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DEVELOPMENT OF A NEW METHOD FOR TREATING THE NEAR-WELLBORE ZONE OF WATER-FLOODED WELLS

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ABSTRACT

At a certain stage of reservoir development, a number of operational challenges arise in well production. One of these issues is the ingress of water into the near-wellbore zone of the formation. Water breakthrough disrupts the normal operating regime of wells and leads to a sharp decline in production. The inflow of formation water into the well causes degradation of the near-wellbore zone, while sand carried by the water results in premature failure of downhole equipment. Consequently, frequent well shutdowns occur, and additional difficulties arise in oil treatment and transportation processes. Water production also adversely affects environmental and ecological balance. One of the main causes of water breakthrough is the heterogeneity of the near-wellbore zone in terms of permeability. The main objective of this study is to reduce the water-phase permeability of the near-wellbore zone. To achieve this, a new hydrophobic composition based on acidol and soapstock was developed, and its effectiveness in isolating water inflows was experimentally investigated under laboratory conditions. The results of the conducted studies indicate that injecting a volume of the composition equal to 15–17 % of the pore volume into the near-wellbore zone results in 12.7-14.5-times reduction in water-phase permeability, the water cut of the produced fluid decreases by 9.3–11 times, and the oil recovery factor increases by 11–14 %.

Keywords: new treatment method; reservoir model; phase permeability; near-wellbore zone; isolation; hydrophobic; acidol; soapstock; oil recovery factor; water cut.

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Introduction

The wettability of rock surfaces significantly affects many properties of hydrocarbon-saturated reservoirs, including saturation, phase permeability, and fluid flow rates. This factor is particularly important in the near-wellbore zone of the reservoir. This zone is subjected to the most severe negative impacts both during the initial formation opening and subsequent well operation.

On the other hand, after a certain period of field development, water injection [1–4] and its various modifications [5–10] are widely used as artificial stimulation methods in oil reservoirs. However, during the application of these methods, as well as during well construction and operation, various types of water enter the near-wellbore zone and are retained by capillary forces, resulting in the formation of highly water-saturated zones. A layer of bound water forms on the surfaces of the rocks composing the near-wellbore zone, which reduces the effective pore volume of the formation. This is particularly common in low-permeability hydrophilic rocks. As water saturation increases in the rocks forming the near-wellbore zone, water-phase permeability increases, while oil-phase permeability decreases. This occurs due to both capillary effects and the physical trapping of "loosely bound water" within the near-wellbore zone.

Water breakthrough into the well leads to a decrease in oil-phase permeability and oil production rates. The hydrophilicity of the rocks in the near-wellbore zone increases, and as a result, water is absorbed by capillary pores, displacing oil from the bottomhole zone deeper into the formation. Consequently, a capillary-bound water zone develops in the near-wellbore region. This reduces the effective thickness of the formation and creates resistance to oil inflow into the well (i.e., increases hydraulic resistance to oil flow).

One of the most important challenges in oil field development is water production control. Water breakthrough leads to reduced oil flow rates, increased problems associated with water separation and disposal, and reduced oil production [10–17]. This problem has recently become particularly relevant, as many reservoirs worldwide have entered the late stage of development, which is characterized by high water cut in wells.

The solution to this problem is associated with either removing water from the near-wellbore zone or altering the wettability characteristics of the rocks (from hydrophilic to more hydrophobic conditions).

Various methods have been developed to isolate water inflows in oil wells [18–24]. However, their application is

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limited due to their short -term technological effectiveness, difficulties encountered during implementation, limited availability and high cost of the components used in plugging compositions, as well as environmental and occupational safety concerns.

For example, gel systems are among the most widely used chemical methods for water shut-off. In this method, a polymer solution and crosslinking agents react within the formation to form a gel structure that partially or completely blocks high-permeability zones. However, precise control of gelation time is difficult, as the composition may become diluted by formation water. In some cases, there is also a risk of blocking oil-producing zones [24, 27].

Polymer-based technologies [27, 28] are applied to reduce water mobility and regulate permeability. These systems limit water production by decreasing the relative permeability of water in porous media. However, under high reservoir temperatures and in the presence of mineral salts in formation water, the breaking of bonds between polymer chains and the formation of precipitates can reduce the effectiveness of these systems.

Silicate-based systems [29–31] react with activators within the formation to form a semi-solid gel structure that blocks water flows. Their main disadvantage is relatively low mechanical strength compared to polymer gel systems, and in some cases, the gel structure is not sufficiently stable over time. These characteristics may limit the application range of silicate systems.

Emulsion-based systems [32] are dispersed systems composed of water and oil phases and are used to create a selective blocking effect in porous media. However, this technology also has certain drawbacks. The stability of emulsions depends on reservoir temperature and salinity, they may be distributed unevenly within porous media, and in some cases, they can create additional hydraulic resistance in reservoir rocks, which limits their application.

Thus, although existing isolation methods have certain technological advantages, most of them operate based on the principle of mechanical blocking in porous media and may, in some cases, restrict the movement of the oil phase. In addition, reservoir conditions such as high temperature, formation water salinity, and other factors can reduce the effectiveness of these systems. For this reason, the use of hydrophobic compositions that modify the wettability of rock surfaces is considered one of the promising approaches for optimizing the operation of watered-out wells.

One of the effective methods for isolating water inflows in oil wells is the hydrophobization of the near-wellbore zone. Treatment of this zone with hydrophobic reagents makes it possible to regulate its filtration properties.

Studies have shown [33, 34] that treatment of the near-wellbore zone with hydrophobic compositions leads to a redistribution of oil and water phases, a decrease in overall water saturation, and the removal of capillary-trapped water from low-permeability regions of the porous medium.

In recent years, the use of hydrophobic materials has attracted attention as a promising solution to prevent water penetration from the formation into the near-wellbore zone.

Changes in the wettability of rock surfaces in the near-wellbore zone lead to alterations in fluid flow behavior in this region. In particular, this results in a change in the direction and magnitude of capillary forces. It is known that capillary pressure is calculated by the Young-Laplace equation as follows [35–37]:

$$P_c = 2\sigma\cos\theta / r$$

here, P_c – capillary pressure; σ – interfacial surface tension; θ – contact (wetting) angle; r – pore radius.

If the rock surface is hydrophilic ($\theta < 90°$), then $\cos\theta > 0$, and water, as the wetting phase, easily enters the pores. Under these conditions, water is retained in pore channels due to capillary forces, its relative permeability increases, and the movement of the oil phase is restricted.

When the rock surface is hydrophobized, the contact angle becomes $\theta < 90°$, and in this case $\cos\theta < 0$. As a result, the direction of capillary pressure changes, creating resistance to the penetration of the water phase into the pores. In this situation, water becomes a non-wetting phase, its mobility in the porous medium is restricted, and more favorable conditions are created for hydrocarbon phase flow.

Thus, transforming the rock surface from hydrophilic to hydrophobic alters the direction of capillary forces, leading to a decrease in water relative permeability and improvement in oil flow conditions.

In addition to influencing the direction of capillary forces, changing the wettability of the rock surface from hydrophilic to hydrophobic also alters the phase distribution within the pore space. Oil, becoming the wetting phase, spreads over the rock surface and occupies smaller pores, pore corners, and constricted pore channels. In this case, water, as the non-wetting phase, occupies the larger pore spaces and flows mainly through wider pore channels. As a result, since water is displaced from smaller pores and does not significantly hinder oil movement, the filtration conditions for oil are improved. Consequently, at the same level of water saturation, the relative permeability to oil increases, while that to water decreases.

Hydrophobization technology and experimental study

Hydrophobization technology is based on altering the wettability characteristics of the porous medium in the near-wellbore zone by the injection of a hydrophobizing composition into the formation. This process increases oil saturation in the near-wellbore zone and improves oil inflow into the well. As a result of hydrophobization of the pore surface in this zone, filtration resistance to oil decreases, restoring the well's production potential and enabling more efficient recovery of oil reserves.

Taking this into account, a hydrophobic composition based on acidol and soapstock was developed, and experimental studies were carried out under laboratory conditions to investigate its effect on reducing water-phase permeability in a porous medium.

Experiments

To conduct laboratory experiments, a linear reservoir model was first constructed using a stainless steel tube 100 cm in length and 3.05 cm in internal diameter. The tube was packed with quartz sand of 0.2 mm fraction to create a porous medium. The prepared porous medium was fully saturated with water at a temperature of 293 K and a pressure of 0.25 atm. After complete saturation, the permeability was determined using Darcy's law and found to be 3.31×10^{-8} cm².

Subsequently, a volume of acidol equal to one pore volume was injected into the model. Both ends of the model (inlet and outlet) were then sealed and was left for a certain period (approximately 24 hours), after this period the water permeability was measured again and found to be 2.6×10^{-8} cm^2.

For further experiments, acidol was added to soapstock in various mass ratios as a solvent, and the mixture was stirred to obtain a homogeneous composition. This composition was then injected into the model (with an initial water permeability of 3.31×10^{-8} cm^2 in different volumes (5–25 % of pore volume), and the resulting changes in permeability were studied. The experimental results are presented in the table.

Table

Results of the effect of hydrophobic compositions with various acidol-to-soapstock ratios on the permeability of water-saturated porous media

Acidol-to-soapstock ratio in the composition injected into the porous medium	Volume of composition injected into the porous medium, %	Permeability, $\times 10^{-8}$ cm^2	Permeability reduction, times
80:20 (4:1)	5	1.06	3.12
	10	0.657	5.04
	15	0.438	7.56
	20	0.372	8.9
	25	0.379	8.94
60:40 (3:2)	The mixture is too viscous and cannot be injected into the model		
75:25 (3:1)	5	1.067	3.1
	10	0.662	5.0
	15	0.441	7.5
	20	0.376	8.8
	25	0.376	8.81

As can be seen from the table, when a composition consisting of a 3:1 mass ratio of acidol and soapstock is injected into the model in an amount of 5–20 % of the pore volume, the permeability of the porous medium decreases sharply. However, with a further increase in the injected volume, the rate of permeability reduction becomes very low.

The effect of a composition prepared with a 4:1 ratio of acidol and soapstock on reducing permeability differs only slightly from that of the 3:1 composition. This indicates that the 3:1 ratio is more optimal for reducing water phase permeability in the porous medium.

Due to the very high viscosity of the 3:2 acidol–soapstock mixture, its injection into the model is not feasible.

The decrease in permeability of the porous medium can be explained by the adsorption of the injected composition onto the surface of water-saturated hydrophilic rocks, leading to their hydrophobization.

To investigate the effect of the 3:1 composition (acidol:soapstock) on the near-wellbore zone, further experiments were conducted as follows. After establishing initial oil saturation and residual water saturation in the model with the above-mentioned permeability, oil was displaced by formation water. In this case, the final oil displacement factor was 0.472 fraction of a unit, the water cut of the produced fluid was 99.8 %, and the permeability was 2.95×10^{-8} cm^2 (figs. 1–3).

Then, by injecting different volumes of the composition (5–25 % of pore volume) into the outlet of the model, the final oil displacement factor, water cut, and permeability were determined. The results of these studies are presented in figures 1–3.

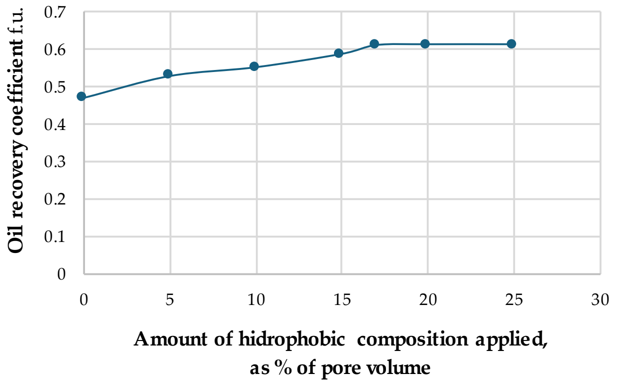

Fig. 1. Dependence of oil recovery coefficient on the volume of hydrophobic composition injected

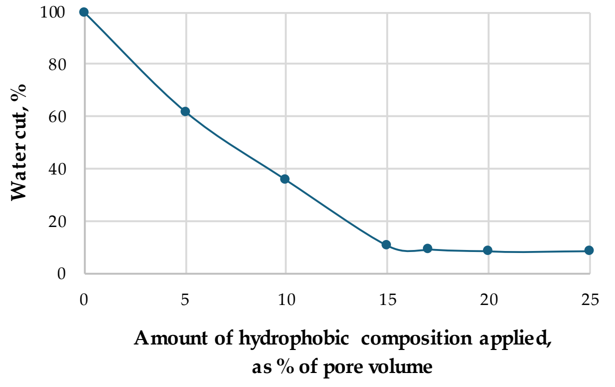

Fig. 2. Dependence of water cut on the amount of applied hydrophobic composition

As shown in figure 1, when the volume of the injected composition is increased up to 15% of the pore volume, the oil recovery factor increases to 0.587 fraction of a unit by 11.5%. At 17% injection, the increase reaches 13.8%. However, at higher injection volumes (20–25 %), the oil recovery factor remains unchanged, and no further increase is observed.

The results of the effect of the injected volume of hydrophobic composition at the model outlet on the water cut of the produced fluid are presented in figure 2.

As can be seen from the figure, prior to treatment, the water cut was 99.8%. When a volume of hydrophobic composition equal to 5% of the pore volume was injected at the model outlet, the water cut decreased to 62%, i.e., by 1.61 times.

When the injected volume was increased to 10%, 15%, and 17% of the pore volume, the water cut values decreased to 36, 10.7 and 9 %, respectively. Correspondingly, the water cut was reduced by 2.77, 9.3, and 11 times.

The results of the effect of the injected hydrophobic composition volume on phase permeability to water are presented in figure 3. As can be seen from the figure, when a volume of hydrophobic composition equal to 5% of the pore volume is injected at the model outlet, the phase permeability to water decreases by 4.2 times. When the injected volume is increased to 10, 15 and 17 % of the pore volume, the phase permeability to water decreases by 8.3, 12.7, and 14.8 times, respectively.

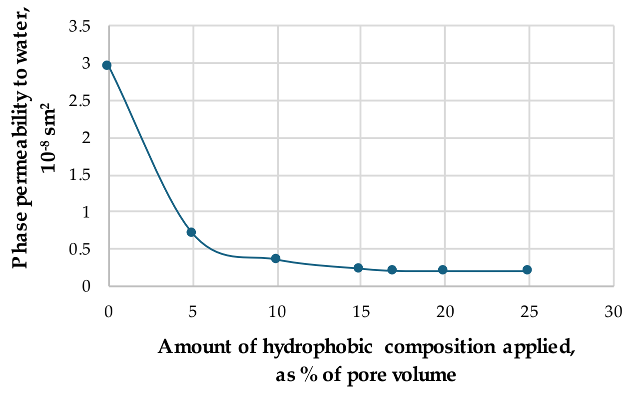

Fig. 3. Dependence of water phase permeability on the amount of injected hydrophobic composition

At an injection volume of 20%, only a very slight additional decrease in water phase permeability is observed compared to the 17% case (approximately 0.01 times). When the injected volume is increased to 25%, the value of water phase permeability remains the same as in the 20% case.

In these experiments, crude oil and formation water from the Fasila Formation of the Gunashli field were used as oil and water models (oil viscosity at 20 °C: 14 mPa·s).

To ensure the reliability of the obtained results, each experiment was repeated three times, and the arithmetic mean of the results was calculated. The standard deviation, variance, and error interval were determined as follows:

For oil displacement by water, three repeated experiments were conducted to determine the final oil recovery factor: 0.470, 0.474, and 0.473. The arithmetic mean of these values is:

$$S\overline{S} = \frac{0.470 + 0.474 + 0.473}{3} = 0.472$$

The variance (dispersion) and standard deviation were calculated as follows:

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1} =$$
$$= \frac{(0.470-0.472)^2 + (0.474-0.472)^2 + (0.473-0.472)^2}{2} =$$
$$= \frac{0.000004 + 0.000004 + 0.000001}{2} = 0.0000045$$

The 95% confidence interval (t-value for comparison of means, $n = 3$, $df = 2$, $t = 4.303$), where n is the number of repetitions and df is the degrees of freedom, was calculated as follows:

$$\text{Error interval} = t \cdot \frac{s}{\sqrt{n}} = 4.303 \cdot \frac{0.00212}{\sqrt{3}} \approx$$
$$\approx 4.303 \cdot 0.00122 \approx 0.00525$$

Thus, the final oil recovery factor is: 0.472 ± 0.005 (95% confidence interval). This indicates high measurement accuracy and good repeatability of the results; the obtained values are statistically reliable, and the recovery factor is expected to remain within the range of 0.467–0.477 upon repetition of the experiment.

Based on the presented graphical dependencies, it can be concluded that injecting the hydrophobic composition into the near-wellbore zone in an amount of 15–17 % of the pore volume is the most optimal option.

Now, let us consider the properties of the components of the hydrophobic composition:

Acidol is a mixture of various naphthenic acids (R – COOH), comprising 42–50 %, obtained through the sulfuric acid decomposition of alkaline refining waste from petroleum and petroleum products (kerosene, diesel, and oil distillates) (Technical Specification: AZ TS 35366012005 – 2006). In addition, acidol contains aromatic and aliphatic hydrocarbon derivatives, which also exhibit surface-active properties and are capable of adsorption on rock surfaces.

Soapstock belongs to the category of recyclable and environmentally safe waste obtained from the alkaline refining of vegetable oils. Its composition consists of 50–60 % sodium or potassium salts of fatty acids (CAS 8002-75-3). It mainly contains salts of oleic, palmitic, and stearic acids, along with small amounts of free fatty acids and neutral fats. These substances have an amphiphilic structure, meaning that one part of the molecule is hydrophobic, while the other is hydrophilic.

The hydrophobic composition prepared based on acidol and soapstock differs from existing water shut-off technologies in several respects. In particular, the proposed technology is not based on mechanically blocking pore space, but rather on altering the wettability of the rock surface. The composition adsorbs onto the rock surface, transforming it from hydrophilic to hydrophobic. As a result, the penetration of the water phase into capillary pores is restricted, while the filtration conditions for the hydrocarbon phase are improved, facilitating oil flow into the well.

Another important distinction is related to the raw material base of the composition. Since acidol and soapstock are by-products of petroleum refining and vegetable oil processing, their use is both economically advantageous and environmentally appropriate. In addition, the preparation technology of the composition is simple, and it demonstrates sufficient stability under reservoir chemical and mechanical conditions.

Thus, the acidol- and soapstock-based hydrophobic composition differs from conventional water shut-off technologies by modifying rock wettability rather than mechanically blocking the pore structure. This leads to a reduction in water-phase relative permeability and makes the method a promising approach for enhancing oil production in watered-out wells.

The contact angle of the composition was measured using a Kruss DSA100/DSA30/DSA25 multifunctional contact angle meter (Germany), and was found to be greater than 90°. This confirms its ability to hydrophobize the rock surface, preventing water spreading and restricting water flow.

The hydrophobic composition based on acidol and soapstock has the following characteristics:

The fundamental chemical structure of acidol and soapstock determines the level of hydrophobicity of the composition. For example, soapstock contains long hydrophobic hydrocarbon chains and hydrophilic groups (carboxylates, etc.) [38, 39].

The bonds between the carbons are mostly single bonds (saturated fatty acids), but can have one or more double bonds (unsaturated fatty acids). Acidol, on the other hand, is distinguished by specific functional groups (e.g., aromatic or aliphatic hydrocarbons, ester or amide groups), which regulate the interaction of the surface with water. The long hydrophobic carbon chain is the fatty acid, usually consisting of 12–18 (or more) carbon atoms [40–42].

The degree of interaction of the molecules in the composition with water determines the water-repellent (hydrophobic) properties of the surface. The long hydrophobic chains of soapstock and the functional groups of acidol together enhance the hydrophobicity of the surface.

The chemical structure of acidol and soapstock ensures their stability under reservoir conditions (high temperature, pressure, and chemical environment). For example, they are resistant to oxidation, hydrolysis, and other chemical reactions. The high thermal stability of the composition enables its application in high-temperature wells.

Long hydrocarbon chains orient themselves on the rock surface, weakening the interaction between water molecules and the surface. As a result, the contact angle increases and the water-repellent ability of the surface is enhanced. This makes water penetration into the pores more difficult and leads to a decrease in relative permeability to water.

Thus, the molecular structure of acidol and soapstock determines their surfactant and hydrophobizing properties, which in turn facilitate the restriction of water flow in porous media.

The resistance of the composition to other reservoir components (such as rock-forming minerals—silicates, carbonates, etc., ions present in formation water, and microorganisms in the reservoir environment) increases its operational efficiency.

The composition is also resistant to mechanical effects under reservoir conditions (such as friction and pressure fluctuations), which allows it to maintain its hydrophobic properties over a long period of time.

Due to its low surface energy, the composition prevents the adhesion of water molecules to the surface.

The mechanism of action of the composition in porous media can be explained by the following main processes:

Surface-active molecules containing acidol and soapstock adsorb onto the mineral surface of the porous medium, forming a monomolecular layer. This process follows a Langmuir-type adsorption mechanism and is characterized by a limited number of active adsorption sites on the surface. According to the Langmuir isotherm, adsorption can be described by the following equation [43, 44]:

$$q = \frac{q_{\max} KC}{1 + KC}$$

where q – amount of adsorbed substance; $q_{\max}$ – maximum adsorption capacity; K – adsorption constant; C – solution concentration.

As a result of adsorption, long hydrocarbon chains become oriented on the rock surface, forming a hydrophobic layer.

The above-mentioned factors represent the main chemical and physical parameters that ensure the effectiveness of the hydrophobic composition based on acidol and soapstock in limiting water inflow into oil wells.

As noted above, the composition reduces water-phase permeability by hydrophobizing the near-wellbore zone, thereby restricting water flow. This, in turn, minimizes water-related corrosion and erosion risks, as well as negative environmental impacts.

Conclusions

1. The injection of an optimally formulated hydrophobic composition based on acidol and soapstock into the near-wellbore zone at 15–17 % of the pore volume allows for an increase in the oil recovery factor by 11–14 %, while reducing water cut and phase permeability to water by up to 12.7–14.5 times, respectively.
2. The hydrophobic composition protects the pore structure of the near-wellbore zone from water invasion, thereby contributing to increased oil production from wells.
3. Compared with conventional technologies, the proposed hydrophobic composition technology is more stable, efficient, and environmentally friendly.
4. The application of the hydrophobic composition opens new prospects for solving water production problems by restricting water influx from the formation into the well and improving oil recovery performance.

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