and exhaustion of developed oil and gas reserves in the Republic of Tatarstan (RT), the substantiation of production volumes and the growth of hydrocarbon reserves is very relevant, and more attention is paid to highly viscious oils (HVO) and natural bitumen (NB) as the alternative sources of fuel and energy resources. The use of thermal methods for oil recovery increase is based on the ability of an oil reservoir to accumulate and transmit heat energy. Heat transfer is carried out mostly by heat conduction and convection. Water serves as a working agent at the application of thermal methods. Water carries more heat per unit mass than any other liquid. In this study, the numerical solution is presented concerning the problem of heavy oil with hot water displacement in the linear formulation. The paper describes a mathematical model and a physical process that occurs during the thermal impact on the oil-saturated during hot water injection into the reservoir with heavy oil. The key assumptions of the model and the methods of these equations solutions are specified. The analysis of numerical experiment allows you to suggest the possibility of using this method when an optimal method of heavy oil field development is seleceted.
Keywords: hot water injection, modeling, heavy oils, influx stimulation, water saturation profiles, viscosity dependence on temperature, thermal methods of oil recovery enhancement.

1. INTRODUCTION

The global energy situation is such that the energy consumption in the world is expected to double by 2050. At the same time, the growth of "easily accessible" oil is not keeping pace with current demand. Due to the trend of a gradual resource depletion, as well as due a significant increase of their costs, they use the development of higly viscious oils and bitumen deposits [1-3]. As you know, this process is accompanied by a number of problems, so new optimization techniques of such a development is a relevant issue today.

2. MATERIALS AND METHODS

In this paper the process of heavy oils displacement with hot water will be considered. This method of influx heat stimulation, despite the relatively low efficiency as compared with other methods, such as the displacement with hot steam, is the most technologically simple one and therefore it is still encountered in practice. According to [4], three areas are observed during the displacement of oil with hot water:

1. The area of oil displacement by hot water.
2. The area of oil displacement by water the temperature of which is equal to the layer temperature.
3. The area unaffected by injected water.

The schematic profiles of water saturation and temperature presented on Figure 1 correspond to the one-dimensional displacement (or piston one) when the processes of gravitational separation, the formation of injected water "fingers" and other processes are neglected. Yet the consideration of such a process makes it possible to note some characteristic features of the process under consideration.

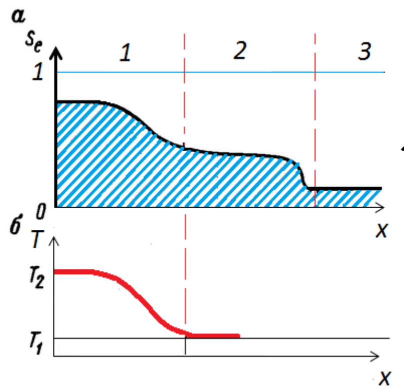

Fig. 1. Water saturation and temperature profiles when oil is displaced with hot water [4]

The temperature effect on the process of displacement is expressed by the following effects [4]:

1. The thermal expansion of oil during heating.
2. The reduction of oil viscosity and, accordingly, mobility relation.
3. The change of rock wettability with water and oil.
4. The change of interphase tension in the oil-water system.

We will study the process of oil displacement with hot water using the numerical calculations.

Let's consider the problem of heavy oil displacement with hot water in a linear system shown on Fig. 2. The production and injection wells are arranged in rows, so in the large-scale approximation the flow between the rows of wells is a linear one. Let's take a lot corresponding to the flow for one injection and one producing well for modeling.

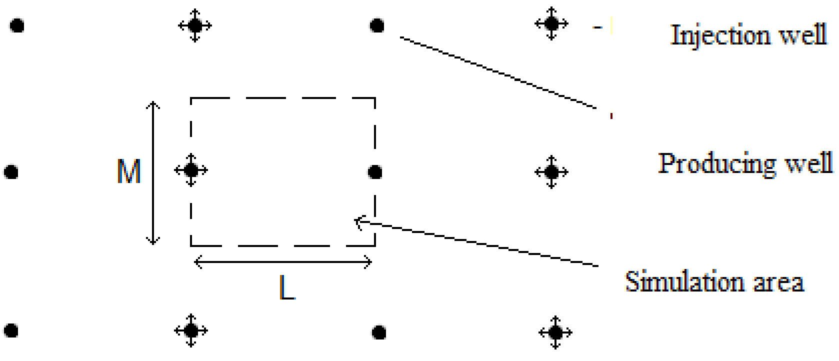

Fig. 2. The location of injection and producing wells

In order to simulate this process it is convenient to use a linear homogeneous production. The selection debit, the pressure on the far border, as well as the temperature of the injected water will be given by the means of boundary conditions. The temperature effect on the filtration process is expressed by the dependence of oil viscosity and relative phase permeabilities on the temperature.

This model is simple enough, so it has the number of approximations:

1. Isotropic and homogeneous layer.
2. The absence of the two-dimensional effects.
3. The filtration occurs according to linear Darcy law.
4. Fluid properties except of oil viscosity are constant ones.
5. The thermodynamic effects and phase transitions are absent.
6. The layer properties are not dependent on temperature and pressure.
7. There are no heat losses in the surrounding impermeable rocks.

Then the system of mathematical equations describing the considered process is presented.

The law of mass conservation in a reservoir is expressed by the equations of continuity, recorded for each phase (index l is water, index 2 is oil):

$$m\frac{\partial s_1}{\partial t}+\frac{\partial u_1}{\partial x}=0 \quad (1)$$

$$m\frac{\partial s_2}{\partial t}+\frac{\partial u_2}{\partial x}=0 \quad (2)$$

Here s – saturations, u– phase rates, m – porosity.

The filtration rate is calculated by the generalized Darcy's law:

$$u_1=-\frac{k}{\mu_1}k_1(s_1)\frac{\partial p}{\partial x} \quad (3)$$

$$u_2=-\frac{k}{\mu_2(T)}k_2(s_1)\frac{\partial p}{\partial x} \quad (4)$$

where k – permeability, k_1 и k_2 – relative phase permeabilities, μ_1. and μ_2 – oil and water viscosities, p – pressure.

The relative phase permeabilities are functions of saturation and oil viscosity is the function of temperature.

Heat transfer equation:

$$\frac{\partial}{\partial t}\left[\left(m(c_1s_1+c_2s_2)+(1-m)c_n\right)T\right]+\frac{\partial}{\partial x}\left[(c_1u_1+c_2u_2)T\right]=\frac{\partial}{\partial x}\left[\bar{\lambda}\frac{\partial T}{\partial x}\right]$$
(5)

Here c – volumetric heat capacity, $\bar{\lambda}$ – thermal conductivity ratio for saturated porous medium, T_0 – surrounding rock temperature, h – layer thickness.

Thermal conductivity ratio of saturated porous medium will be defined as follows:

$$\bar{\lambda}=m(s_1\lambda_1+s_2\lambda_2)+(1-m)\lambda_n$$

where λ_n – the thermal conductivity of rock matrix.

The terms in the equation of thermal energy transfer are responsible for the following physical effects: accumulation, convective and conductive heat energy transfer and also heat loss to the surrounding rock layer.

The natural ratio supplementing the system of equations (1) - (5):

$$s_1+s_2=1 \quad (6)$$

Boundary conditions:

$$\left.\frac{\partial p}{\partial x}\right|_{x=0} = -\frac{Q}{hMk\left(\dfrac{k_1}{\mu_1}+\dfrac{k_2}{\mu_2}\right)}$$

$$p|_{x=L} = p_L \quad (7)$$

$$s_1|_{x=L} = 1$$

$$T|_{x=L} = T_L$$

where M is the distance between the wells in a row, Q – selection debit.

In order to make a basic system of equations (1) - (5) a closed one, it must be supplemented by closing relations. In this paper, we use the expressions for phase permeability from two papers [5] and [7] as an example. The first of these represents direct dependencies on the temperature of phase relative permeabilities and residual oil saturation, and the second one has the dependencies on oil viscosity. It should be noted that the oil in the second case (the papaer [7]) is less viscous than oil, used in [6]. Now, the basic system of equations is a closed one and, therefore, has a unique solution. The system of equations will be solved iteratively as follows:

1. We find the pressure distribution at the current step by time, which is solved by a sweep algorithm.
2. Then the filtration rate is calculated.
3. Let's obtain the saturation of the first and second phase.
4. Let's calculate the temperature using the sweep method.
5. Let's return to the step one until you reach the convergence of pressure, temperature and saturation. The problem solution algorithm was implemented using the programming language Borland Delphi.

3. RESULTS

Let's consider the features of one-dimensional non-isothermal process of oil displacement for two different types of fluids (which will be denoted as oil 1 [3] oil and 2 [4]) using the previously developed numerical model.

The results of numerical calculations for oil 1 are given below.

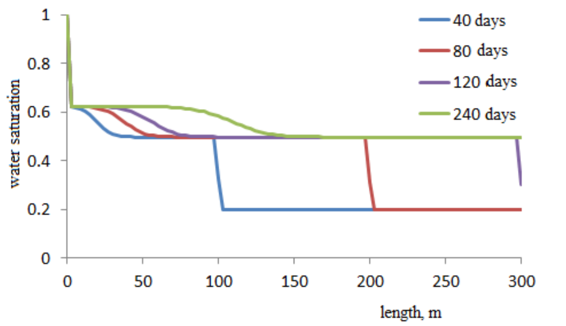

Fig. 3 Calculated profiles of water saturation (oil 1).

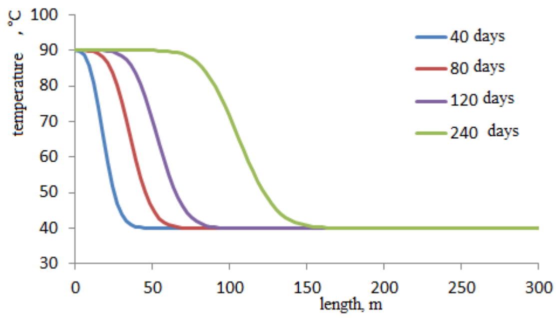

Рис. 4. Calculated profiles of temperature (oil 1).

The obtained profiles of water saturation and temperature repeat the profiles schematically shown at the beginning of the chapter at a qualitative level. Three zones are traced on the calculated curves: the displacement by hot water, the displacement by water at reservoir temperature and unaffected area injected by water.

The backlog of temperature front from the front of injected water is explained by the fact that the part of water heat energy is spent on the heating of a layer matrix. The increase of water saturation in a heated zone happens due to the reduction of residual oil saturation at temperature increase. At that the backlog is large enough: by the time when the water breaks in a production well, the temperature front passes only one-fifth part of the same distance.

The following figure shows the calculated oil recovery for the cases of displacement with different water temperature: calculations were added at 90 °C from 65 °C, as well as the case of an isothermal displacement.

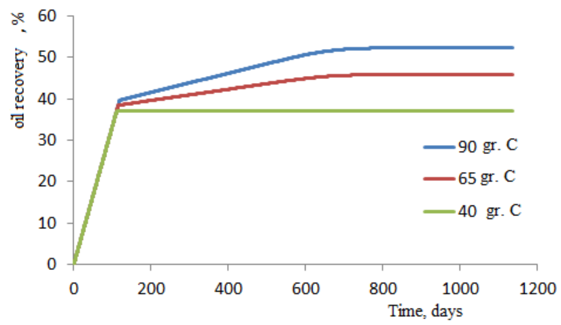

Fig. 5. Calculated oil recovery (oil 1).

The calculated curves have three stages of development. The first one is the return of oil prior to water breakthrough. In this case, the oil recovery is the maximum one. The second stage is the displacement of oil by warming a reservoir and thus the reduction of the residual oil saturation. This stage is a longer one, but less productive. And the last stage is the achievement of residual oil saturation value throughout the reservoir, the flooding of a well reaches 100%.

For oil 1 the oil recovery increase during the displacement of oil with hot water compared to the isothermal case made about 15%. At that the temperature rise of injected water in comparison with reservoir one made 50 °C. It is also worth noting that before the breakthrough of injected water the oil recovery, according to the calculations, does not depend on temperature.

Then, let's consider the calculation results obtained for oil 2. At that all other parameters remained the same as for the first case.

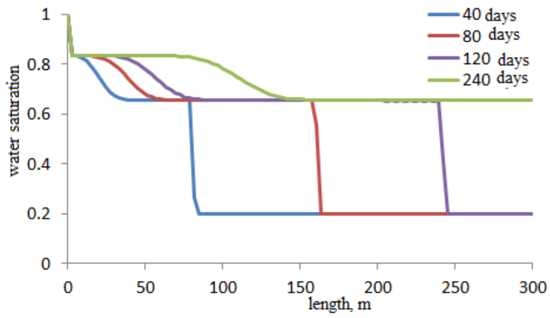

Fig. 6. Calculated profiles of water saturation (oil 2).

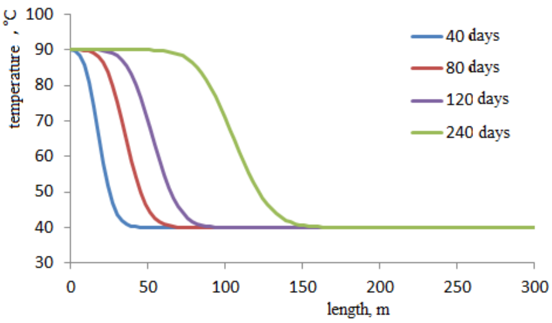

Fig. 7 Calculated profiles of temperature (oil 2).

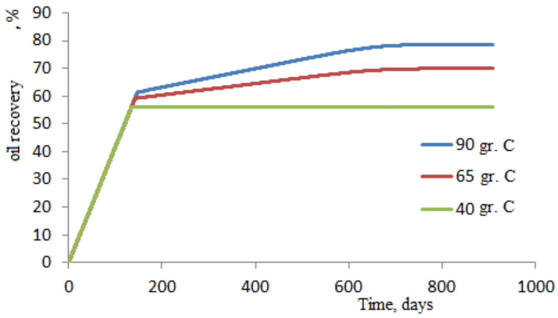

Fig. 8. Calculated oil recovery (oil 2).

As you see, the oil recovery in this case is higher, since the oil 2 is less viscous than the oil 1, and, accordingly, more mobile. The increase of ultimate oil recovery compared to the isothermal case made approximately 22%.

Also, comparing the calculations for oil and oil 2, we may make some conclusions about the features of a one-dimensional displacement model. Despite significantly different relative phase permeabilities for oil 1 and oil 2 the obtained saturation and oil recovery distributions are very similar at a qualitative level. This suggests that a major factor for one-dimensional model influencing the calculation is the value of the residual oil saturation, and the form of relative permeability curves has almost no influence on the result. This is a natural limit for the one-dimensional model. In order to study the finer processes associated with the changes in relative permeability, it is necessary to use two or three-dimensional models.

4. SUMMARY

In this paper, the following conclusions may be made:

1. The mathematical model of one-dimensional two-phase nonisothermal filtration was built and implemented.

2. The calculations were carried out, which proved the presence of three zones at hot water injection described in literature: the warmed part, the zone of oil displacement at reservoir temperature and the zone unaffected by injection water.

3. The oil recovery estimates were performed, which showed its increase up to 15% and 22% for various oils.

4. Oil saturation (depending on temperature) is the basic parameter which determines the calculation result for a one-dimensional model.

Overall, the one-dimensional model provides an overview of quantitative understanding concerning a sustainable displacement process of heavy oil with hot water. Also, the model is simple for implementation and requires less time for calculation compared with two- or three-dimensional models.

But if the multidimensional processes (gravity separation, unstable displacement, etc.) are predominant ones, the one-dimensional model will give incorrect results.

CONFLICT OF INTEREST

The author confirms that the presented data do not contain any conflict of interest.

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