Perspectives of application of simultaneous water and gas injection for utilizing associated petroleum gas and enhancing oil recovery in the Arctic fields

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Abstract. At present, it is becoming more relevant to use other displacing agents, which are more effective in comparison with waterflooding, for increasing oil and gas condensate deposits component recovery. One of such promising methods is simultaneous water and gas injection. In this article, we present the principal options for using simultaneous water and gas injection in Arctic fields, case study of the Urengoykoye and Prirazlomnoye fields. Technological schemes for its implementation in the Urengoykoye field at low reservoir pressures are considered. Filtration studies of oil from reservoir models with water-gas mixtures at various gas contents allow increasing hydrocarbon recovery efficiency by determining the area of rational gas contents. For the conditions of the Prirazlomnoye field, the possibility of using pump-ejector system for the utilization of associated petroleum gas has been established.

1. Introduction
The Arctic has a huge potential for the further development of domestic oil and gas industry in the coming decades. In 2017, more than 95 million tons of oil were produced in the Arctic, which is 4% more than in 2016 [1]. Every year, the share of oil production in the Arctic from the total Russian production continues to grow [2], since oil companies show increasing interest in the Arctic largest natural resources.

Irrational flaring of associated petroleum gas (APG) remains a big issue for oil industry. About 150 billion cubic meters of APG are burned annually in the world, while Russia is among the world leaders in APG flaring. In 2017 in our country, 12.9 billion cubic meters, or 13.1% of the total APG production, were burned out in flares [3].

The transportation of associated petroleum gas produced in the Arctic shelf fields compounds the problem of its processing. The rational use of APG in Arctic fields is possible by its injection into the reservoir during the implementation of simultaneous water and gas injection.

The use of simultaneous water and gas injection in several fields is turned out to be effective [4-7]. In foreign practice, gas treatment units, high-pressure pumps and compressors are used for the implementation of simultaneous water and gas injection [8].

In Russia, several attempts have been made to use booster systems for WAG, which, unlike compressors, do not require careful gas treatment.

The problems arising from the use of pumping and booster units for the implementation of simultaneous water and gas injection with APG are described in enough detail in article [9].
Both compressor and booster technologies require the use of sophisticated equipment, qualified maintenance and repair. It is also very problematic to ensure acceptable reliability of compressor and booster equipment during long-life operation at high discharge pressures.

The water-alternating-gas injection performed into the reservoir with compressor and booster technologies is often followed by breakthroughs of large volumes of gas to the bottom of the producing wells. That leads to the shutdown of their normal operation and losses in oil production [10].

Previous theoretical and bench studies [10–15] have shown that with the use of pump-ejector systems, which allow preparing a water-gas mixture at the surface. The mixture is pumped in a wide range of flow rates and pressures. It is possible to organize simultaneous water and gas injection into the reservoir with simple and reliable equipment. The pump-ejector system can successfully operate in the field conditions of Russian fields. The application of simultaneous water and gas injection technology with the use of a pump-ejector system on the example of the Samodurovskoye field showed a positive result. The system worked steadily in various modes and there were no disruptions in the supply of ejectors and pumps [15].

The purpose of this study is to develop process flow diagrams for the implementation of simultaneous water and gas injection in relation to the Urengoyskoye and Prirazlomnoyе fields’ conditions in the Arctic using pump-ejector systems.

2. Method of research

On the basis of the identified shortcomings when analyzing the technologies used for the implementation of simultaneous water and gas injection at fields in Russia and abroad, technological diagram for the use of pump-ejector systems for injecting water-gas mixtures into oil and oil-gas condensate reservoirs were described in [16]. Technological parameters for known field conditions were calculated according to the method presented in [17].

An attention is draw to the importance for carrying out filtration studies on field core material, to calculate the rational value of the gas content. The research methodology is reflected in the work [16, 17].

In addition, researches on the composition of the produced water used to create a water-gas mixture were performed. The presence of cations and anions of certain salts have a positive effect on the stability of the obtain gas-water system [18].

To assess the environmental efficiency of the use of APG for injection into the reservoir at the Prirazlomnoyе field, predictive calculations of the amount of gas flared and water injected into the reservoir were performed. Economic efficiency was determined by reducing the amount of APG flared, i.e. to reduce the fines paid by the company.

3. Results and discussions

We have proposed various technological schemes of pump-ejector systems for performing simultaneous water and gas injection at the initial stage at low reservoir pressures and at the next stage with an increase in reservoir pressure considering the Urengoyskoye field conditions.

For the Prirazlomnaya offshore ice-resistant fixed platform (OIRFP), a technological scheme with parallel pumps and ejectors operation lines for creating a water-gas mixture has been developed.

3.1. Pump-ejecting system for the Urengoyskoye field

Oil rims of the Urengoyskoye oil-gas condensate field are developed to depletion without maintaining reservoir pressure [19]. Work [20] and experimental studies of V. N. Khlebnikov and P. M. Zobov show the efficiency of water-gas mixtures injection into the neocomian productive reservoirs Bu 112.

Regarding to the conditions of the Urengoyskoye field at the initial stage of simultaneous water and gas injection performance at low reservoir pressures, the principal technological scheme of the pump-ejector system for simultaneous water and gas injection shown in Figure 1 may be recommended.
Figure 1. Technological diagram of the pump-ejector system for simultaneous water and gas injection at the initial stage of its implementation at low reservoir pressures.

The pump-ejector system (see Fig. 1) contains power pump 1, ejector 2, booster pump 3, as well as water supply line 4 to the power pump 1, water injection line 5, gas pumping line 6, and water-gas mixture injection line 7 into the formation. The suction chamber of the ejector 2 is connected with the gas pumping line 6, and the water injection line 5 is directed to the ejector nozzle 2. The output line 8 of the ejector 2 is connected with the suction chamber of the booster pump 3. An adjustable gate valve 9 is installed on line 5.

The system can also accommodate a controlled volume pump 10 with a surfactant feed line 11 from the tank 12 and an adjustable gate valve 13 at the output.

In the system variant, the power pump 1 and the booster pump 3 are equipped with frequency-controlled drives 14 and 15. The controlled volume pump 10 can also be equipped with a frequency-controlled drive 16.

In the system versions, an adjustable gate valve 17 and a low-pressure compressor 18 can be installed on gas pumping line 6.

A multiple-impeller pump or a screw displacement pump can be installed as booster pump 3.

The proposed system in the execution variant (Figure 2) for the implementation of the next stage of simultaneous water and gas injection when the reservoir pressure increases, contains booster pump 3 manufactured in the submersible design and lowered on tubing 19 to the ultimate pump running depth in the injection well 20 drilled to the reservoir 21.

An "inverted" type of the booster pump 3 is driven by a submersible motor 22 located above it. The motor is in the sealed casing 23 attached to the lower end of the tubing 19. The suction 24 of the booster pump 3 is also located in the sealed casing 23. The outlet of the booster pump 3 is equipped with a shank 26. The annular space between shank 26 and production string of injection well 20 is overlapped by packer 27.

Simultaneous water and gas injection on the formation in accordance with the proposed diagrams is carried out as follows.

Water is pumped by the power pump 1 from the water supply line 4 along the water supply line 5 into the nozzle 2 of ejector that pumps gas from the gas pumping line 6. The ejector 2 allows creating, dispersing and increasing pressure of water-gas mixture that is directed along line 8 to the booster pump suction 3.
Figure 2. Principal technological scheme of the pump-ejector system at the next stage of implementation of simultaneous water and gas injection when the formation pressure increases.

Then, water-gas mixture is pumped by booster pump along the water-gas mixture injection line 7 into the reservoir.

At the same time, the free gas content of the mixture at the booster pump suction 3 is set lower than the value of critical gas content of cavitation-free operation of the booster pump 3 on the water-gas mixture. The free gas content in the mixture at the booster pump suction 3 is regulated by changing the gas supply by the ejector 2. The critical gas content is regulated by changing the pressure at the booster pump suction 3 by changing the pressure of water injected into the ejector 2 and/or by changing the foaming characteristics of the water-gas mixture. In the latter case, foaming surfactants are pumped out of the tank 12 along the line 11 with a controlled volume pump 10, which supplies surfactants to the water discharge line 5. The change in foaming characteristics is achieved by changing the consumption of surfactants when regulating the supply of the controlled volume pump with a frequency-controlled drive 10 and an adjustable valve 13. The regulation of gas and water flow rate, pressure and free gas content in the mixture at the booster pump suction 3 is carried out by changing the size of the ejector's wet end 2 and/or changing the gas pressure in the ejector's suction chamber.

In the implementation variant (see Fig. 2), when the reservoir pressure increases, it is necessary to ensure higher gas discharge. A growth in critical gas content, an increase in pressure and a decrease in free gas content in the mixture at the booster pump suction 3 are, in this case, carried out by using the Earth's gravitational field for compressing the water-gas mixture from ejector outlet 2 to booster pump suction 3. This is obtained by launching the submersible booster pump 3 into injection well 20 up to its bottomhole.

Taking into account that friction pressure losses are incommensurably lower than the pressure created by the weight of the water-gas mixture column in the Earth's gravitational field, the pressure at the booster pump suction 3 is much higher than the pressure at the injection wellhead 20. In addition, the downhole depth of the booster pump 3 increases with a growth in this difference. Therefore, the greater the setting depth, the higher the critical gas content, pressure at the suction and the lower the content of free gas in the mixture at the booster pump suction 3. That expands the field of application of simultaneous water and gas injection method on reservoir towards higher gas discharge.
After the ejector 2 the water-gas mixture is directed along the line 8 to the tubing column 19 and further along the annular space between the sealed casing 23 and the submersible motor 22 – to the suction 24 of the submersible booster pump 3. Electric power is transmitted to the submersible motor 22, rotating shaft of the booster pump 3 via cable 25 from surface, from an installed control station with frequency-controlled drive 15. Booster pump 3 injects water-gas mixture through the shank 26 into the reservoir 21. Packer 27 is necessary to prevent high injection pressure from being transferred to the production string 20.

3.2. Pump-ejecting system for the Prirazlomnoye field

According to performed calculations for Prirazlomnoye field conditions (Table 1), the values of gas-water factor for pump-ejector system at standard working conditions were determined. The reservoir water density is 1044 kg/m$^3$, salt content - 5.73%. The maximum value of gas-water factor is 32.2 m$^3$/m$^3$ in 2017. This value will make it possible the implementation of simultaneous water and gas injection technology, as the possibility to use it at low gas-water factor of 43.5 m$^3$/m$^3$ is experimentally confirmed in oil and gas industry.

**Table 1.** Water and gas data for the Prirazlomnoye field.

| Parameters                          | 2017        | 2018        | 2019        | 2020        | 2021        |
|------------------------------------|-------------|-------------|-------------|-------------|-------------|
| Gas flaring, million m$^3$/year    | 104.19      | 145.61      | 160.68      | 152.10      | 140.57      |
| APG consumption, thousand m$^3$/day| 311.01      | 434.66      | 479.64      | 454.04      | 419.60      |
| Screw up water injection, thousand m$^3$/year | 2969.4 | 4601.9 | 5589.1 | 5892.9 | 6458.1 |
| Water discharge for repressuring, thousand m$^3$/day | 8.86 | 13.74 | 16.68 | 17.59 | 19.28 |
| Gas-water factor, m$^3$/m$^3$     | 32.20       | 29.04       | 26.39       | 23.69       | 19.98       |

To ensure the utilization of all APG flared on the Prirazlomnaya offshore ice-resistant fixed platform (figure 3), a diagram of the pump-ejector system was developed. According to this technological diagram, an excess gas from the first stage and from the second stage of separation, after increasing the pressure at the compressor to the value not less than 1 MPa, enters the suction chambers of two parallel installed ejectors 3. The system drives water into the nozzle of the ejectors 3 from the primary 1 and intermediate 2 power pumps.

**Figure 3.** Technological diagram of the pump-ejector system at the Prirazlomnaya OIRFP.

Water after being mixed with gas in ejector 3 is driven to the intake of multiphase pumps 4, which in turn are the main power elements for water pumping into wells with injection pressure 27 MPa. The proper selection of pumping equipment will allow operating the pump-ejector system taking into account the changing in APG flow rate. The dynamics of the volumes of APG fared and water injected into the reservoir when performing simultaneous water and gas method with pump-ejector system are shown in Figures 4 and 5.
Figure 4. Forecast of APG flaring at Prirazlommaya OIRFP.

Figure 5. Water injection for reservoir pressure maintenance at Prirazlommaya OIRFP for simultaneous water and gas injection.

As a result of the implementation of pump-ejector systems, the predicted annual fines for APG flared at Prirazlommaya OIRFP during soot flaring are reduced (Figure 6).

The total amount of fines is over 0.15 billion dollars. The implementation of a pump-ejector system does not require significant changes in the repressuring system, and significant capital investment for purchasing the equipment. Thus, the use of this technology provides a positive economic effect. Additional growth of oil production due to the effect of water-gas mixture on the reservoir will increase the obtained effect.

Figure 6. Annual fines for APG flaring at Prirazlommaya OIRFP during soot flaring.

3.3. Improving the efficiency of simultaneous water and gas injection with a pump-ejector system

In order to improve the efficiency of the exposure before water-gas mixture injection, it is recommended to conduct filtration studies, which show the effect of water-gas mixtures on oil displacement from reservoir models at various gas contents. The experiments allow determining the area of rational gas content of the mixture under reservoir conditions. The rational gas content is referred to the highest values of oil displacement coefficient (±10% of the maximum value). Then the mixture is pumped into the reservoir while maintaining the gas content of the mixture $\beta_{\text{res}}$ under reservoir conditions, on the basis of ratio $\beta_{\text{min}} \leq \beta_{\text{res}} \leq \beta_{\text{max}}$, where $\beta_{\text{min}}$ – minimum gas content corresponding to the left boundary (-10% of the maximum value of displacement coefficient) of the
mixture rational gas content area under reservoir conditions, $\beta_{max}$ – maximum gas content corresponding to the right boundary (+10% of the maximum value of displacement coefficient) of the mixture rational gas content area under reservoir conditions.

The study of the composition of associated produced water from the field is required to determine the effect of salting-containing ions on the degree of suppression of gas bubbles coalescence in the liquid. Depending on the amount and composition of salts, the associated produced water can increase the stability of the fine water-gas mixture. With a slight mineralization of the used water, it is possible to add salts (up to rational concentrations) or surfactants.

4. Conclusions
The proposed fundamental solutions make it possible to increase the efficiency of simultaneous water and gas injection at the Urengoygskoye field with a significant reduction of implementation costs. It will also make it possible to implement the technology using pump-ejector systems at Prirazlomnoye field for APG utilization.

Analysis of changes in the amount of flared gas and injected water at Prirazlomnoye field showed that the proposed system will allow using the entire APG for injection into reservoir by 2031. The accumulated environmental effect for 3 years during implementation of this technology at PrirazlomnayaRF is characterized by the prevention of flaring about 1 billion st. m$^3$ of gas.

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