Application of pump-ejecting system for SWAG injection and utilization of associated gas

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Abstract. The work provides an analysis of the operating experience of the pump-ejecting system for simultaneous water and gas injection (SWAG) injection, at the Samodurovskoye field of Orenburgneft PJSC. The results of earlier theoretical and experimental studies were confirmed. The pump-ejecting system worked stably in various modes; there were no disruptions in the supply of ejectors and pumps. At the same time, the experience of operating the system made it possible to outline measures to improve not only the equipment, but also the technology of water and gas impact on the formation using pump-ejecting systems. To implement SWAG, it is necessary that the gas content of the mixture in reservoir conditions reach 13-20%. In those cases when the volume of associated petroleum gas (APG) is not offered, it is proposed to use nitrogen. Adding nitrogen as a gas component to the water-gas mixture will help to obtain a mixture with the desired gas content. This solution allows utilizing APG and significantly increasing oil production.

Keywords: Water-alternating-gas injection (WAG), simultaneous water and gas injection (SWAG), utilization of associated petroleum gas (APG), enhanced oil recovery, pump-ejecting system, water-gas mixtures.

1. Introduction

In recent years, there has been a growing interest in the processes associated with the injection of water-gas mixtures into the reservoir. An extensive overview of the water-alternating-gas injection implementation process is described in [1-3]. According to the analysis of the data in this article, the increase in production is equal to 5-10% of the total production. In [4-5], it is proposed to use carbon dioxide as a gas. In the experiments carried out, the process of oil displacement is investigated during the injection of a water-gas mixture containing miscible and immiscible gases. The article [6-9] describes the study of the water-gas mixture injection process, as well as the processes taking place in the reservoir.

Water-alternating-gas injection (WAG), which allows increasing oil recovery using associated petroleum gas (APG), has not yet become widespread due to the complexity, low reliability and limited functionality of the equipment used. To solve the problem, pump-ejecting system can be used, which make it possible to prepare a water-gas mixture and pump it into the formation in a wide range of flow rates and pressures. However, until recently, there were no field tests of pump-ejecting system for WAG in oil fields. This work presents the results of such tests carried out at one of the fields in the Ural-Volga region and the possibilities for improving the technology.

The objective of the current study was the peculiarities of the pump-ejecting system operation for simultaneous water-alternating-gas injection (SWAG) of the reservoir and associated gas utilization, introduced at the Samodurovskoye field, as well as the development of an improved WAG technology using nitrogen, in addition to associated gas.
2. Method of research
Initially, laboratory filtration studies were carried out according to the technique presented in [10], with modeling the reservoir conditions of the field. It was experimentally found that due to the SWAG, it is possible to increase the oil displacement coefficient. Further, hydrodynamic calculations of the movement of water-gas mixtures in conduits and injection wells were performed, and the required injection pressure was determined according to the methods presented in [10]. The work [11], which contains a methodology for calculating the movement of a water-gas mixture under the conditions of the field was published last year. Then the scheme of the pump-ejecting system was developed and the parameters of the equipment were calculated according to the technique presented in [10]. Bench studies of model ejectors have confirmed the calculation results. For field tests, the Samodurovskoye field was selected, which is located near the village of Ponomarevka in the Orenburg region (Russia). The bench research methodology consisted in a comprehensive testing of the equipment of a block pumping station with a pump-ejecting system (PES) for SWAG in several operating modes of the PES with continuous, non-stop operation for at least one hour. At the first stage, the operability of the equipment and valves was checked. Then, the valves were opened on the lines for supplying water, gas and the line for supplying the water-gas mixture to the intake of the booster pump. The pump was started in automatic mode according to the following algorithm:

1) the electric regulator valve 1 on the water supply line opens smoothly;
2) when a certain pressure value is reached in the receiving line of the booster pump (to be specified during complex testing), the pump electric-motor starts;
3) with the help of a frequency converter, the pump is started to operate at a low frequency “to a closed valve”. With an increase in the receiving pressure, the frequency increases and when the pump reaches its operating characteristics, the electric regulator valve 2 opens on the water drain line to the pressure maintenance system to decode;
4) regulation of electric control valves, as well as with the help of a frequency converter, the pump is brought to operating power on the water;
5) the electric valve opens on the gas supply line and the ejector starts to mix gas into the produced water;
6) the system is brought to operating power when operating on a water-gas mixture by regulating electric control valves, as well as a frequency converter;
7) after reaching the operating parameters for the water-gas mixture, the mixed flow of water and gas is directed to the water-distribution point and further to the injection wells;
8) if necessary, adjust the operating mode of the block pumping station with the NPP, and if necessary, it is possible to add surfactants to the water, and methanol to the gas pipeline.

Using a block pumping station with a pump-ejecting system SWAG injection of the reservoir at the Samodurovskoye field was carried out as follows. The power pump from a cluster pump station pumps water under pressure into the working nozzle of the ejector. When water flows out through the nozzle, a vacuum is created in the receiving chamber of the ejector, where low-pressure associated gas is sucked. In the flow part of the ejector, the flows are mixed, and a water-gas mixture is created. At the outlet of the ejector, the mixture has some increased pressure, which, however, is not enough high to inject the water-gas mixture into the injection wells. Therefore, after the ejector, the water-gas mixture was compressed by a multi-stage centrifugal pump and pumped under the necessary pressure into the injection wells.

3. Results and discussion
Filtration studies on the bulk models of the carbonate-porous reservoir of the Samodurovskoye field were carried out with extraction of residual oil from the model, already experienced water flooding, through using water-gas mixture [10]. This method of research was due to the fact that the Samodurovskoye field is in the final stages of development using water flooding.

For the carbonate-porous reservoir T1 of the Samodurovskoye field, the reservoir conditions and fluid properties are as follows: reservoir pressure – 16 MPa, reservoir temperature – 30 °C, oil
viscosity under reservoir conditions – 7.7 MPa·s, formation water density is 1156 kg/m³, average permeability is 0.17·10⁻¹² m². Associated gas from the Samodurovskoye field contains, in addition to hydrocarbon components, a significant amount of nitrogen (up to 44.7%) and hydrogen sulfide (0.6%).

Since there was no T₁ core material during the research period, bulk models were made of crushed marble chips. The permeability of bulk models for nitrogen ranged from 0.13 to 0.21·10⁻¹² m². As shown by experiments (Figures 1, 2), the values of the oil displacement coefficient while using SWAG increased markedly compared to the water flood, with the similarity of the final values of the displacement factors for input gas contents of 13 and 25%. The addition of surfactants contributed to a slight increase in oil displacement to 74-78%.

![Figure 1. Scheme of the pump-ejecting system at the Samodurovskoye field.](image1)

**Figure 1.** Scheme of the pump-ejecting system at the Samodurovskoye field.

![Figure 2. Schematic diagram of the pump-ejecting system](image2)

**Figure 2.** Schematic diagram of the pump-ejecting system

1 - power pump; 2 - booster pump; 3 - ejector; 4 - nitrogen compressor; 5 - manometer; 6 - container with surfactant (SAA); 7, 8, 9 - valves; 10 - water injection line; 11 - line for supplying the water-gas mixture to the booster pump; 12 - water conduit to the injection well; 13 - surfactant supply line; 14 - nitrogen injection line; 15 - line for supply of associated petroleum gas from annular spaces; 16 - gas mixture supply line.

Associated petroleum gas from the Samodurovskoye field contains a large amount of non-hydrocarbon components (nitrogen, hydrogen sulfide) and does not meet the requirements of standards for its use and transportation. Therefore, the use of its utilization in the field is injection together with water into the reservoir.
A detailed calculation for the initial data of the water-distribution point (WDP-1) of the T1 reservoir of the Samodurovskoye field is given in [10].

Calculations on the assessment of the possibility of delivering to a reservoir specified volumes of associated petroleum gas by means of an uncompressed pump-ejecting system were carried out as follows. Initially, bottomhole and wellhead pressures were calculated for all injection wells. Then, water lines from injection wells to the water distribution station and to the cluster pumping station were calculated.

The values of the required pressure at the outlet of the pump-ejecting system were determined – 12 MPa at the current gas flow rate.

Calculations at the current gas flow rate showed that it is possible to use only one stage of ejector compression of the mixture, and in the second stage to inject the water-gas mixture using a multi-stage centrifugal pump.

### Table 1. Data from field tests at the Samodurovskoye field

| Ejector nozzle diameter, mm | Water pressure at the block pumping station inlet, MPa | Pressure after the ejector, MPa | Block pumping station outlet pressure, MPa | Water consumption for block pumping station, m³/day | Gas consumption at the block pumping station, m³/day | Gas consumption for block pumping station, m³/day | Test duration, h |
|----------------------------|------------------------------------------------------|--------------------------------|-------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------|
| 13.7                       | 9.28                                                 | 1.97                           | 9.49                                      | 1140                                          | 0.205                                         | 10416                                        | 2               |
| 11.1                       | 2.19                                                 | 1.92                           | 9.82                                      | 1248                                          | 0.194                                         | 10596                                        | 2               |
| 12.47                      | 2.49                                                 | 1.98                           | 1320                                      | 205                                           | 11424                                        | 2               |
| 14.2                       | 8.47                                                 | 1.79                           | 8.78                                      | 1176                                          | 0.207                                         | 5532                                         | 2               |
| 10.35                      | 2.24                                                 | 9.08                           | 1260                                      | 0.223                                         | 10476                                        | 2               |
| 10.74                      | 2.16                                                 | 9.16                           | 1308                                      | 0.215                                         | 10812                                        | 6               |
| 12.3                       | 2.19                                                 | 9.47                           | 1404                                      | 0.195                                         | 10980                                        | 2               |
| 14.8                       | 9.11                                                 | 1.55                           | 6.84                                      | 1236                                          | 0.177                                         | 7200                                         | 2               |
| 10.96                      | 2.24                                                 | 6.87                           | 1332                                      | 0.215                                         | 10128                                        | 4               |
| 12                         | 2.6                                                  | 7.28                           | 1404                                      | 0.223                                         | 10716                                        | 2               |
| 12.51                      | 2.46                                                 | 7.32                           | 1428                                      | 0.213                                         | 10896                                        | 2               |
| 13.03                      | 2.41                                                 | 7.24                           | 1464                                      | 0.202                                         | 11004                                        | 2               |
| 15.3                       | 9.9                                                  | 2.45                           | 7.57                                      | 1404                                          | 0.216                                         | 9204                                        | 2               |
| 11.16                      | 2.44                                                 | 7.75                           | 1464                                      | 0.199                                         | 9228                                         | 2               |
| 12.05                      | 2.83                                                 | 8.13                           | 1524                                      | 0.208                                         | 10200                                        | 2               |
| 12.51                      | 2.71                                                 | 7.88                           | 1548                                      | 0.206                                         | 10452                                        | 2               |
| 15.8                       | 7.19                                                 | 2.1                            | 9.29                                      | 1164                                          | 0.25                                          | 11880                                       | 2               |
| 8.29                       | 1.93                                                 | 7.26                           | 1248                                      | 0.22                                          | 9744                                         | 2               |
| 10.3                       | 2.38                                                 | 8.92                           | 1404                                      | 0.2                                           | 10260                                        | 2               |
| 10.9                       | 2.44                                                 | 9.92                           | 1452                                      | 0.217                                         | 10884                                        | 2               |
| 11.76                      | 2.37                                                 | 10.05                          | 1500                                      | 0.212                                         | 11028                                        | 2               |
| 16.3                       | 8.96                                                 | 2.13                           | 9.2                                       | 1440                                          | 0.2                                           | 8508                                         | 2               |
| 10.01                      | 2.42                                                 | 9.24                           | 1548                                      | 0.226                                         | 10968                                        | 2               |
| 11.35                      | 2.4                                                  | 9.84                           | 1632                                      | 0.219                                         | 11088                                        | 6               |
| 12                         | 2.55                                                 | 9.85                           | 1668                                      | 0.223                                         | 11244                                        | 2               |
| 16.8                       | 9.98                                                 | 2.56                           | 9.33                                      | 1644                                          | 0.183                                         | 8844                                        | 2               |
The calculations of the characteristics of jet devices for pump-ejecting system were carried out according to a specially developed technique. To verify the results of the calculations, experimental studies of the characteristics of jet devices were carried out in simulating the operating parameters for the conditions of the Samodurovskoye field at the bench [10]. The bench allows you to remove the full characteristics of liquid-gas ejectors at different pressures of the working fluid (up to 20 MPa) before the nozzle and pressures at the reception (up to 5 MPa). According to the test results, the calculated characteristics of the jet apparatus were confirmed.

The developed flow chart of the pump-ejecting system for the Samodurovskoye field was adopted for implementation.

The system, manufactured by JSC Novomet-Perm, was commissioned to inject a mixture into 11 wells from the pilot site of the Samodurovskoye field. Figure 1 shows the layout of the production system.

Water is injected into the ejector nozzle by a pump from the cluster pump station CPS-240-1422, which also pumps water into the injection wells of the field, which are not part of the SWAG section. The ejector pumps out the gas of the first separation stage and delivers the water-gas mixture to the inlet of the horizontal multistage booster centrifugal pump of the ESP-1600-1450. The operating parameters of the system: water consumption - 1535 m³/day, gas consumption - up to 20000 m³/day, gas pressure at the intake of 0.2-0.4 MPa, mixture discharge pressure - up to 13 MPa. The installation of water-gas injection was transferred to round-the-clock operation for injecting a mixture into 11 wells of the water distribution station WDS-2 of the Samodurovskoye field. In the process of implementation, some structural defects of the manufactured equipment were also identified, which were subsequently eliminated.

The field tests of the pump-ejector unit were carried out at various values of the ejector nozzle diameter. The frequency of the electric motor current was 50 Hz, the current values varied in the range 42.4 - 57.6 A. The results obtained are presented in Table 1.

The results showed that the pump-ejecting system adapts to changing operating conditions, completely takes in associated gas of the first stage of separation of the Samodurovskoye, Efremovsky, Zykovskoye and Spasskoye fields. In addition, it makes it possible to utilize APG from the neighboring Ponomarevskoye field which is also supplied through a gas pipeline to the inlet of the pump-ejecting system by a low-pressure compressor. The pump-ejecting system operated steadily at the Samodurovskoye field in various modes; there were no disruptions in the work of ejectors and pumps.

Thus, the results of previously performed theoretical and experimental studies, based on which the SWAG technology was developed using pump-ejecting system were confirmed when introduced into the field.

At the same time, the experience of operating the system at the Samodurovskoye field also made it possible to outline measures to improve the Water-alternating-gas injection technology itself using pump-ejecting system at other fields in the Ural-Volga region, taking into account the results of previously published work.

In work [12] it is proposed to carry out water-alternating-gas injection using associated petroleum gas (APG) pumped out from the annular spaces of producing wells. It is known that in mechanized pumping wells the annular pressure can reach critically high values due to the large line pressure in the oil gathering. In this case, the dynamic level decreases so much that there is a disruption in the supply and failure of the downhole pump. To eliminate these undesirable factors, it is proposed in [12] to use APG from the annular spaces of production wells by pumping it out with an ejector and directing it together with water in the form of a mixture into an injection well; implement water-gas impact. The data presented in [12] show the importance of this problem for many fields in Tatarstan.

However, it should be noted that in many fields of the Ural-Volga region, gas factors of oils have low values, usually not exceeding 60 m³/t (for deposits of the Middle and Lower Carboniferous). At the same time. APG flow rates from the annular spaces of production wells are insufficient to create a water-gas mixture with the required gas content values, which can significantly increase oil recovery.
It is known [13-16] that for a significant increase in the oil displacement coefficient, it is advisable to provide a gas content of the water-gas mixture in reservoir conditions of at least 13-20%. One of the options for resolving this issue is to inject nitrogen together with APG from a nitrogen unit using a pump-ejecting system. It should be noted that the water-alternating-gas injection with nitrogen, as shown in the work of the authors from the Institute “TatNIPIneft” [17] increases oil recovery for the conditions of fields in Tatarstan.

Therefore, in this work in order to improve the technology the calculation of the water-gas impact process and the calculation of the pump-ejecting system using nitrogen and APG for the conditions of one of the license areas of the N field of the Ural-Volga region of PJSC TATNEFT were carried out.

Nitrogen possesses low corrosiveness does not have a harmful effect on equipment and is non-flammable. Nitrogen can be obtained from the air almost anywhere which makes it possible to produce it with nitrogen plants (membrane, adsorption, etc.) in the field next to injection wells.

In one of the sections of the N field there is an injection well A. and in its immediate vicinity there are three production wells – B, C and D, which are operated by sucker rod pumps. At the same time, well D operates two formations. In order to avoid disruption of the flow of borehole pumps associated with an increase in the annular pressure to the value of the buffer (from 1.3 to 1.7 MPa depending on the ambient temperature) the wells are periodically stopped in accumulation. The proposed solution is the selection of gas from wells mixing of associated gas and nitrogen with water. and their injection in the form of a water-gas mixture into an injection well. Production well data are shown in Table 2.

| Parameter name                          | Values by well number |
|-----------------------------------------|-----------------------|
| Collector type                          | B         | C         | D         |
| Reservoir pressure, MPa                 | terrigenous | terrigenous | carbonate | terrigenous |
| Gas density at standard conditions, kg / m³ | 16.4       | 15.3       | 7.84       | 11.83       |
| Current gas consumption from the annulus under standard conditions, m³/day | 53.27 | 89.86 | 9.69 | 2.98 |
| Gas factor of oil, m³ / t               | 38.6       | 38.6       | 2.6        | 11.78       |
| Reservoir temperature, °C               | 37.4       | 35.9       | 23         | 25          |

Table 2 shows that the gas ratio is low one associated gas is not enough to create the required gas content of the water-gas mixture in reservoir conditions. This problem can be solved by adding nitrogen from a nitrogen compressor to the associated gas.

The schematic flow diagram of the pump-ejecting system for the conditions of the PJSC TATNEFT field is shown in figure 2. In this case, in accordance with the recommendations [18], one stage of ejector compression is provided. At the second stage the water-gas mixture is pumped by a booster pump. As it you can use a multistage vane pump.

The system located near the injection well operates as follows. The power pump (1) injects water into the reservoir pressure maintenance system (RPM) from where it enters the ejector nozzle (3) through the water line. Gas coming from the annulus of production wells through line (15) is mixed with nitrogen injected by the compressor (4) through line (14) forming a gas mixture. This water-gas mixture is prepared with the foaming surfactant coming from the container (6) through the line (13) and is taken by the ejector (3) through the line (16). The ejector (3) promotes the formation of a finely dispersed water-gas mixture which has a certain increased pressure at the outlet. Through line (11) it enters the intake of the booster pump (2) which injects the water-gas mixture under the required pressure into the water line (12). Then the mixture enters the injection well. The system includes
valves (7), (8) and (9) to adjust the gas flow rate if necessary as well as a pressure gauge (5) to control the pressure at the inlet of the ejector (3).

The calculation of the pressure at the mouth of the injection well A was carried out according to the following initial data:

- water injectivity of the injection well $Q_{\text{well}} = 70 \, \text{m}^3/\text{day}$;
- density of the injected water $\rho_{w} = 1122 \, \text{kg}/\text{m}^3$;
- the vertical depth of the well to the top of the formation $H_{\text{well}} = 1745.96 \, \text{m}$;
- nominal tubing diameter $d = 60 \, \text{mm}$;
- inner diameter of tubing $d_{in} = 50.3 \, \text{mm}$;
- pressure at the wellhead during water injection $P_{m,w.} = 14.6 \, \text{MPa}$;
- reservoir pressure $P_{r} = 17 \, \text{MPa}$;
- gas mixture consumption under standard conditions $Q_{g.st} = 3761.8 \, \text{m}^3/\text{day}$;
- the density of the gas mixture under standard conditions $\rho_{\text{mix.st}} = 1.1621 \, \text{kg}/\text{m}^3$;
- value of gas-water factor in standard conditions $R = 53.74 \, \text{m}^3/\text{m}^3$.

This ensures the value of the gas content of the mixture in reservoir conditions, which is 24%. To inject the required flow rate, a unit is required that generates 140 normal m$^3$/h of nitrogen with a purity of 95% and a discharge pressure of 1 MPa (for example, an adsorption nitrogen station of the "PROVITA-N" type).

Calculations of the required values of pressures, as well as the parameters of the pump-ejecting system were carried out according to the method described in [10], and the calculation of the ejector - according to the method [18]. The design wellhead pressure in the injection well during the injection of the water-gas mixture was 20 MPa. and at the outlet of the pump-ejecting system - 20.1 MPa. With a gas pressure at the ejector intake of 1 MPa and a working water pressure in front of the nozzle of 15.6 MPa, which is provided by the power pump of the pressure maintenance system, the pressure and energy characteristics of the ejector are obtained, shown in figure 3.

![Figure 3. Pressure characteristic of the ejector (1) - the dependence of the discharge pressure of the mixture on the gas supply Q at the intake $P_{\text{mix}} = f (Q)$ and the energy characteristic of the ejector (2) - the dependence of the efficiency $\eta$ on the gas supply Q at the intake $\eta = f (Q)$: $A_{st}$, $A_{opt}$, $A_{lim}$ - respectively, points of stall, optimal and limiting modes; $A_{resp}$ is the point of resumption of gas pumping.](image-url)

A multistage centrifugal vortex pump VNN5A-124-3000 was selected as a booster pump according to the methods [10]. With an average integral flow rate of 115 m$^3$/day, the pump develops a head of about 2500 m, a pressure of 17.7 MPa with an efficiency of 59% and a power consumption for a water-gas mixture of 58.69 kW.
It is advisable to study the need for surfactant supply in the future by conducting special studies of suppressing the coalescence of gas bubbles in water. Since the injected water in the considered field is highly mineralized, it is highly likely that its composition will prevent the merging of negatively charged gas bubbles due to their repulsion in an aqueous solution of salts-electrolytes. as shown in [10,19].

For the pilot area of the N field which includes 7 production wells including B, C and D. responding to injection in injection well A. an estimate of the expected additional production due to Water-alternating-gas injection was made. based on the geological information. According to filtration studies for similar fields the increase in the oil displacement coefficient due to Water-alternating-gas injection is up to 15 %. Considering this, it can be expected that the estimated annual additional production will be up to 1,500 tons of oil.

Expanding the area of application of WAG in the fields of Tatarstan is also possible due to the use of high-pressure nitrogen reserves which were discovered during gas production during well drilling. Gas-bearing reservoirs were found in the areas of Biklyanskoye. Afanasovskoye. Novo-Suksinskoye. Azevo-Salaushskoye and Novo-Elkhovskoye fields. According to well logging data. penetrating the deposits of the Vereya horizon the depth of occurrence of nitrogen layers was determined - 731.2-743.8 m. In addition, gas-bearing strata were found in other horizons at depths: 642.0-652.5 m. 670.5-673.0 m. 878-892 m. 928.6-948.4 m. At a depth of 863-866 m an inflow of nitrogen gas was obtained as a result of testing with a buffer pressure of 6.5 MPa. To assess the possibility of using nitrogen from such formations in the future. it is required to assess reserves test wells that penetrate these formations.

4. Conclusion
An efficient reliable and easy-to-maintain technique has been created for the technology of enhanced oil recovery and utilization of associated gas by SWAG using pump-ejecting systems. When implementing the technology, the existing infrastructure of the fields is used. There is no need to build separate high-pressure gas pipelines and complex gas injection wells. In this case, a significantly lower discharge pressure is required than when gas is pumped by a compressor and a several times higher discharge pressure of the water-gas mixture is achieved in comparison with known ejector technologies.

Measures have been developed to further increase the efficiency of SWAG. The prospects of using nitrogen as a gas for water-alternating-gas injection are shown. The importance of conducting research on mineralization to improve the efficiency of the pump-ejector system is noted. The concentration of salts in water should be in the range of rational values to increase the stability of the finely dispersed water-gas mixture. An additional source of nitrogen on the territory of the Republic of Tatarstan (Russia) can be shallow strata that contain high-pressure nitrogen reserves (6.5 MPa at a depth of 850 m).

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