Optimization of parameters influencing the nonequilibrium process of extraction of hard-to-recover oils in a gas-liquid environment

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Abstract

In this work, the problem and methods of residual oil extraction, analysis and interpretation of oil-technological and physical-chemical data aimed at increasing the degree of oil extraction from depleted oil reservoirs in the fields of Azerbaijan were studied. The developed effective aqueous solution of surfactants together with air was pumped through an ejector into producing oil wells. The proposed system of oil reservoir processing and methods of intensifying the inflow of a solution of surface-active substances with air through an ejector increase the degree of oil extraction. They significantly improve not only the optimal modes of oil production, but also stabilize the development system, which has a positive effect on the final oil recovery. The developed surfactant solution and ejector allow for improved treatment of oil reservoirs and increased efficiency of oil extraction. The designations of the elements and the diagram of the developed ejector for feeding a surfactant solution with air into an oil well are given. The studies show that the highest oil recovery factor (≥ 50%) is possible in formations with an oil viscosity of 0.5–1.5 mPa s. At higher oil viscosity values, the efficiency of the solution injection method for extracting residual oil is low. The experiments were carried out at production wells No. 1580, 1858, 1715 and injection well No. 1544 "Siyazaneft" of PO "Azneft". The results of the experiments conducted in the fields of Azerbaijan showed that the ejector we developed and used allows us to increase the efficiency of extracting residual viscous oil from depleted formations.

Keywords: Enhanced oil recovery; ejector; surfactant solution; residual oil extraction method.

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1. Introduction

Efficient extraction of oil from depleted and hard-to-recover deposits is becoming especially important [1-4]. In this regard, one of the key indicators characterizing the efficiency of oil production is the oil recovery factor [5,6].

One of the methods of increasing oil recovery is the method of pumping a water-gas mixture into depleted formations [7]. When pumping a water-gas mixture, an improvement in the bottomhole zone of an oil well is usually observed. This can be explained by the fact that part of the gas dissolves in the oil, reducing its density. Another part of the gas forms a hydrate mixture and is transported by the flow. And the remaining undissolved gas enters the highly permeable layers of the heterogeneous formation.

There are known methods of influencing a depleted formation that allow increasing the formation's oil recovery when compressing oil with a water-gas mixture [8,9]. These methods can be used to extract residual oil reserves from long-exploited fields using a water-gas mixture. However, the use of such methods requires increasing their efficiency.

The article [10] presents the results of a study of oil displacement by a miscible liquid in a porous medium associated with the injection of hydrocarbon gas into an oil reservoir. Thermophysical properties of the mixtures are compared with the efficiency of oil displacement from a porous medium by methane or water. It is shown that at the initial stages of injection, oil displacement by water is more efficient at a fixed volumetric flow rate of the injected liquid. However, at the last stages, gas injection becomes more efficient for displacing light hydrocarbon components.

It should be noted that fluid injection into the reservoir in the oil and gas business requires compression for a number of completely different conditions. This is due to the purpose and requirements for these applications in the context of oil and gas production and transportation of hydrocarbons to the consumer. In the paper [11] typical operational requirements for oil and gas compressors and solutions to meet these requirements are presented.

The productivity of a field in tight and difficult to recover formations usually declines rapidly after repeated extraction and processing of the field. Therefore, reprocessing is widely used in such formations to improve the productivity of the field. Reprocessing of depleted fields can be generalized into two categories: first, reprocessing the original oil reservoir by injecting fluids [12], and second, creating new devices. For the processing of the formation, a semi-analytical model for characterizing the transient fluid flow of reoriented repeated formations is proposed in [13]. The model takes into account interference from initial cracks. To simulate the transient flow in a system of cracks, a finite-difference approximation to the flow in initial cracks is used. The fluid flow in the model is characterized by the Green function and the Newman product method. Taking into account the continuity of flow and pressure, the equations of flow in cracks are related to the equations of fluid flow. It is shown that early in the production of a well, two pseudo-steady-state flows in fractures can occur due to interference of initial fractures. In a reservoir with anisotropic permeability, the azimuth of the refracture and its position can affect the productivity of fractures. In the immediate vicinity of the initial fractures, there is a region in which refracture can lead to high productivity of the field. This does not take into account the pore structure for bound water and potential storage of oil and gas [14].

The presence of aquifers in the formations affects the development of oil and gas wells. Water will penetrate into the productive formations when the formation pressure decreases during well production, and then greatly change the well production characteristics. Therefore, the mechanisms of liquid penetration into the horizon are studied and the degree of liquid inflow into the horizon is estimated [15]. It is also important to take into account other factors, such as the structure of oil and gas reservoirs [16].

Based on the above and the analysis of known data, it follows that both traditional and model oil recovery methods are insufficient to extract the remaining heavy oil from the reservoirs [17-21]. Therefore, enhanced oil recovery (EOR) methods are being improved to extract the remaining oil [22]. This requires taking into account the economic and technological factors that affect the choice of method and the expected oil production. Only one third of the total available oil is produced in the world. Therefore, improving EOR methods can help increase oil production [23].

One of the most commonly used conventional EOR methods is chemical treatment: polymer flooding, surfactant flooding and alkaline flooding [24]. In this case, the key mechanisms are wettability modification, interfacial tension (IFT) reduction and viscosity reduction at the liquid-oil interface [25].

Chemical EOR methods have their limitations [26,27]. For example, polymer flooding subsequently leads to viscosity loss in the presence of formation brines and elevated temperatures [28]. The efficiency of surfactants and alkalis is also reduced when flowing through porous media due to adsorption phenomena [29]. Therefore, various alternative approaches to chemical flooding are used for EOR processes [30]. For example, ionic liquids (ILs) and deep eutectic solvents (DES) are used [31–35].

Experiments show that in flooded fields of Azerbaijan with a large amount of residual oil in the formations, the influence of the gas factor is weak.

In order to increase the extraction of residual oil, in this work, instead of gas injected into the formation, a mixture of air and a solution of surfactants was used. Based on the analysis of gas-liquid flows in horizontal pipes, study the process of working with an improved liquid-gas ejector.

For this purpose, we have developed a new ejector device, which has been used in industrial conditions. Experiments using an ejector to supply a surfactant solution with air were conducted at three production wells No. 1580, 1858, 1715 and one injection well No. 1544 of Siyazaneft of Azneft Production Association.

2. Methodological part

A method of secondary oil recovery, i.e. flooding, involves injecting water into a depleted formation. In this case, water is pumped into the oil formation to increase pressure and displace the remaining oil to the production wells. n other words, the purpose of this process is to increase reservoir pressure, which decreases as the field is developed, and to displace oil from the porous rock to the production wells. The flooding process includes the following stages:

1. Selecting an injection well and equipping it for pumping an aqueous surfactant solution.

2. Water supply - the aqueous surfactant solution is pumped into the formation through this well.

3. Movement of the surfactant liquid - the solution spreads in the porous medium, displacing oil to the production wells.

4. Oil production - oil comes to the surface through the production wells under the influence of increased pressure.

The specified method has its own characteristics. The advantages are an increase in the oil recovery factor and economic efficiency compared to some other methods of increasing oil recovery. The limitations are that it requires accurate geological data. Since the method can lead to waterlogging of the extracted product, i.e. increase the water content in the oil.

When flooding a formation, the calculation of the volume of injected water depends on the formation parameters and process tasks. This procedure was carried out as follows.

1. The volume of pore space (effective pore volume) was determined

$V_{\text{pore}} = \text{A} \times h \times h_i \times \text{k}$ (1)

where A is the area of the oil reservoir (m²), h is the effective thickness of the reservoir (m), h_i is the porosity (fraction, for example 0.2 for 20%), k is the flooding coverage factor (fraction, 0–1).

formation area (m²), effective formation thickness (m), porosity (share, for example 0.2 for 20%), flooding coverage factor (share, 0–1).

The effective pore volume in reservoirs is determined by the formula

$V_{pore}^{\text{ef}} = V_{\text{total}} \times \phi_{\text{ef}}$ (2)

where V_{pore}^{ef} is the effective pore volume (m³), V_{total} is the total rock volume (m³), ϕ_{ef} is the effective porosity (fraction or %, usually a dimensionless value, e.g. 0.15 for 15%). The effective porosity is the portion of the total porosity that is related to interconnected pores through which fluid can filter. It excludes closed and capillary-connected pores from the calculation.

2. The current saturation is taken into account. If there is already oil/water in the reservoir, then the oil can be replaced with water. For this, the following ratio is used:

$V_{\text{water}} = V_{\text{pore}} \times \left(S_w^{\text{final}} - S_w^{\text{initial}}\right)$ (3)

where S_w^{initial} is the initial water saturation, S_w^{final} is the final desired water saturation.

3. Conversion to volume at standard conditions. Adjustment for reservoir pressure and temperature when calculating in volumes at reservoir conditions is carried out according to the formula:

$V_{\text{water}}^{\text{st}} = \frac{V_{\text{water}}^{\text{reservoir}}}{B_w}$ (4)

where B_w is the volume coefficient of water (1.02–1.05 for reservoir conditions).

Oil viscosity is known to be one of its most important physical characteristics, as it affects its fluidity. Viscous oils are difficult to transport and process. The viscosity of reservoir oil differs from that of separated oil. This mainly depends on the concentration of dissolved gas contained in it and the reservoir temperatures. The viscosity of oils in the depleted areas of the Siyazaneft (Azerbaijan) of the Azneft Production Association was 5–15 mPa·s. The highest oil recovery factor (≥ 50%) in formations is possible with low oil viscosity (≤1.5 mPa·s).

The composition and concentration of the surfactant aqueous solution and a detailed description of the new ejector will be discussed in another article. Below, the data for the 5% surfactant solution and the general appearance of the ejector are provided.

The efficiency of production was estimated by calculating the oil recovery factor (K_{ORF}) using the formula

$$K_{\mathrm{ORF}} = \frac{V_{\mathrm{ect}}}{V_{tot}} \cdot 100\% \quad (5)$$

where V_{ect} is the volume of extracted oil, and V_{tot} is the total volume of oil in the field. This formula allowed us to determine the percentage of residual oil recovery from a depleted oil field.

Among dynamic hydraulic machines, jet devices are the most common. With a simple design, they operate effectively by linking mass and energy exchange between liquid and gas flows. In this regard, jet two-phase hydraulic machines and methods for calculating their characteristics need clarification and revision. The ejector diagram presented here is one of the results of a series of studies conducted by the Research Institute "Geotechnological Problems of Oil, Gas and Chemistry".

To extract hard-to-recover oil using the water-gas method of affecting oil formations, a pump-ejector unit was used. It should be noted that the stages of designing and implementing new equipment, fine-tuning the pump-ejector unit on experimental stands and in field conditions were part of this work.

The features of the pumping equipment operation, when pumping gas-liquid mixtures, were studied experimentally. The conditions for the optimal operation of the ejector were difficult to model on the bench. Therefore, the interrelations of the working processes and the geometric dimensions of the working chambers of the ejector and centrifugal pump were studied in a single system. The novelty of the developed method for calculating the characteristics of a liquid-jet ejector was based on taking into account the shape of the velocity diagram and the compression ratio of the working jet. Experiments substantiated the conditions for optimal hydrodynamic similarity for the ejector. A field experimental test of the adequacy of the developed design of the jet device was also carried out. The novelty of the completed developments is confirmed by the AR patent for a utility model.

Below we will consider the main parts of the ejector developed by us used in oil production. To describe the operation of the technical details of the developed ejector for feeding the solution into the oil well and the specific applications of the device in this article, we will need more information and space. Therefore, these data will be published in a separate work. The type of ejector, concentration and composition of the surfactant solution, depth and pressure of the well, the source of the solution (tank, pump, dispenser), mixing system, type of supply of surfactant solution with air (supply under pressure or gravity), the necessary elements (filters, check valves, pressure gauges, pressure/flow sensors, etc.), the control system (automatic or manual) will be specified. Technological parameters, their range, well depth, oil type, equipment corrosion problems, and infrastructure costs will also be taken into account.

Schematic elements of an ejector for feeding a surfactant solution with air into an oil well are shown in Fig. 1.

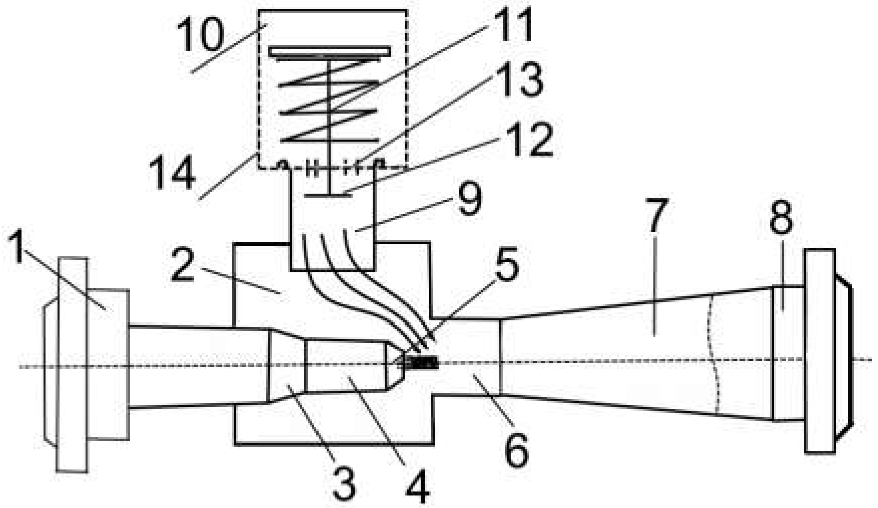

Figure 1. Diagram of the ejector assembly designed by the Scientific Research Institute of Geotechnological Problems of Oil, Gas and Chemistry of the Azerbaijan Republic. Liquid supply pipe 1, receiving chamber 2, confuser 3, liquid inlet pipe 4, nozzle 5, mixing chamber 6, diffuser 7, outlet pipe 8, lever tube 9, exhaust chamber 10, compression spring 11, disc valve 12, ventilation openings 13, air intake openings 14.

The extreme characteristics of the ejector were determined taking into account the pressure in the corresponding design section (H_i) using the formula

$$\frac{\Delta H_{5,2}}{\Delta H_{1,2}} = \frac{H_5 - H_2}{H_1 - H_2} \quad (6)$$

The energy characteristic of the ejector was determined by the dependence of the relative increase in the pressure of the passive flow on the ejection coefficient (α is the ratio of the flow rates of the ejected and active flows).

The ejector studies were conducted at low values of working fluid pressure in front of the ejector nozzle (up to 3 MPa), gas pressure in the ejector receiving chamber (up to 0.5 MPa), and gas-liquid mixture pressure at the ejector outlet (up to 1.5 MPa). The initial data may affect the convergence of the calculated and experimental characteristics of the LGE operation.

To organize the control flow that affects the active jets and the gas-liquid mixture in the mixing chamber, the ejector parts are modified, which makes it possible to sum up the deflecting jets of liquid from the axial movement and to somewhat narrow the flow sections of the channels in the area of the mixing shock formation. Such a liquid-gas jet ejector is both a mixer of media and a hydraulic compressor. The jet pump works effectively in systems where not only the energy acquired by the passive flow is used, but also the residual energy of the active liquid flow. Thus, a liquid-gas jet ejector was designed based on the experimental characteristics of the device, rational selection of the length of the mixing chamber and recommendations for its optimal use. This design allows the jet pump to operate with minimal energy consumption and stable operation in industrial conditions. The ejector has been tested in industry, is available to a range of users and can be recommended for practical use.

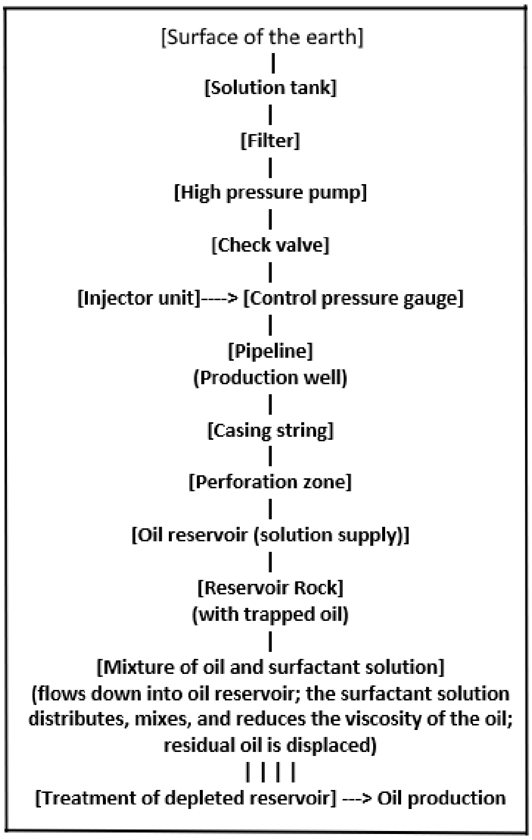

Figure 2. Schematic diagram of the elements of the ejector for feeding surfactant solution with air into an oil well.

Below in Fig. 2 is a diagram of the operation of the ejector for feeding a surfactant solution with air, constructed by us based on the analysis of the design of a liquid-gas jet pump. Here, the basic principles of optimal synthesis of a jet device, the use of a surfactant solution are used and optimal conditions for their real implementation are proposed.

Here, the solution tank is where the aqueous surfactant solution is stored. The filter was used to clean the solution from mechanical impurities. The pump provides the necessary pressure for pumping the surfactant solution with air. The ejector check valve prevents the backflow of the surfactant solution. The ejector unit is the section where the surfactant solution with air is pumped into the oil well pipe. The pressure gauge is used to control the feed pressure of the solution with air. The casing pipe is the inner pipe of the well through which the solution with air is fed to the formation impact zone. The perforation zone is the hole in the column through which the solution with air enters the formation.

Using a surfactant-water-air mixture (5% solution of NaOH, Na_2CO_3 and sulfanol) and pumping this mixture through an ejector into an oil well for a certain period of time allowed us to increase the oil recovery factor. In other words, the use of the volumetric data method, based on the comparison of the volume of extracted oil with the total volume of oil in the field, also allowed us to determine the efficiency of using the ejector we developed. The extracted oil reserves were divided by the total reserves and the time recovery factor was obtained.

3. Results and discussion

It is known that oil recovery can be increased by injecting a water-gas mixture into an oil-depleted formation. This allows increasing the oil recovery factor when injecting a water-gas mixture into such a formation. The efficiency of this method depends on many factors, in particular, on the pressure and temperature of the formation, the initial water saturation and permeability of the formation, the degree of compression of oil by gas, water or water-gas mixtures, the composition of the water-gas mixture, and the porosity of the formation. The pore composition of uncemented clastic rocks, which mainly depends on their granulometric composition, also affects the compressibility of oil when a water-gas mixture is introduced into an oil reservoir. Experiments have shown that as a result of pumping a surfactant-air mixture into a depleted oil reservoir through an ejector, the oil flow rate of the production well increased. At the same time, the volume of water released together with the oil decreased.

It has been established that compression of oil by gas is less than compression of oil by a water-gas mixture. The difference in the degrees of oil compression is 5-7%. However, the consumption of the compression agent - water-gas mixture - increases by 50%. Gas quickly enters the bottomhole zone of production wells, moving along the near-ceiling part of the formation when it is pumped into the oil formation. In this case, it is necessary to regulate the movement of the flow formed in the formation. For this purpose, a water-gas mixture is used.

The use of a modified ejector shows that the ejector design we propose allows for an increase in residual oil flow rates from the reservoir. At the same time, the negative factors affecting oil displacement from the reservoir are weakened.

It has been established that the resistance of the porous medium increases when injecting a surfactant-water-gas mixture into an oil reservoir. And an increase in the pressure drop in the mixing zone of the mixture with the oil-water phase creates an emulsified state. By adjusting the concentration of surfactants in the water-gas mixture, it is possible to increase the efficiency of developing depleted oil deposits. The injected surfactant-water-gas mixture, under the action of capillary forces, occupies hydrophilic pores in the oil-flooded zone of the formation. The gas component of the mixture, being a non-wetting phase, occupies, unlike water, the highly hydrophobic pores of the formation. Then, under the action of gravitational forces, the gas moves to the upper part of the formation. The combination of these properties allows for an increase in oil recovery from the formation when oil is compressed with a surfactant-water-gas mixture. The use of special gases injected into formations creates difficulties in oil-depleted fields. The use of air instead of such gases and a solution of surfactant in water allows the process of oil extraction to be intensified.

As stated above, when the mixture is pumped, air, being a non-wetting phase, penetrates into the fine-permeable pores of the formation. This facilitates the squeezing out of oil from there and prevents the formation of oil-water formations in the formation. The surfactant added to water increases the oil-washing capacity of the mixture and also weakens capillary forces by reducing the surface tension at the liquid-oil interface. Thus, the reservoir coverage increases, which will ensure an increase in reservoir oil recovery. The coefficient of formation coverage by flooding (K_f) depends on various factors. As a first approximation, one can use [36] the empirical formula

$$K_f = 1 - \frac{Z}{3} \cdot \frac{P(1-P)(0.427+0.733P-0.826P^2)}{\exp[13.19(P-0.60)^2]} \quad (7)$$

where P is the coefficient of sandiness of the reservoir, Z is the distance between the injection zone and the solution extraction zone (dimensionless parameter).

The value of the sandiness coefficient is determined by the formula

$$K_s = \frac{h_\alpha}{H} \cdot 100\% \quad (8)$$

where h_α is the thickness of sandstones, H is the total thickness of cyclite.

Taking into account the formula (7) for determining the flooding coverage factor at different sandiness factors of four-fold washing of the pore volume, the dependence of the flooding factor on the sandiness factor was constructed. The sandiness factor varied from 0 to 1. An extreme was observed at a sandiness factor of 0.6. This may be due to the complication of the geometry and sizes of pores, and sand bodies of the reservoir and formation. Fig. 3 shows the dependence of the flooding coefficient on the sand-to-gross ratio in the studied wells.

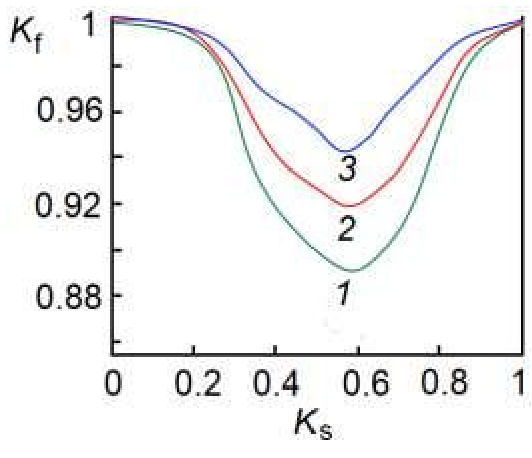

Figure 3. Dependence of the waterflooding coefficient on the sand-to-gross ratio in the studied wells. *1* – No. 1580, *2* – No. 1858, *3* – No. 1715.

The initial data used were the dimensionless distance between the injection and extraction zones Z = 2, the formation thickness Ht = 20 m and the minimum height of the productive formation, h_{min} = 1 m. Changing these parameters changes the position of the extremum in Fig. 3. The type of dependence of the waterflooding coefficient on the sandiness coefficient P for the studied wells remains similar to each other.

Let's consider the features of the ejector we developed for pumping a surfactant solution-air mixture into an oil reservoir. It has been established that the injection coefficient of the ejector used affects the oil yield when injecting a surfactant-water-air mixture into the formation. Optimal results were obtained with an ejector injection coefficient of 0.6.

Based on the above ejector diagram, let's consider the operating principle of the ejector. The surfactant-containing solution is fed into the ejector, through the nozzle and the inlet pipe, and from there into the receiving chamber. Then the mixture enters the mixing chamber and the diffuser. As the solution moves to the outlet pipe of the ejector, air is sucked in at a radial speed through the two-sided holes due to the vacuum in them. The sucked air is transported into the ejector body, and from there, mixing with the surfactant solution, it is fed into the oil well through the outlet pipe.

The ejector was used in the oil fields of Azerbaijan by pumping a mixture of surfactant-solution-air (60% air - 40% solution) into the oil reservoir through this device. By pumping the mixture, it was possible to compress about 50% of the residual oil. This work was carried out in industrial conditions at the site of NGDU Siyazaneft of PO Azneft. A site with three production wells (No. 1580, 1858, 1715) and one injection well (No. 1544) was selected. Oil well No. 1544 was connected to a special water pipeline.

The results of treatment of production wells No. 1580, 1715 and injection well No. 1544 also gave positive results, which will be published elsewhere. Testing work began on 15.06.22. Five tons of 5% solution of the surfactant "AzEl" developed by us were fed by the unit through an ejector into an oil well. In the ejector, the surfactant solution was mixed with air and pumped into the well. Injection of the resulting surfactant-water-air mixture through the ejector allowed to increase the oil flow rate of the specified wells located near the injection wells. At the same time, the amount of water extracted together with the oil also decreased.

Table 1 shows the daily flow rates of oil and water from production well No. 1858, near the injection well, before and after using a surfactant-containing mixture. As a result of injecting a surfactant-containing mixture into the injection well through an ejector within ten days, the oil flow rate from production well No. 1858 increased from 1.5 tons/day to 1.9 tons/day. In this case, the volume of water released with the oil decreased from 86% to 80%.

Table 1. Results obtained before and after injection of the surfactant-air mixture solution through the ejector into production well No. 1858. Well treatment time from 13.07.2022 to 23.07.2022

Average daily productivity of an oil well № 1858 before and after injection of a mixture (surfactant-water-air) by an ejector, t/day					
Oil		Water		Water yield, %	
before	after	before	after	before	after
	1.9	8.4	7.8		80

4. Conclusions

Field studies of the operational characteristics of the developed liquid-gas ejector (LGE) in the working range of parameters and characteristics of the impact of water-gas surfactants on the oil reservoir and the pumped oil well showed the following. The developed method of processing depleted oil wells was used in field conditions. Experiments were conducted on production wells No. 1580, 1858, 1715 and injection well No. 1544 "Siyazaneft" of PO "Azneft".

1. Using the dimensionless distance between the injection and extraction zones Z = 2, the formation thickness H_t = 20 m and the minimum height of the productive formation h_{min} = 1 m gave similar dependencies of the waterflooding coefficient on the sand-to-grit ratio for the studied wells No. 1580, 1858 and 1715. An increase in these parameters shifts the position of the extremum from 0.6 to 0.55. However, the nature of this dependence remains similar.

2. The optimal operating characteristics of the LGE took into account the change in the operating parameters of the LGE during full-scale tests of the pump-ejector system. Taking this into account, the LGE was designed and used to treat wells No. 1580, 1858 and 1715.

3. Injection of a 5% aqueous surfactant solution (5% solution of NaOH, Na_2CO_3 and sulfanol) with an air mixture allowed to increase oil recovery and estimate the oil recovery factor in depleted oil wells. This method is an important step in planning and assessing oil production, and the calculation performed can help optimize the production process and increase its efficiency.

4. Injecting a surfactant-water-air mixture into a formation containing residual oil increases the oil recovery factor from an oil well by 27% over ten days and also reduces the volume of water injected into the formation by 7%.

5. Field tests of the pump-ejector system for exploitation of depleted oil wells in Azerbaijani fields indicate the following. Further improvement of designs and application options of pump-ejector systems in general and liquid-gas ejectors in particular can significantly increase oil recovery.

Conflıct of ınterest

The authors of this work declare that they have no conflicts of interest.

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