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Satbayev University

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HYDRODYNAMIC CHARACTERISTICS OF ONE DIMENSIONAL DISPLACEMENT OF OIL BY LIQUID

Abstract. This article deals with a technique that has been developed for the purpose of calculating the displacement of oil by a homogeneous liquid based on hydrodynamic law considering the physical properties of fluids and reservoir permeability. Taking into consideration filtration methods and materials for underground hydraulics, volume flow of oil, time of the contour advancement and the total time of hydrocarbon extraction are determined.

It is known that with increasing depth, the methods of influence become more complex. In this case, it is more appropriate to use combined methods of exposure. Increasing the impact of various reagents also increases the productivity of the well, since in this case the method makes it possible to control the total production by hydrocarbons. To increase the productivity of wells, various methods are used, the purpose of which is to increase production, and thereby increase oil recovery from reservoirs. The most used method is water injection. However, such a problem is often very complex and, therefore, a limited number of methods are applicable to its solution.

So, in previously published works, to solve the problem, the viscosities of oil and water are equated. At the same time, it is believed that the oil and water permeability are also equal. Such a formulation distorts the results obtained.

To solve this problem, the authors reject such a formulation. At the same time, the results obtained are more applicable in practice, which makes it possible to more realistically apply this technique to solve numerous problems for enhanced oil recovery.

It should be noted, that the process of injection another fluid into the reservoir gives additional energy to the reservoir that is, in this case, the reservoir pressure increases and ultimately has a positive effect on increasing oil production. At the same time, the physical properties of the injected fluid also affect the productivity of production wells.

In a particular case, this also affects the oil recovery. However, when sweet or formation water is injected, in some cases, an increase in well water cut is observed, which sharply reduces the cost of oil produced, that is, regardless of the production method – naturally flowing, gas lift or mechanized - water cut dramatically affects oil recovery.

The proposed work, in a particular case, makes it possible to regulate the process of advancing the water-oil-bearing contour in the reservoir, creating a displacement process in the reservoir, which is of a piston nature, which in practical conditions contributes to an increase in oil production and a decrease in water cut in production wells.

Key words: oil and water permeability; dynamic viscosity; contour and bottomhole pressure; volume flow; displacement time; permeability; porosity; pressure gradient.

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ГИДРОДИНАМИЧЕСКИЕ ХАРАКТЕРИСТИКИ ОДНОМЕРНОГО ВЫТЕСНЕНИЯ НЕФТИ ЖИДКОСТЬЮ

Аннотация. В статье рассматривается методика, разработанная для расчета вытеснения нефти однородной жидкостью на основе гидродинамического закона с учетом физических свойств флюидов и проницаемости коллектора. С учетом методов фильтрации и материалов для подземной гидротехники определяют объемный расход нефти, время продвижения контура и общее время извлечения углеводородов.

Известно, что с увеличением глубины методы воздействия усложняются. В этом случае более целесообразно применение комбинированных методов воздействия. Увеличение воздействия различными реагентами также увеличивает производительность скважины, так как при этом метод дает возможность регулирования суммарной добычи по углеводородам. Для увеличения произво_ дительности скважин применяются различные методы, цель которых –увеличивать добычу, и тем самым увеличивать нефтеотдачу пластов. Наиболее применяемым методом является закачка в пласт воды. Однако часто такая задача является очень сложной и поэтому для ее решения применимо ограниченное число методов.

Так, в ранее опубликованных работах для решения задачи вязкости нефти и воды приравниваются. При этом, считают, что проницаемости по нефти и воде тоже равны. Такая постановка искажает полученные результаты.

Для решения данной задачи авторы отвергают такую постановку. При этом полученные результаты более применимы на практике, что дает возможность более реально применять данную методику для решения многочисленных задач для увеличения нефтеотдачи пластов.

Необходимо отметить, что процесс закачки в пласт иной жидкости дает дополнительную энергию пласту, то есть в этом случае увеличивается пластовое давление и в конечном итоге оказывает положительное влияние на увеличение объемов добычи нефти. При этом физические свойства закачиваемой жидкости также влияют на производительность добывающих скважин.

В частном случае это влияет и на нефтеотдачу. Однако при закачке пресной или

пластовой воды, в отдельных случаях наблюдается рост обводненности скважин, что резко снижает себестоимость добываемой нефти, то есть независимо от способа добычи – фонтанный, газлифтный или механизированный – обводненность резко влияет на нефтеотдачу.

Предлагаемая работа, в частном случае, дает возможность регулировать процесс продвижения контура водонефтеносности в пласте, создавая в пласте процесс вытеснения, который носит поршневой характер, что в практических условиях способствует увеличению добычи нефти и уменьшению обводненности эксплуатационных скважин.

Ключевые слова: проницаемость нефти и воды; динамическая вязкость; контурное и забойное давление; объемный расход; время вытеснения; проницаемость; пористость; градиент давления.

Introduction. Field practice shows that for many decades the development of the oil industry was carried out by drilling production wells and extracting hydrocarbons from reservoirs and horizons as a result of the use of resources of all natural types of reservoir energy. Water is a companion of oil from the moment of its formation, and the appearance of formation water in production wells was considered as contingency. However, it was noticed that more oil was extracted from wells where water appeared, and production was stable. At the same time, the problem of increasing the efficiency of oil displacement from the reservoir arose. As well, the natural water-drive mode of oil field development was adopted in the most efficient way. However, this method was first put forward in the post-war years.

The applicability of water injection, the displacement process in oil fields around the world is due to indisputable advantages:

a) the availability of water;

b) relative ease of injection implementation;

c) relatively high coefficients of oil displacement efficiency by water.

At present, conventional oil flooding, the process of oil displacement by water is the most effective method of enhanced oil recovery.

The process of oil displacement by liquid is aimed at replenishing reservoir energy resources and improving the ratio of viscosities of the displaced (oil) and displacing liquids. Therefore, the improvement of systems and technology for oil displacement by liquid are the main directions for increasing oil recovery from reservoirs and the volume of recoverable oil reserves.

The development of systems, technologies and methods for flooding oil fields in the world occurs simultaneously and independently. The analysis showed that the main aspects of the process of oil displacement by liquids with different physical and chemical properties, as a result of the complexity of the waterflooding principle, include the start time of waterflooding, the order of well drilling, well grid placement systems, waterflooding systems, process technology, etc.

Literary analysis shows that these works mainly consider the general principles of displacement. However, this paper considers the general case of oil displacement by water or other liquids that have different physical properties, both under atmospheric and reservoir conditions.

It should be noted that although the development of oil deposits makes it possible to study the structure of reservoirs, determine the mechanism of oil movement in reservoir conditions and use reservoir energy more economically, nevertheless, flooding of oil fields is carried out at associated high costs, which indicates the relevance of studying the displacement process in our time.

Theory and mathematical model. Field experience reveals that the task of oil displacement by water or gas represents a large theoretical practical process. The so-called secondary oil production methods consist in injecting water into oil reservoirs, which in the process of development essentially reaches a complete depletion. From the hydrodynamic point of view, these methods can be considered as extreme methods of field development. The development of fields by pressure maintenance is to stop the pressure drop when the field is not fully exploited (Shelkachev, 2002:132; Schterenlicht, 2005:655; Dontsov, 1977:360).

It should be noted that increasing of reservoir pressure is observed while injecting water or some other liquid. This is particularly noticeable when injecting liquid into the formation, when water flooding is carried out on a large scale and the injected liquid exceeds the extracted oil. However, key difference between secondary methods and reservoir pressure maintenance is based on the initial conditions of the production process. Secondary methods are the state of natural energy for the displacement of oil from the porous medium, and in the development with maintaining the reservoir pressure by water injection; it is carried out during the entire period of primary operation until oil deposits are depleted. More serious factors differing degree of impact on the process of oil recovery are closely connected with these differences.

These parameters include oil saturation fall in the reservoir, increasing of the viscosity of oil, reducing the reservoir volume ratio and increasing the surface tension of oil-water. These factors are more actively expressed at the secondary stage of field operation.

It should be noted, that increasing of the viscosity of oil as a result of a decrease in oil saturation worsens its mobility, and decrease of the oil reservoir volume coefficient increases the equivalent of commercial oil per unit of oil porosity decrease when pumping water into the reservoir.

Secondary methods of hydrocarbon extraction have the advantage, mostly when the pressure required for water injection, in some cases, is much lower than that used in the development of deposits by pressure maintenance. (Pikhachov et al., 2013:354., Novruzova et al., 2021:6)

In case of injection of water into the oil reservoir, the hydrocarbon flow into the production well occurs under the influence of the water pressure and the water-oil contour is advancing. During injection of water the oil reservoir is in a state of steady development at the time when the reservoir is completely filled with water. It should be noted that the main part of water flooding process occurs in unsteady state. The total oil production following the establishment of the stationary flow of the liquid will likely constitute an insignificant part of the entire production received during the extraction (Morris, 2004:622)

The hydrodynamic conditions of water flooding indicate that during established period of filling the drained sections, pressure distribution and fluid motion is mainly determined by the operating mode of the injection wells (Masket 2004:327., Shchelkachev et al., 2001:763., Entov et al., 2018:204).

Actually, process of water flooding of a homogeneous reservoir will be higher than the corresponding value at a steady state, where the discharge of the injection liquid is taken equal to the selected oil production rate.

Initially, questions about the advancement of the water boundary; the viscosity and density of oil and water were assumed to be the same. In subsequent works while solving the problems of oil displacement by water, the difference in the viscosities of oil and water was taken into account, which makes it possible to regard the plane of contact between oil and water as vertical.

Considering the works, it can be noted that the plane of contact will be vertically flat if the distance from a number of wells to the contour of the field of supply of the formation is greater than the distance to the water boundary. It should also be noted, that in case of lack of plantar water, the assumption of verticality of the oil-water contact plane, even in a small slope of the layer, does not cause a significant error to results of solving the problem of displacement of oil by water. (Economides et al., 2015:430., Schlichting 2018:783).

It should be noted, that the rate of the reservoir pressure drop depends on the rate of advancement of the contour water. In case of contour advancement and without of taking it into consideration it can lead to large errors in the calculation of oil reserves. (Basniev et al., 2005:497).

Taking in consideration mentioned above, in this article we consider the problem of oil displacement by liquid taking into account the difference in viscosity and phase permeability of oil and liquid (in the particular case of water).

Research material and methods. On the basis of a mathematical model, a method for studying the process of displacement of one fluid by another, referring to the laws of filtration of a homogeneous system, phases in reservoir conditions is proposed.

On figure 1 schematic movement of water and oil with taking into consideration the progress of the water-oil contact is shown. As seen, the part of the reservoir between the water boundary contour and the gallery will be called the oil-bearing region, and part of the reservoir between the supply contour and the water boundary contour will be called the water boundary area.(James 2014:164., Discs 2015:5., Kelbaliev et al., 2017:7).

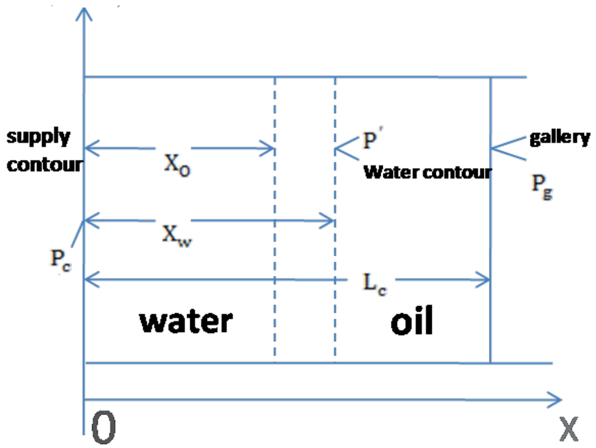

Figure 1. Schematic motion of water and oil.

The parameters applied in the task are following:
P_c — pressure in the supply contour;
P_g — gallery pressure;
P' — pressure on a moving water boundary;
X_0 — distance from the supply contour to the initial position of the water boundary;
L_c — distance from the supply contour to the gallery;
m — reservoir porosity;
k — reservoir permeability;
X_w – distance to the moving water boundary;
μ_{oil} and μ_w — respectively, oil and water dynamic viscosity.

In the beginning, the speed of movement of water and oil during piston displacement is determined.

$$\nu_{oil} = -\frac{K_{oil}}{\mu_{oil}} * \frac{dP}{dX} \quad \text{and} \quad \nu_w = -\frac{K_w}{\mu_w} * \frac{dP}{dX} \qquad (1)$$

If we multiply the left and right parts to the cross-sectional area of the formation, we will determine the volume flow of oil.

$$Q_{oil} = \frac{K_{oil}}{\mu_{oil}} S \frac{dP}{dX} \qquad (2)$$

Let's solve this equation within the boundary conditions

$$X = X_w \; ; P = P'$$
$$X = L_c \; ; P = P_g$$

By substituting the boundary conditions, we will determine the volumetric flow of oil.

$$Q_{oil} = \frac{K_{oil}}{\mu_{oil}} S \frac{(P' - P_g)}{(L_c - X_w)} \quad (3)$$

And the speed of the oil phase.

$$\nu_{oil} = \frac{K_{oil}}{\mu_{oil}} \frac{P' - P_g}{L_c - X_w} \quad (4)$$

By solving this equation for the water phase, taking into consideration the boundary conditions.

$$X = 0 \, ; P = P_c$$

$$X = X_w ; P = P'$$

Integrating the equation within following boundary conditions

$$Q_w = \frac{K_w}{\mu_w} \frac{dP}{dX} \quad (5)$$

Taking into consideration mentioned above, we can determine the volumetric flow rate and the average water velocity.

$$Q_w = \frac{K_w}{\mu_w} S \frac{P_c - P'}{X_w} \quad (6)$$

or

$$\nu_w = \frac{K_w}{\mu_w} \frac{P_c - P'}{X_w} \quad (7)$$

Assuming the piston displacement and the speed of the phases are equal to each other, we can determine the pressure on the supply contour.

$$P' = \frac{P_c K_w \mu_{oil} (L_c - X_w) + P_g K_{oil} \mu_w X_w}{K_w \mu_{oil} (L_c - X_w) + K_{oil} \mu_w X_w} \quad (8)$$

If we equate the permeability of oil and water, we will have the formula proposed in the paper. [Basniev, 2014].

By substituting this value, it is possible to determine the volume flow of oil.

$$Q_{oil} = \frac{K_{oil} S (P_c - P_g)}{\mu_{oil} (L_c - X_w) + \frac{K_{oil}}{K_w} \mu_w X_w} \quad (9)$$

In the same way, we can determine the rate of oil filtration.

$$\nu_{oil} = \frac{K_{oil} S (P_c - P_g)}{\mu_{oil} (L_c - X_w) + \frac{K_{oil}}{K_w} \mu_w X_w} \quad (10)$$

If $K = K_{oil} = K_w$, then we have the formula proposed by Professor V.N. Shelkachev, however, if $\mu = \mu_{oil} = \mu_w$, and then we will have the formula of M. Muskat.

Considering the fact that displacement has piston character, then the rate of filtration of oil and water are equal, then it is possible to determine the speed of movement of the water-oil contact.

$$V = \frac{d\bar{X}_w}{dt} = \frac{\nu_w}{m} = \frac{\nu_{oil}}{m} \tag{11}$$

By substituting the value of the filtration rate and solving with respect to time, we will have

$$dt = \frac{m}{K_{oil}(P_c - P_g)}\left[\mu_{oil}(L_c - \bar{X}_w) + \frac{K_{oil}}{K_w}\ \mu_w\ \bar{X}_w\right] dX_w \tag{12}$$

By integrating this equation within the limits from (o) to (t) and from to, then we will have

$$t = \frac{m}{K_{oil}(P_c - P_g)}\left[\mu_{oil} L_c (X_w - X_o) + \frac{X_w^2 - X_o^2}{2}\left(\mu_w \frac{K_{oil}}{K_w} - \mu_{oil}\right)\right] \tag{13}$$

This expression enables us to determine the time of advancement of the water-oil contact. If we equate the phase permeability of water and oil, then the resulting formula proposed in (Basniev, 2014:520).

Assuming that $X_w = L_c$, it is possible to determine the time of total extraction of oil from the formation or advancement of water from the initial position of the water boundary to the gallery.

$$T = \frac{m}{2K_{oil}(P_c - P_g)}\left[\mu_{oil}(L_c - X_o)^2 + \mu_w \frac{K_{oil}}{K_w}(L_c^2 - X_o^2)\right] \tag{14}$$

The proposed formula indicates that the time of displacement of oil by liquid (water) is directly proportional to the porosity of the formation and inversely proportional to the permeability of the formation over oil and depression.

The analysis reveals that the greater porosity of the formation, with other equal conditions, the time for advancement of the water boundary from the supply contour to the gallery is greater. On the other hand, if the porosity of the formation is greater, it means greater oil reserves in it, and therefore, with other equal conditions, it takes more time to extract this oil. The greater permeability of formation and greater depression, with other equal conditions, means the greater velocity of the homogeneous fluid.

Let's suppose that a homogeneous system moves from the power contour to the gallery, that is then we will have

$$T_{oil} = \frac{m\ \mu_{oil}(L_c - X_o)}{K_{oil}(P_c - P_g)} L_c \tag{15}$$

By solving the last equation together, we will find

$$\frac{T}{T_{oil}} = \frac{1}{2\bar{\mu}L_c}\left[\bar{\mu}(L_c - X_o) + \frac{K_{oil}}{K_w}(L_c + X_o)\right] \quad (16)$$

where $\bar{\mu} = \frac{\mu_{oil}}{\mu_w}$ is dimensionless viscosity.

If $K_{oil} = K_w$, we will have the formula proposed in the work (Morris, 2004:622).

The analysis revealed that the difference in viscosities of oil and water, as well as the permeability of oil and water, during the oil exerts a great influence to contour extension.

Results and discussion. As seen from the figure 2, the calculations carried out showed the dependence of oil flow rate on the distance from the moving water boundary with using M. Muskat, V.N. Shelkachev, and proposed model which shows the character of the movement of the system.

The consideration of permeability ratios is more permissible for solving numerous problems of field experience.

The results obtained can be used in the development of oil fields in order to increase oil recovery and maintain reservoir pressure.

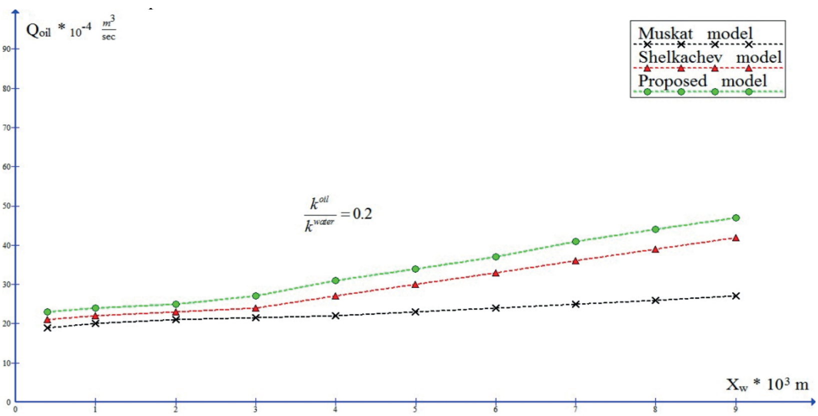

Figure2. Dependency of oil flow rate VS moving water boundary.

The present method of taking into consideration the impact of the dynamic viscosity of displaced and displacing liquids and the permeability of individual fluids makes it possible to take into consideration the displacement process for other liquids with different rheological properties. Taking into consideration the changes in the physical properties of the displacing liquid affects the character of the contour advancement, as well as the displacement process. It should be noted that the coverage of the formation, distribution of pressure and the process of displacement, considering the characteristic parameters of the formation and fluid, changes dramatically.

The proposed calculation scheme enables us to regulate the operation process when reservoir stimulation with purpose to increase the oil extraction.

The main conclusions are that further improvement of fluid injection methods, increasing their technological efficiency and expanding the range of equipment and technologies for stimulating the productivity of oil wells can be predicted in the following areas:

a) according to thermochemical methods, the most promising research is in the field of heating solvents directly at the bottomhole, in the interval of the productive formation with the least heat loss;

b) according to implosion-chemical methods, one can expect the effectiveness of studies on the combined injection of hydrocarbon solvents in water, compositions of specially selected surfactants with implosive and thermal-implosive effects on the reservoir system;

c) according to pulse-drawdown methods, research is planned to develop a new class of equipment that allows for cyclic multiple drawdown pumping of reservoir fluid to the surface, which would significantly reduce time losses and increase the efficiency of the technological process.

It should be noted that conventional methods of fluid injection and the displacement process make it possible to control the injected fluid. On real objects in the process of field operation, along with reservoirs that require injection limitation, reservoirs with low permeability are identified, requiring increased injection pressure for development. A more detailed study of the displacement process makes it possible to increase the oil recovery of an oil deposit as a whole or a horizon.

Every year, the volume of implementation of methods for increasing oil recovery in old fields is growing and, mainly, through physical and chemical methods that do not require a radical reconstruction of the oil field. Full identification of these issues and their solution requires a detailed study of the problem of displacement of one fluid in reservoir conditions by another.

Conclusion. 1) The analysis reveals that the displacement process is also strongly influenced by permeability, relative to oil and water.

2) The difference in phase permeability for oil and water has a significant impact not only on the time of oil extraction, but also on the nature of the advancement of the water boundary.

3) If the viscosity of oil and water, the permeability for oil and water were the same, then the velocity of the fluid at all points of the formation, including the beginning, would be the same.

4) The late stage of oil field development is the result of the process, so the prospects for the use of injection of various fluids into the reservoir should be a main element in the design of the development system.

5) Basically, further development of methods for increasing oil recovery will be associated with the development of a theoretical basis for the model-based analysis of the new methods of oil displacement by liquid from the point of view of EOR technology.

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