Nafta-Gaz 2023, no. 6, pp. 406–411, DOI: 10.18668/NG.2023.06.04

Filtration of compressible viscous-plastic oil in a porous medium

Filtracja ściśliwego oleju lepkoplastycznego w medium porowatym

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ABSTRACT: Numerous laboratory studies have shown that the change in physical and chemical properties and the geological conditions of the occurrence of hydrocarbons depend on depth. It should be noted that the change in oil properties with depth and the identification of the properties of such oils are poorly understood. In this research work, an attempt is made to study the filtration properties of anomalous oils, taking into account compressibility in reservoir conditions. The work carried out shows that the density, dynamic viscosity and the content of resins, sulfur, paraffin and asphaltene of different oil reservoirs are mainly depth dependent. The filtration characteristics of such oils that manifest themselves at a given pressure have been established. The results of modeling the filtration processes leading to the emergence of zones of increased oil compressibility, forming deep hydrocarbon fields, were used to discuss the regularities obtained. This makes it possible to determine filtration characteristics of anomalous liquid, taking into account the compressibility, which determine their higher quality indicators. The analysis shows that in the development of oil fields with anomalous properties of hydrocarbons, when recalculating the volumetric flow rate of individual wells in reservoir conditions it is necessary to use the value of the volumetric oil coefficient, taking into account its non-Newtonian properties. This technique will enable future works to study the effect of hydrodynamic imperfection of wells and the effect of formation permeability violation in their bottomhole zone on the reservoir pressure redistribution characteristics and well test results.

Key words: deep-seated oil fields, compressibility, oil basin, reservoir, physical and chemical properties of oils, porosity, permeability.

STRESZCZENIE: Liczne badania laboratoryjne wykazały, że zmiana właściwości fizycznych i chemicznych oraz warunki geologiczne występowania węglowodorów zależą od głębokości usytuowania akumulacji. Należy zauważyć, że charakter zmiany właściwości ropy naftowej wraz z głębokością jest słabo rozpoznany. W niniejszej pracy podjęto próbę zbadania właściwości filtracyjnych rop anomalnych, biorąc pod uwagę ściśliwość w warunkach złożowych. Przeprowadzone prace wykazały, że gęstość, lepkość dynamiczna oraz zawartość żywic, siarki, parafiny i asfaltenów w różnych złożach ropy naftowej zależą głównie od głębokości. Określono właściwości filtracyjne tych rop, ujawniające się przy określonym ciśnieniu. Do omówienia uzyskanych prawidłowości wykorzystano wyniki modelowania procesów filtracji, prowadzących do powstania stref o zwiększonej ściśliwości ropy w głębokich złożach węglowodorów. Pozwala to na ustalenie charakterystyki filtracyjnej cieczy anomalnej z uwzględnieniem ściśliwości, które determinują ich wyższe wskaźniki jakościowe. Analiza pokazuje, że przy zagospodarowaniu złóż ropy naftowej o anomalnych właściwościach, przy przeliczaniu objętościowego natężenia przepływu poszczególnych odwiertów w warunkach złożowych, konieczne jest wykorzystanie wartości współczynnika objętościowego ropy, z uwzględnieniem jego właściwości nienewtonowskich. Technika ta umożliwia w przyszłych pracach badanie wpływu niedoskonałości hydrodynamicznej odwiertów i wpływu naruszenia przepuszczalności formacji w strefie przyodwiertowej na cechy redystrybucji ciśnienia złożowego, jak również na wyniki opróbowania odwiertów.

Słowa kluczowe: głęboko zalegające złoża ropy, ściśliwość, basen naftowy, zbiornik, właściwości fizyczne i chemiczne rop, porowatość, przepuszczalność.

Introduction

The analysis showed that due to the depletion of the reserves of the most easily accessible oil fields, hard-to-recover oils will be the main base for the growth in hydrocarbon production in the coming years globally. Laboratory and field studies have shown that the growth in the production of hard-to-reach oils in recent years makes it necessary to study the qualitative features of hard-to-recover deposits. It should be noted that, according to Mirzajanzade and Shirinzade (1986), a special place among oils with complicated physical properties is occupied by viscous-plastic oils.

Scientific literature analysis has shown that, according to the classification (Ibraev, 2006; Lisovsky and Khalimov, 2009),

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Article contributed to the Editor: 16.01.2023. Approved for publication: 13.06.2023.

deep-seated deposits include reservoirs whose oils are located at a depth of more than 4500 meters.

Literature analysis has shown that poor knowledge of such deposits, formations at great depths, complicates the development of hydrocarbon resources in deep-seated reservoirs of oil basins. At the same time, the geological factors in the formation of deposits of deep horizons remain the same as for the formation of hydrocarbon deposits in the upper layers of the reservoirs at shallow and medium depths (Punanova and Shuster, 2018). However, with increasing depth, the characteristics of these factors change.

Also, one of the reasons for the significant difference in filtration conditions with increasing depth is the significant compaction of rocks at great depths under the influence of overburden pressure, which leads to a change in the structure of the formation and hydrocarbon, and in general, to a change in the structure. It should be noted that increased tectonic activity is observed at greater depths, compared with depths of 2000–4500 meters. This also causes a significant difference in the structure of fluid and rocks. Another main reason for significant differences in filtration at different depths is the change in hydrocarbon compressibility. As a result of this process, the viscosity, density, and properties of the hydrocarbon system change with depth.

Some physical and chemical characteristics of such oils are considered in a number of publications (Yashchenko and Polishchuk, 2014a, 2014b, 2016, 2019). An analysis of changes in physical properties of oils depending on depth is considered in Yashchenko and Polishchuk (2014a, 2014b). However, their rheological characteristics have not been studied enough, which makes it difficult to solve technological problems, such as production and processing in the conditions of an increase in the extraction of hydrocarbons from a large depth of reservoirs. On the other hand, insufficient knowledge of rheology makes it very difficult to assess the prospects and determine the main directions for the development of oil and gas production.

Given the above, the main goal of this work is to study the patterns of changes in the rheological properties of compressible viscous-plastic oil filtered in a porous medium.

Materials and methods

The information basis for research is the materials published in domestic and foreign literature. At the same time, to study the patterns of changes in the rheological properties of oils depending on the depth of occurrence and to study the features of the conditions for the formation of deep-seated oil-bearing formations, materials from works of Glukhmanchuk et al. (2018) and Vyalov (1978) were used. The results of the conducted studies provide an opportunity to describe the rheological model of a compressible fluid in a reservoir as follows. During the evolution of hydrocarbon reservoirs, the rheological properties of the compressible fluid enter the main phase of filtration.

The evolution of subsequent filtration flows of the compressible fluid leads to a change in the technological parameters of the reservoir and the well (Devlikanov et al., 1975; Vyalov, 1978). Given the above, it is possible to predict the processes that occur in the reservoir during the filtration of a viscous-plastic compressible fluid (Bulina et al., 1977). This filtration mechanism at great depths makes it possible to consider in more detail the process of filtration of compressible anomalous fluid.

Results

It should be noted that, according to the classification (Yashchenko and Polishchuk, 2016), at depths up to 2000 m, oils can, on average, be classified as resinous, asphaltene, paraffin, with a low gas content. The established patterns of changes in the properties of oils with increasing depth in the hydrocarbon basins around the world are manifested in a change in the rheological properties of individual oils. It is enough to refer to the results (Devlikanov et al., 1975; Fertl, 1976; Bulina et al., 1977) of studies of trends in the properties of oils in Western Siberia with increasing depth of occurrence. The results obtained based on the analysis of data on the rheological properties of oils located at shallow and medium depths (Yashchenko and Polishchuk, 2016) show that deep-seated oils are mainly characterized by specific physical and chemical properties of oil.

As shown in the works of Yashchenko and Polishchuk (2014a, 2014b), in Russia, the largest number of such oil fields is concentrated in the North Caucasus (82% of Russian oil fields) and Volga-Ural (12% of fields) regions. Geological studies show that 33 fields with this kind of oil have so far been found in Western Siberia. Studies have shown that these oil fields, on average, differ in physical and chemical properties.

It should be noted that the West Siberian oil fields show the highest quality indicators in terms of the number of physical and chemical parameters. In the group of lower quality oils, the Caspian oils are the most viscous, and the oils of the South Caspian Basin are additionally characterized by high density (Leonov and Isaev, 2006). In terms of rheological characteristics, these oils are similar to oils with anomalous properties.

Numerous field studies have shown that during the development of oil fields, start-up or shutdown, as well as a change in production rates, create prerequisites for the occurrence of unstable processes in the reservoir (Shchelkachev and Lapuk, 2001). Under certain conditions, the features and parameters of these unstable processes depend on the influence of the elasticity of oil reservoirs and on the elasticity of the hydrocarbons that saturate them.

To solve numerous problems in the oil reservoir and the process of its development, the concept of oil reservoir regimes was introduced. It is important to emphasize that the classification of regimes is based on a comparison of the main forms of reservoir energy. At the same time, it is worth noting that different methods can be employed to influence oilfield reservoirs, and it is possible to apply them in different modes and change the regime of a given reservoir throughout the region or in separate areas (Masket, 2004). Prior to considering the elasticity of the fluid and the formation, the following four modes were identified: water-pressure, gas-pressure, dissolved gas and gravity.

However, a new regime – elastic – will emerge in the future. A reservoir regime is called elastic if the behavior of energy during its development is significantly influenced by the elasticity of the reservoir and the fluid that saturates it – oil and reservoir water.

In the elastic mode, the main feature is that the pressure in the pressured oil reservoir is higher than the saturation pressure, which provides a single-phase flow. In this case, the movement of the fluid into each well starts due to the use of the potential energy of the elastic deformation of the fluid and the formation. This process first occurs in the immediate vicinity of the bottomhole, and then in more remote areas of this reservoir. It should be noted that with a decrease in reservoir pressure, the volume of compressed fluid should increase, and the volume of the pore space should decrease. All this contributes to the displacement of fluid from the formation into the well. According to the textbooks on hydraulics (e.g. Gusev, 2009), although the coefficient of volumetric elastic deformation of the liquid is very small, the volumes of the reservoir and the fluid saturating it are very large.

It should be emphasized that during the development of oil and gas condensate fields, the pressure drop in them is significant and extends over large areas. Given the above, we can conclude that the elastic reserve of fluid in the reservoir, i.e. the amount of fluid that is extracted from the oil reservoir after a reduction in pressure due to its volumetric elasticity and the fluids that saturate it, can be quite significant.

It should be noted that if the reservoir and the fluid that saturates it were absolutely incompressible, then not only would the elastic reserve of fluid in the reservoir be equal to zero, but the redistribution of pressure in the reservoir would occur instantaneously. Unfortunately, the volumetric elasticity of reservoir oils and waters is still much less studied than, for example, physical properties such as viscosity, density, gas solubility, and others. Additional information showing the parameters of the volumetric elasticity coefficient of various oils around the world can be found in the course of oil reservoir physics (Mirzajanzade et al., 2005). According to the works (e.g. Shchelkachev, 1959), theory and field observations show that during unsteady processes, the redistribution of reservoir pressure proceeds the more slowly, the lower the permeability of the reservoir, the greater the viscosity of the oil and the greater the coefficient of volumetric elasticity of oil and water. These two interrelated properties turn out to be very characteristic in the development of an oil reservoir under elastic conditions:

1. a very long process (time) of reservoir pressure redistribution after the start of development and after each change in oil production from the reservoir;
2. extraction of the elastic reserve of oil and water from the reservoir with a decrease in pressure in it, or vice versa, the accumulation of an elastic reservoir of fluid in the reservoir with an increase in pressure in it.

Many authors (e.g. Aziz et al., 2005) point out that all of the above proves that the water-drive mode of an oil reservoir can correctly be called elastic-water-drive. It should be noted that it is typical for the elastic water-drive mode that the potential energy of the reservoir in the aquifer region surrounding the developed hydrocarbon deposit and having good hydrodynamic connection with it, far exceeds the potential energy of the reservoir.

Here, the potential energy of the formation is the sum of the potential energies of the elastic deformation of the oil and the formation.

Analysis of the features of filtration of a compressible viscous-plastic fluid in a reservoir

It is known that according to the linear law of filtration of a compressible fluid with a one-dimensional nature of the flow, the volumetric elasticity for a viscous-plastic fluid is defined as:

$$\beta = -1/dP \cdot dV/V \tag{1}$$

where:

β – is the coefficient of volume elasticity or the coefficient of compressibility of the liquid (Shchelkachev, 1959),

V – volume of liquid corresponding to pressure P,

dV/V – relative volumetric deformation when the pressure changes by dP.

The coefficient of volumetric elasticity characterizes the tendency of a liquid to change volume with a change in pressure. This value is positive, and the "–" ("negative") sign on the right side of this formula indicates that the volume of the liquid decreases as the pressure increases.

In numerous studies of the development of oil reservoirs under elastic conditions, the process of fluid movement in the reservoir can be considered isothermal.

It is known that:

$$V = M / \rho \tag{2}$$

where:
M – is the mass of the liquid,
ρ – is the density of the liquid.

Then, after differentiation, we have:

$$dV = -Md\rho / \rho^2 \tag{3}$$

Solving these equations together:

$$\beta = d\rho / \rho \cdot 1 / dP \tag{4}$$

We write the equation in the form:

$$dP / dx = 1 / \rho\beta \cdot d\rho / dx \tag{5}$$

Thus, we have determined the relationship between pressure and density.

It is known from literary sources that (Mirzajanzadeh et al., 2005) the filtration equation for a viscous-plastic fluid can be written as:

$$v = -\frac{k}{\mu}\left(\frac{dP}{dx} - i_0\right) \tag{6}$$

where:
k – reservoir permeability,
μ – dynamic viscosity,
i_0 – initial pressure gradient.

Let's solve this equation for density. Then:

$$v = -\frac{k}{\mu}\left(\frac{1}{\rho\beta}\frac{d\rho}{dx} - i_0\right) \tag{7}$$

We multiply the left and right parts by the cross-sectional area, taking into account the volume flow, and obtain:

$$\beta\left(\frac{Q\mu}{kF} + i_0\right)dx = -\frac{d\rho}{\rho} \tag{8}$$

where:
$Q = Fv$ is the volumetric flow rate of the liquid,
F – formation cross-sectional area.

Taking into account the boundary conditions, at $x = 0$; $\rho = \rho_c$ and $x = L$; $\rho = \rho_{gal}$ we obtain:

$$Q = \frac{kF}{\mu}\left(\frac{1}{\beta L}\ln\frac{\rho_c}{\rho_{gal}} - i_0\right) \tag{9}$$

where:
ρ_c – density of the liquid at the contour pressure,
ρ_{gal} – density of the liquid at pressure on the gallery,
L – layer length.

This formula makes it possible to determine the flow rate of a reservoir producing a compressible viscous-plastic fluid.

According to Shchelkachev and Lapuk (2001), this expression can also be written with respect to pressure. In such a case:

$$Q = \frac{kF}{\mu L}\left[(P_c - P_{gal})(1 + \beta\overline{P}) - i_0\right] \tag{10}$$

where $\overline{P}$ is the mean pressure

$$\overline{P} = \frac{P_c + P_{gal}}{2} - P_0 \tag{11}$$

where:
P_c – pressure on the contour,
P_{gal} – pressure on the gallery.

As can be seen, a change in the volumetric elasticity coefficient affects the productivity of wells. It should be noted that the elasticity coefficient is not constant for these oils, while all other conditions remain the same. Thus, with increasing pressure, this parameter decreases (Shchelkachev and Lapuk, 2001). Furthermore, apart from pressure, the elasticity coefficient depends on temperature, the amount of gas dissolved in oil, the fractional composition (asphaltenes, paraffins, resins, etc.) of oil and gas.

The discussion of the results

The performed analysis shows that with an increase in the depth of occurrence of oil reservoirs, the reservoir itself and the oil in this medium are significantly compacted. The increase in depth is comparable to the increase in pressure, which creates the compressibility of these systems. As a result, reservoir permeability and porosity decrease with depth. In this regard, without taking into account the coefficient of elasticity, traditional methods of forecasting the assessment of reserves and the development and operation of such fields become ineffective. Given the above, taking into account the compressibility of visco-plastic oil is now an urgent task when developing these deep-seated fields.

Due to the decline in oil production in traditional oil reservoirs around the world, the development of such little-studied deep fields is now a pressing issue, especially in Azerbaijan, the USA, Venezuela, etc.

According to scientific works (e.g. Glukhmanchuk et al., 2014), at present in the regions of Western Siberia, where the main oil and gas production centers in Russia are located, exploration work is carried out at depths in the range of 3000–4000 m. It should be noted that the industrial development of these resources at the indicated depths is technologically complex, but studied. In this case, methods and technologies that have proven successful in the development and operation of traditional oil fields are applied. At the same time, deep reservoirs are insufficiently studied. At present, it is necessary to develop new approaches, methods and technologies for the development of deep-seated oil fields with anomalous properties.

Field observations and laboratory studies have shown that, taking into account the compressibility of the fluid, it is partially necessary to consider the process of formation and fluid deformation. In this case, we will consider the deformation of the reservoir and non-Newtonian fluid as elastic and reversible.

The values of the compressibility coefficient of viscous-plastic oils in a porous medium obtained by us fall within the limits indicated in this method and they can be used with a degree of accuracy quite sufficient for practice, taking into account the theory of the elastic regime of the formation.

According to the works (e.g. Shchelkachev, 1959), when developing an oil field in an elastic regime, the pressure cannot fall below saturation pressure, that is

$$P \geq P_{sat}$$

where:

P – current pressure,

P_{sat} – pressure drawdown.

Then the pressure drawdown

$$\Delta P = P_{res} - P \leq P_{res} - P_{sat}$$

where:

P_{res} – initial reservoir pressure,

ΔP – pressure drop.

Field analysis shows that (P_{res} – P) significantly exceeds 100 atm. Furthermore, it could be taken into account that in the elastic mode

$$\Delta P \leq 100 \text{ atm}$$

According to field data, the compressibility factor for Russian and Azerbaijan fields reaches minimum values within

$$\beta_o = (7 \div 30)\ 10^{-5}\ 1/\text{atm}$$

Accordingly, when carrying out typical calculations, especially in relation to reservoir conditions of oil fields (Shchelkachev, 1959)

$$\beta_o = 10^{-4}\ 1/\text{atm}$$

Based on these data, it is possible to estimate the relative change in the volume of oil in reservoir conditions with a pressure change of 100 atm.

$$\Delta V_o / V_o = \beta_o \Delta P = 10^{-4} \times 100 = 0.01$$

Consequently, when the pressure drops by 100 atm., the volume of oil under reservoir conditions changes by 1%, which is significant for large oil reserves.

This must be taken into account when recalculating the volumetric flow rate of reservoirs or wells under reservoir conditions to the volumetric flow rate under normal conditions. At the same time, the calculation of reserves and current production are highly dependent on the value of the volumetric compressibility factor.

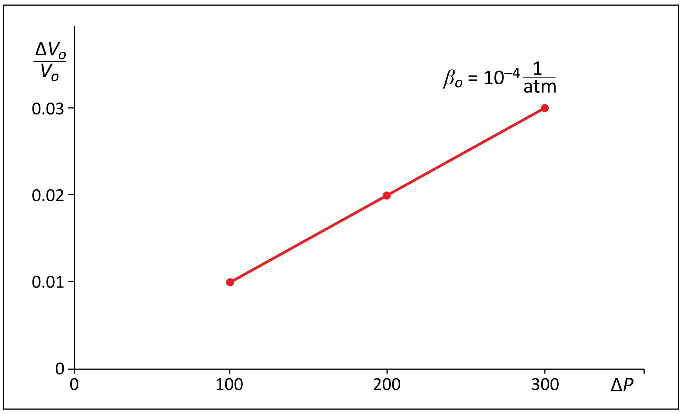

Figure 1. Change in reservoir productivity depending on the compressibility factor

Rysunek 1. Zmiana wydajności złoża w zależności od współczynnika ściśliwości

Figure 1 shows the change in reservoir productivity depending on the compressibility factor. Thus, at a constant compressibility coefficient, with an increase in pressure drop, the volume of oil increases significantly for oil fields with large reserves of hydrocarbons.

Conclusion

The article is devoted to the study of filtration of compressible viscous-plastic oil. The results of preliminary studies of quantitative patterns of changes in the physical and chemical properties of oils and rocks are shown with new information is presented. It should be noted that the indicated explanation of the mechanism of abnormal oils in deep-lying horizons with different conditions of oil formation and accumulation may be insufficient and require additional scientific information array.

So far, there is no convincing evidence that in the development of oil-bearing formations with viscous-plastic oils, quite noticeable violations of the reversibility of the development process would be observed with changes in reservoir pressure. Nevertheless, taking into account the works of cited authors, it is necessary to continue field and laboratory studies, and, based on them, to undertake a theoretical study that would make it possible to establish under what conditions and to what extent the processes of developing reservoirs with abnormal oils should be considered, taking into account the coefficient of elasticity of the liquid.

The analysis shows that the most important task of the theory of the elastic regime is associated with the identification of the features of the processes occurring in the developed oil reservoirs and depending on the elasticity of the viscous-plastic oils that saturate them. In order to simplify and clarify the nature of the solution of the mentioned problems, this article considers their formulation in the simplest conditions.

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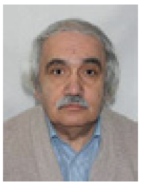

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