Approaches to the effective implementation of SWAG-technology and technology for intrastratal carbon dioxide generating

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Abstract. This article provides an overview of the results of studies of water-gas methods and carbon dioxide generation in reservoir conditions as methods for increasing oil recovery. It is shown that the efficiency of technology implementation is influenced by the choice of technical device and the composition of the selected agents selected for injection into the reservoir. The effectiveness of the implementation of these methods is directly influenced by reservoir conditions (pressure and temperature), as well as the mineralization composition of the liquid phase (injected in the form of a water-gas mixture or formation water). It turned out that in the case of an optimal mineralization composition of the liquid, the technological efficiency of the methods increases. In other cases, it is necessary to use foaming surfactants. Recommendations on the composition and concentration of surfactants are given. To implement methods in a specific field, it is recommended to conduct laboratory studies to determine the optimal composition of the agent acting on hydrocarbon-saturated rock.

1 Introduction

In the world practice of production of liquid and gaseous hydrocarbons, the technology of non-stationary flooding of reservoirs is aimed at both maintaining reservoir pressure and increasing oil recovery and intensifying oil production. The accumulated experience [1-6] indicates the effectiveness of the method.

Along with a number of advantages, waterflooding technology is characterized by disadvantages of natural [1-2] and technogenic origin [7-9]. This is expressed in rapid filtration of water to production wells with subsequent watering of their products, which in turn provokes the formation of stagnant and poorly drained zones. It should be noted that establishing the sources, causes and consequences of high water cut in well production is not an easy task, and it is not always possible to effectively deal with these problems [10].

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Adding an additional agent - gas - to the water allows you to increase the area of coverage of the formation by the influence [11-13]. However, numerous issues related to the introduction of water-gas methods in fisheries have not been sufficiently studied.

One of the areas among enhanced oil recovery (EOR) methods that help reduce interfacial tension, wash out film oil, accelerate capillary impregnation, change rock wettability (rock hydrophilization) and increase phase permeability for oil is technology using surfactants.

2 Materials and methods

The main method used in preparing this review is the analysis of data on previously conducted studies of methods of SWAG-technology and carbon dioxide generation in the reservoir. Particular attention is paid to research into factors influencing the effectiveness of technology implementation in the fields.

Among the factors characterizing the composition of water for injection of a water-gas mixture or the formation of a water-gas rim in a formation, the mineralization composition of water and the presence of surfactants are highlighted.

Using the experimental method on a stand of a pump-ejector system, the characteristics of the operation of the booster pump were obtained.

Based on the research, recommendations have been formed that will increase the popularity of these technologies.

3 Results

3.1 Technology of injection of water-gas mixtures

Among the main methods of WAG, SWAG is characterized by the greatest promise; the best technical solution is pump-ejector systems [3].

The pump-ejector system (Figure 1) includes a booster pump to increase the injection pressure of the water-gas mixture. The scheme involves adding surfactants. From [3] it is obvious that the proposed system is the most effective option, which allows the injection of mixtures in a wide range of operational parameters (which directly affects the success of the method).

The injection pressure is calculated taking into account reservoir pressure and hydraulic losses during the injection process [14-15]. Therefore, numerous studies are aimed at developing technology for producing water-gas mixtures with suppressed coalescence.

![Fig. 1. Schematic diagram of the pump-ejector system for SWAG-technology [3].](image)

It was concluded in [16] that the most promising technology is the production of microseeds—gas bubbles of small diameters. In this case, the interaction of gas bubbles is similar to the interaction of solid particles. This technology requires numerous rather expensive studies due to the lack of a formulated theory of the process of coalescence of gas bubbles in liquids.
Numerous studies have paid special attention to the influence of water salinity on the behavior of the gas phase. A number of works [17-19 and al.] have become fundamental in understanding the nature of gas dissolution processes in organic and inorganic solvents. Based on the results of these studies, it was possible to make a number of discoveries that have a positive impact on the technological efficiency of enhanced oil recovery methods. It was shown in [20] that the mineralization composition of formation waters can help suppress the coalescence of gas bubbles if the chemical composition of dissolved electrolytes corresponds to the theory presented in [17-19]. The results [21-24] give an idea of the filtration of various liquid systems through porous media; they can be used in studying the influence of a water-gas mixture on formation fluids.

3.2 Influence of the composition of the water-gas mixture on the characteristics developed by the pump-ejector system

The efficiency of pump-ejector systems is influenced by the composition of the pumped gas-liquid mixture. An increase in the gas content of the mixture at the ejector outlet negatively affects the operation of the booster pump [16]. An increase in the diameters of gas bubbles also worsens the characteristics developed by the pump. Selecting the operating parameters of the ejector allows you to increase the efficiency of the ejector and the pressure it develops [25-27], however, in many cases in the fields, reducing the gas content and adjusting the operating parameters is not enough to obtain a water-gas mixture with the required gas content.

The optimal mineralization composition of water in the water-gas mixture makes it possible to increase the efficiency of the liquid-gas ejector [28-29] and the booster pump as part of the pump-ejector systems [16]. This phenomenon is explained by the intensification of energy exchange between the working fluid and the ejected gas. The use of formation water of optimal composition, as in the Samodurovskoye field (Table 1), makes the technology cheaper, since in this case there is no need to purchase reagents to suppress coalescence.

However, in cases where formation water does not have these properties, it is advisable to select a surfactant.

In [30-31] it is shown that a number of external factors affect the efficiency of the booster pump. Adding a surfactant and increasing the inlet pressure significantly reduces the negative effect of free gas on the developed pressure. However, in [30-31] there are no recommendations on the chemical composition and concentration of surfactants.

Under laboratory conditions, a relationship has been established between the pressure developed by the pump and the chemical composition and concentration of the surfactant. Tap water was used as the liquid, and the gas content at the pump inlet was regulated. Figure 2 illustrates the dependence of the pressure developed by the pump on the composition of the pumped mixtures (gas content, chemical composition and surfactant concentration) [32]. An increase in the input gas content reduces the developed pressure, but an increase in the surfactant concentration significantly improves the performance. The dependencies are nonlinear, and for each type of surfactant there is a certain concentration range; with increasing concentration within the range, the performance improves, then the regime breaks down, and the pressure developed by the pump sharply decreases.

It turned out that Neftenol VVD with a concentration of 0.03% allows one to obtain almost the same result as that obtained by adding disolvane of the same concentration. The tendency for the progressive pump efficiency to decrease with increasing surfactant concentration indicates that 0.03% is the optimal concentration. It is not advisable to increase the concentration of surfactants.
Table 1. Composition of formation water of the Samodurovskoye field.

<table>
<thead>
<tr>
<th>Element</th>
<th>Name of indicator</th>
<th>Unit change</th>
<th>The value of the indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Density according to GOST 3900 - 85</td>
<td>kg/m³</td>
<td>1115</td>
</tr>
<tr>
<td>2.</td>
<td>pH</td>
<td></td>
<td>7.35</td>
</tr>
<tr>
<td>3.</td>
<td>Ionic composition of water according to OST 39 – 071 – 78</td>
<td>mol/l</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HCO$_3^-$</td>
<td>10$^{-3}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cl$^-$</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SO$_4^{2-}$</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca$^{2+}$</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mg$^{2+}$</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K$^+$ + Na$^+$</td>
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<td></td>
</tr>
<tr>
<td>4.</td>
<td>General mineralization</td>
<td>mol/l</td>
<td>~2.28</td>
</tr>
<tr>
<td>5.</td>
<td>Mass fraction of iron</td>
<td>mg/dm$^3$</td>
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</tr>
<tr>
<td>6.</td>
<td>Mass fraction of hydrogen sulfide</td>
<td>mg/dm$^3$</td>
<td>210</td>
</tr>
</tbody>
</table>

Fig. 2. Dependences of the pressure developed by the ESP5A-100 pump on the input gas content in “water-gas” and “water-surfactant-gas” mixtures when using Neftenol VVD and dissolven 4411 with different concentrations [32].

3.3 CO$_2$ generation in reservoir conditions

Interesting from a technology point of view is the technology of generating CO$_2$ in reservoir conditions. A solution of chemical reagents is pumped into the formation. During the chemical reaction, CO$_2$ is released. Gas with formation water forms a gas-liquid rim, which interacts with oil in the rock. This indicates that this technology is a modification of SWAG-technology.

In [33], the mechanism of CO$_2$ generation with the formation of a rim, which is used as an agent displacing residual reserves and increasing the reservoir coverage area, is considered. Laboratory studies [33] have shown that the addition of surfactants affects the interaction of the generated gas with liquids. This helps to reduce the mobility of low-viscosity CO$_2$, prevent premature gas breakthrough and reduce the instability of the displacement front.

To better understand the nature of the phenomena occurring in the reservoir during the generation of CO$_2$, experimental modeling of the processes of changes in pressure and temperature in the system was carried out [34]. The experiment was carried out for the conditions of a carbonate section of one of the fields in Azerbaijan. It has been established that the pressure of the resulting CO$_2$ gas depends significantly on the concentration of the
polymer additive and slightly depends on the concentration of the surfactant added to the GY reagent.

In [35], information is provided on an experimental setup that allows one to regulate the reaction temperature and record the volume and pressure of the gas formed. Experimental studies were also carried out on the influence of formation fluid salinity on the parameters (volume and pressure) of the generated gas. A comparative analysis of experimental data showed that at the same concentrations and volumes of reacting solutions, the intensity of the generated gas is higher in solutions prepared with formation water. This indirectly points to the results obtained in [16, 20] (the mineralization composition of formation waters can contribute to the effective implementation of technologies).

In [36], experiments showed that the thermobaric parameters of the generated gas depend on the quantitative ratios of the reagents. That is, the component composition of the liquid affects the implementation of the process in a pseudo-boiling gas-liquid system. To effectively influence the formation with gas-generating solutions, it is necessary to take into account the dynamic conditions of injection of process agents and the thermodynamic parameters of the oil deposit.

Gas pressure increases with the addition of a surfactant, a decrease in temperature and an increase in the salinity of the formation fluid [37]. In [38], these results were confirmed and the addition of polymer additives was proposed.

4 Discussion

SWAG-technology has great prospects due to the wide range of problems that this method solves. In addition to increasing oil recovery, the method helps reduce the carbon footprint. In addition to increasing oil recovery, the method helps reduce the carbon footprint with virtually unchanged operating costs [39].

However, the experience of introducing the method in domestic and foreign fields has pointed out the main shortcomings in the practical implementation of the method. They are associated with the impossibility of injecting a stable mixture into the formation, since during the process of movement along the injection well bore, the mixture is affected by various factors, leading to the stratification of the mixture into gas and water. In turn, this leads to complications, such as breakthrough of individual phases in the most permeable areas. This circumstance requires further research in order to improve the technology.

The introduction of the method of alternating injection of water and gas at the Novogodny field led to a sharp decrease in the injectivity of the reservoir. At the same time, the expensive compressor units that were purchased for water injection at this facility became unusable after three injection cycles. This experience indicated an urgent need to improve the technological component of the SWAG method.

Core studies during the design of the pilot project at the Willmar field showed greater efficiency of WAG compared to flooding and gas flooding [40-41]. No evidence of large-scale implementation of WAG at Willmar was found.

An example of the negative implementation of SWAG is the SWAG injection on the Indian offshore Heera field [42, 43]. Interpretation of data from a complex of geophysical studies made it possible to establish that the mixture began to stratify as it moved along the wellbores.

Known cases [3, 44] of using pump-ejector systems have shown their ineffectiveness. Basically, the limitation in the scope of application was due to the need to develop a relatively high injection pressure of the mixture into the formation. Injecting a stable water-gas mixture with the required gas content using a modification of the device (Figure 1), adapted to field conditions, will increase oil recovery. In this case, part of the gas is utilized in the reservoir. Economic efficiency is ensured by increased production and a reduction in
fines due to a reduction in the volume of APG flared (if petroleum gas is injected as part of a mixture). The use of surfactants will increase the stability of the mixture. Adding a surfactant to water with rational mineralization provides a synergistic effect of the influence of electrolytes and a chemical reagent: coalescence is suppressed. Experimental studies of the displacement of reserves by a water-gas mixture with a surfactant, a mixture with mineralized water without a surfactant, and a mixture with mineralized water and a surfactant will allow us to determine not only the greatest increase in $K_{\text{dis}}$, but also to further analyze the profit of an oil producing company from three different options. If mineralization is optimal, and the addition of a surfactant does not contribute to a significant increase in $K_{\text{dis}}$, then the addition of a surfactant is not recommended. In this case, the use of mineralized water reduces the cost of technology due to the absence of the need to purchase surfactants [45] and the use of technologies that separate surfactants from well products.

Numerous studies [46-48] have shown that carbon dioxide flooding, in the form of miscible or immiscible flooding, is one of the most effective alternative methods for enhanced oil recovery. There are a number of reasons that reduce the widespread use of CO$_2$ injection technology: environmental problems, equipment corrosion, rapid CO$_2$ breakthrough, the source of this gas, the cost of transportation, preparation and injection.

This technology eliminates the need to pump a gas agent from the surface and the use of appropriate equipment. In-situ CO$_2$ generation is more economically advantageous compared to surface gas injection technology. Positive experience of introducing this technology in the fields is described in [49].

5 Conclusions

Technologies for injecting water-gas mixtures and generating CO$_2$ are technologically and economically promising ways to increase oil recovery. They help increase the efficiency of the development process and can be used at various stages.

The SWAG-technology using pump-ejector systems solves a number of problems. For effective implementation, it is recommended to conduct a series of studies in order to select the optimal composition of the water-gas mixture. Adding a surfactant of the required concentration will improve the performance of the liquid-gas ejector and booster pump. If the mineralization composition is optimal, the addition of a surfactant is not required.

CO$_2$ generation is an alternative method that does not require specialized equipment.

These technologies show high efficiency according to the results of laboratory and field studies, however, for wide replication it is recommended to experimentally select the optimal composition of the agent acting on the rock.

Acknowledgement

The author express their gratitude to the authors of the considered works for the opportunity to write this review.

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