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METHODOLOGY FOR CALCULATING THE OPERATING PARAMETERS OF A LIQUID-GAS EJECTOR USING THE AVERAGE INTEGRAL PERFORMANCE

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ABSTRACT

This article presents a method for calculating the operating parameters of a liquid-gas ejector using the average integral performance, which simplifies the selection of an ejector when configuring a pump-ejector system. Previous studies have shown that it is possible to generalize the performances of the ejector using dimensionless parameters – relative pressure drop and average integral injection coefficient. However, the method itself with an explanation was not developed and published. To fill this gap, a method for calculating the operating dimensional parameters of the ejector (gas flow rate and developed pressure) using the average integral performance was created and tested. The developed method makes it possible to calculate, with sufficient accuracy for practical purposes, the pumped gas flow rate and outlet pressure in different modes in the range of absolute pressures at the entrance to the ejector receiving chamber from 3 to 10 bar and operating pressures in front of the nozzle from 61 to 121 bar. The technique is applicable not only in bench conditions, but also in field conditions. A comparison of the calculated and actual values of gas consumption showed that the maximum relative deviation of the calculated values from the actual ones does not exceed 5%. The scientific novelty consists in the development of a graphical-analytical method for calculating the operating parameters of a liquid-gas ejector based on the average integral characteristic, which ensures good convergence of calculated and actual data. This will allow increasing oil recovery by introducing the SWAG-technology and reducing annular pressures.

Keywords: waterflooding; simultaneous water and gas injection (SWAG-technology); associated petroleum gas; pump-ejector systems; liquid-gas ejectors (or jet devices); average integral injection coefficient.

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Introduction

World practice of development and exploitation of hydrocarbon deposits shows that most of the deposits are developed using flooding. This technology of maintaining reservoir pressure and increasing oil recovery has shown its advantages in domestic and foreign fields, but at the same time a number of shortcomings have been identified [1-4].

The most common disadvantage of flooding is the breakthrough of displacing water and flooding of producing wells, which is explained by the instability of the displacement front [5].

Involvement in the development of hard-to-recover reserves requires special scrupulousness in the design of the development process and the selection of EOR to increase oil recovery and intensify oil production [6-8].

The solution to the problem of increasing the efficiency of maintaining reservoir pressure involves predicting the movement of the front of displacing water and preventing flooding of wells [9, 10], as well as the use of adding various substances that change the properties of the injected water [11], or in-situ generating of gas phase [12, 13]. Ultimately, these solutions contribute to solving the problem, which is formulated on the basis of the Buckley-Leverett model.

In [14, 15] the results of the analysis of data on the implementation of various EOR methods are presented. According to the data analysis, gas EOR methods occupy the leading position (47% of projects), followed by thermal technologies (44%), 9% are represented by other methods.

The choice of EOR is a complex engineering task, since the success of using any method is influenced by a number of factors (the clarity and reliability of data on the composition and properties of rocks and saturating fluids, the conditions of rock occurrence, the water content of the extracted product, the stage of development, the oil and gas field infrastructure, etc.). Experts offer various approaches to the choice of technology, which are based on the results of mathematical calculations [16, 17].

Numerous studies by domestic and foreign authors are devoted to the topic of choosing EOR, ways to increase the efficiency of technologies, their adaptation to new conditions, unsuccessful examples of implementation in the fields, as

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well as ways of further research, which increases the interest of researchers and companies in this topic.

In terms of EOR gas technologies, the leading positions are occupied by the USA, Brazil and Canada. Moreover, the USA dominates here with production volumes of over 75% of the global production using these methods.

EOR, as noted by R.Kh. Muslimov are becoming more and more in demand [18].

Simultaneous water and gas injection (SWAG-technology) as a method of increasing oil recovery and intensifying oil production is a more advanced method compared to flooding, which is confirmed by laboratory research data [19, 20] and field tests [21-25]. This technology makes it possible to effectively pump a water-gas mixture into the formation and eliminate the disadvantages of a more widely used technology – waterflooding [26-30], as well as increases the share of useful petroleum gas in the fields [31].

This technology can be applied with various technical devices that differ significantly in their operating principle, technical performances, degree of necessary preparation and adaptation to the industry, possible technical difficulties during operation and price offers from suppliers. A comparative analysis of these devices shows that pump-ejector systems have the greatest potential.

One of the key components of these systems are liquid-gas ejectors (jet devices). They are simple in design, reliable, and easy to adjust. Due to their obvious advantages, these devices have found application in the preparation of liquefied natural gas [32], in pumping out annular gas in water-gas-methods processes [14, 33], in transporting well products, and in extracting gas from flooded gas wells and high-viscosity oil [34], and rock breakage with a water jet [35]. However, the operation process of a liquid-gas ejector has not been fully studied, which complicates the selection of jet devices and limits the use of pump-ejector systems [36-39]. Published sources provide recommendations (selection of an ejector with a specific mixing chamber length [37], calculation of the operating parameters of an ejector as part of a pump-ejector system [34], composition of the pumped liquid [35]), compliance with which allows increasing the efficiency of ejectors.

This paper proposes a graphic-analytical method for calculating the operating parameters of a liquid-gas ejector based on its average integral performance, which makes it possible to determine with sufficient accuracy for practical purposes the values of the flow rate of the pumped gas and the outlet pressure developed by the jet apparatus under various operating conditions for use in water-and-gas-technologies.

Problem statement

Studies carried out in [35] showed that when ejecting liquid, the dimensionless performances of jet devices $U_l - \Delta P_j/\Delta P_{op}$ (U_l is the liquid injection coefficient, $\Delta P_j/\Delta P_{op}$ is the relative dimensionless pressure drop created by the jet device) in the absence of cavitation depend only on the geometry of the flow part. The pressure values of the operation liquid in front of the nozzle and the pressure in the receiving chamber do not affect the dimensionless performances of jet pumps.

However, when pumping gas with a jet of liquid, that is, when operating a liquid-gas ejector, a different picture is observed. The dimensionless performances of the same ejector in the coordinates $U_g - \Delta P_j/\Delta P_{op}$ (U_g is the gas injection coefficient in the conditions of the receiving chamber of the jet apparatus) when changing the values of the operating pressure P_{op} and the pressure in the receiving chamber P_{rec} differ significantly from each other, as shown in figure 1 according to [40].

Figure 1 shows the dimensionless performances of the ejector in the coordinates $U_g - \Delta P_j/\Delta P_{op}$. The geometric parameters of the ejector are presented in [40] and in table 1. In the experiments [40], air was pumped out of the atmosphere by a jet device using a water jet. The performances obtained at different values of the operation pressure in front of the nozzle (from 0.4 to 2.13 MPa) are plotted in the coordinates $U_g - \Delta P_j/\Delta P_{op}$ traditionally used [35] for ejectors.

As follows from figure 1, the performances of the same ejector in these dimensionless coordinates differ significantly from each other when the operating pressure changes.

Therefore, in [40] an attempt was made to generalize the performances of liquid-gas ejectors. The average integral gas injection coefficient $U_{g.av}$ was proposed as one of the operating performances parameters of the jet apparatus.

When the ejector is operating, the pressure of the pumped gas along the length of the mixing chamber and diffuser increases, the gas is compressed and can partially dissolve in the liquid, so that its volumetric flow rate decreases. The parameter $U_{g.av}$ takes into account this decrease and, in its physical meaning, characterizes the ratio of the average gas

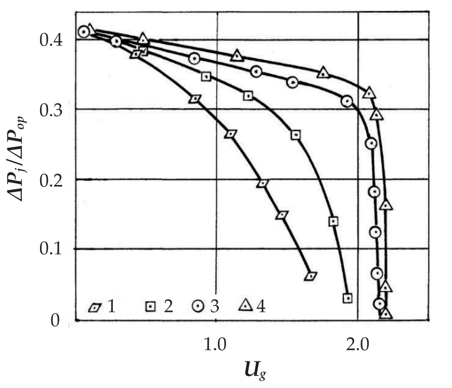


Fig. 1. Performances of an ejector with a mixing chamber with a diameter of 14 mm, a length of 30 diameters and a diaphragm nozzle with a diameter of 9 mm at P_{op} of 0.4 MPa (1), 0.8 MPa (2), 1.6 MPa (3) and 2.13 (4) MPa [40]

Table 1

Data for constructing the average integral performance of the ejector, obtained in experiments at different operation pressures before the nozzle [40]

Geometric parameter	Value
Nozzle diameter, mm	9
Cross-section type	Rectangular edges
Mixing chamber shape	Cylindrical
Mixing chamber diameter, mm	14
Mixing chamber length, mm	420 (30 mixing chamber diameters)
Diffuser opening angle	9°

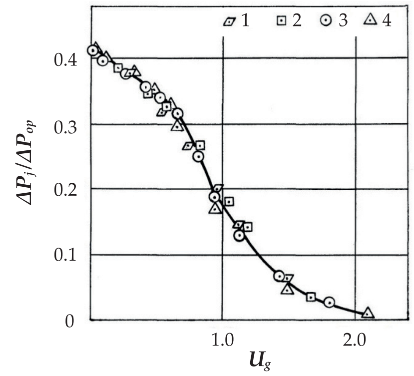


Fig. 2. Average integral performance of the ejector. The P_{op} values are 0.4 MPa (1), 0.8 MPa (2), 1.6 MPa (3) and 2.13 (4) MPa [40]

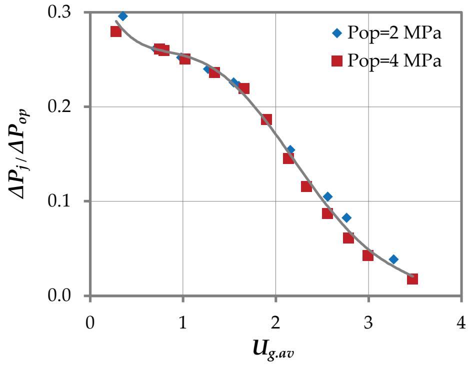


Fig. 3. Generalized dimensionless pressure performance of the liquid-gas ejector studied in [41] at various operating pressures

flow rate in the flow part of the jet apparatus to the supply of operation liquid.

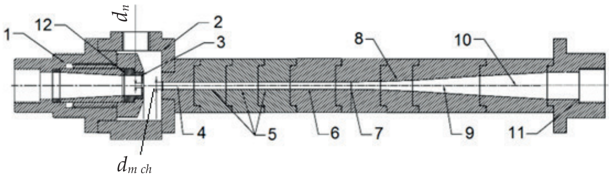
The use of the average integral injection coefficient, which takes into account the decrease in gas volume flow along the length of the jet apparatus with increasing pressure, in the studied range of pressure changes allowed in [40] instead of a series of graphs to construct one performance curve (dependence of $\Delta P_j/\Delta P_{op}$ on $U_{g.av}$) of the ejector operation (fig. 2).

An analysis of the ejector research data obtained in [41] also showed that it is possible to generalize its performances at operating pressures P_{op} from 2 to 4 MPa (in the region of highest efficiency) and an absolute pressure at the entrance to the receiving chamber of 0.5 MPa using dimensionless parameters – relative pressure drop and average integral injection coefficient. It turned out to be possible, as shown in [41], to generalize the experimental points obtained at different operating pressures (2 and 4 MPa) by a single dependence in the coordinates $U_{g.av} - \Delta P_j/\Delta P_{op}$ (fig. 3).

The use of one operating performance instead of several can, according to [40, 41], significantly clarify and simplify the process of calculating jet devices for specific operating conditions.

However, the method itself with an explanation of how to do this has not been developed and published. To fill this gap, it was necessary to create and test a method for calculating the operating dimensional parameters of the ejector (gas flow rate and developed pressure) using the average integral performance.

Therefore, the purpose of this study was to develop and test a methodology for calculating the operating dimensional parameters of the ejector (gas flow rate and developed pressure) at various values of the operation liquid pressure in front of the nozzle and the pressure in the receiving chamber using the average integral performance.



1 – inlet, 2 – receiving chamber, 3 – nozzle, 4 – inlet to the mixing chamber, 5 – intermediate blocks of the mixing chamber, 6 – output block of the mixing chamber, 7 – transition block from the mixing chamber to the diffuser, 8 – inlet part of the diffuser, 9 – middle part of the diffuser, 10 – outlet part of the diffuser, 11 – outlet, 12 – washer; d_n – nozzle diameter, $d_{m\,ch}$ – mixing chamber diameter [35]

Fig. 4. Ejector diagram

To achieve this goal, three main tasks have been solved.

The first of them is associated with conducting experiments on a bench to obtain the average integral performance of an ejector with certain geometric parameters of the flow part.

The second main objective of the study was to develop a methodology for calculating the operating parameters of a liquid-gas ejector based on its average integral performance.

The third objective of the study was to check the adequacy of the proposed calculation methodology, i.e. its testing.

Methodology

Conducting bench experiments and processing their results to solve the first research problem were carried out in accordance with the methodology presented in [40].

The experiments were carried out on a stand, the principle diagram of which and the research methodology are presented in [35]. The stand included a pump, a liquid tank, a compressor, an ejector, as well as a pipeline system, shut-off and control valves and instrumentation. The diameter of the ejector diaphragm nozzle was 3.2 mm, the cylindrical mixing chamber was 7.1 mm, the diffuser opening angle was 5.5°, the length of the mixing chamber was 340 mm, the distance between the nozzle and the entrance to the mixing chamber was 14.1 mm. The diagram of the ejector under study is shown in figure 4.

Fresh water was used as the liquid phase, and atmospheric air was used as the gas phase. This approach makes it possible to simulate quite well the real operating conditions of pump-ejector systems when pumping associated petroleum gas [35, 41].

Air from a compressor at an absolute pressure of 10 bar was supplied to the entrance to the ejector receiving chamber, and water was pumped into the operation nozzle with absolute pressures from 51.5 to 90.8 bar.

The operation pressure in front of the ejector nozzle was created by a pump. The pressure at the inlet and outlet of the ejector was regulated by valves. During the experiments, using an adjustable valve, various back pressures were created at the ejector outlet, changing its flow and the developed pressure, which made it possible to measure the parameters of the jet apparatus. This research method allows us to record performances in different modes by changing the hydraulic resistance at the ejector outlet. It allows you to take performances in different modes by changing the hydraulic resistance at the ejector output. Another advantage of this method is the short time required to stabilize the parameters when changing the mode [35].

The value of the average integral injection coefficient was calculated according to [40] using the formula

$$U_{g.av}=\frac{1}{P_j-P_{rec}}\int_{P_{rec}}^{P_j}U_g\left(P\right)dP \tag{1}$$

where is the dependence of the gas injection coefficient on pressure, P_j is the pressure of the gas-liquid mixture at the ejector outlet, P_{rec} is the pressure in its receiving chamber.

This methodological approach is due to the fact that when gas is pumped out by an ejector, the pressure along the length of the displacement chamber and diffuser increases. As a result, the gas is compressed and can dissolve in the liquid, which leads to a decrease in its volume flow. Since the $U_{g.av}$ parameter takes this into account, its use is the best method in accordance with the purpose and objectives of this study. Based on the results of bench experiments, a graph of the average integral performance of the ejector was plotted in the coordinates $U_{g.av}-\Delta P_j/\Delta P_{op}$.

When solving the second research problem – developing a methodology for calculating the operating parameters of a liquid-gas ejector based on its average integral performance – a graph-analytical calculation method was used, since such methods are distinguished by clarity, ease of control and speed of solving a wide range of practical problems in various subject areas.

The main provisions of the proposed method for calculating the operating dimensional parameters of the ejector (gas flow rate and developed pressure) at different values of the operation liquid pressure in front of the nozzle and the pressure in the receiving chamber according to the average integral performance are as follows.

The process of gas compression in the ejector is practically isothermal due to the fact that the heat capacity of the liquid is much higher than the heat capacity of the gas. Therefore, for many cases of operation in relation to water-gas technology, when gas solubility can be neglected (for example, for the ejection of methane, APG or nitrogen with water, etc.), after integrating expression (1) we can write

$$U_{g.av}=\frac{U_gP_{rec}\ln\frac{P_j}{P_{rec}}}{P_j-P_{rec}} \tag{2}$$

where U_g is the gas injection coefficient under conditions of entry into the receiving chamber of the ejector.

If the value of $U_{g.av}$ is known from the graph of the average integral performance, the value of U_g can be calculated from expression (2) as

$$U_g=\frac{U_{g.av}\left(P_j-P_{rec}\right)}{P_{rec}\ln\frac{P_j}{P_{rec}}} \tag{3}$$

The gas flow rate Q_g pumped out by the ejector under the conditions of its receiving chamber is calculated taking into account the flow rate Q_{op} of the operation liquid – water according to the formula

$$Q_g=Q_{op}U_g \tag{4}$$

Considering that the relative pressure difference $\Delta P_j/\Delta P_{op}$ created by the ejector is equal to

$$\frac{\Delta P_j}{\Delta P_{op}}=\frac{P_j-P_{rec}}{P_{op}-P_{rec}} \tag{5}$$

pressure ΔP_j developed by the jet apparatus,

$$\Delta P_j=P_j-P_{rec} \tag{6}$$

and the pressure drop ΔP_{op} in the operation nozzle of the ejector when liquid flows through it

$$\Delta P_{op}=P_{op}-P_{rec} \tag{7}$$

you can write down how to find the pressure at the outlet of the ejector P_j, knowing the value $\Delta P_j/\Delta P_{op}$ on the average integral performance:

$$P_j=P_{rec}+\left(P_{op}-P_{rec}\right)\frac{\Delta P_j}{\Delta P_{op}} \tag{8}$$

Such calculations were carried out for various ejector operating modes.

To solve the third problem of the study (testing the methodology), a comparison of the calculated performances and the actual parameters of the ejector obtained in bench experiments was subsequently carried out, which is a proven and well-feasible method for checking the calculation results. In addition, a comparison was made of the calculated and actual values of the gas flow rate pumped out by the ejector, according to field studies at the Samodurovskoye oil field.

Results and discussion

The values of the average integral gas injection coefficient $U_{g.av}$ and the relative dimensionless pressure drop $\Delta P_j/\Delta P_{op}$, obtained during the research, are presented in table 2.

Based on the results of bench studies, the average integral performance of the liquid-gas ejector was constructed (fig. 5), which quite well, just as in [40, 41], describes with a single dependence the data obtained in the experiments at different

Table 2

Data for constructing the average integral performance of the ejector, obtained in experiments at various operating pressures in front of the nozzle

Operation pressure in front of the nozzle 51.5 bar							
$U_{g.av}$	4.24	3.99	3.71	3.23	2.80	2.42	1.61
$\Delta P_j/\Delta P_{op}$	0.043	0.060	0.080	0.104	0.123	0.141	0.174
Operation pressure in front of the nozzle 61.5 bar							
$U_{g.av}$	3.99	3.73	3.46	3.10	2.76	2.42	1.64
$\Delta P_j/\Delta P_{op}$	0.062	0.080	0.098	0.114	0.128	0.144	0.176
Operation pressure in front of the nozzle 70.9 bar							
$U_{g.av}$	1.53	2.00	2.40	2.87	3.20	–	–
$\Delta P_j/\Delta P_{op}$	0.183	0.164	0.146	0.126	0.109	–	–
Operation pressure in front of the nozzle 81.0 bar							
$U_{g.av}$	1.17	1.65	1.99	2.34	2.66	3.24	–
$\Delta P_j/\Delta P_{op}$	0.196	0.178	0.164	0.149	0.133	0.107	–
Operation pressure in front of the nozzle 90.8 bar							
$U_{g.av}$	0.86	1.39	1.81	2.18	2.53	2.99	–
$\Delta P_j/\Delta P_{op}$	0.208	0.190	0.173	0.157	0.140	0.119	–

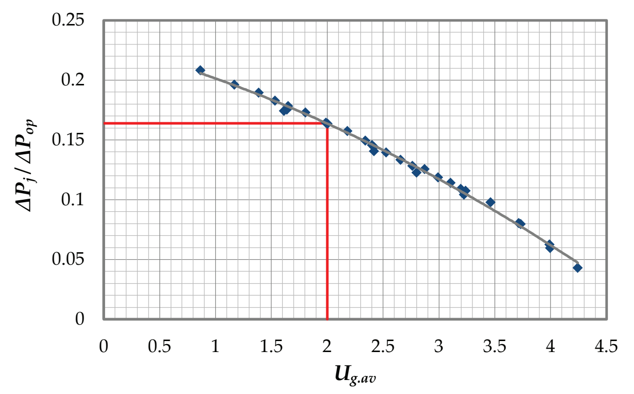


Fig. 5. Average integral performance of a liquid-gas ejector

Table 3

Calculation of ejector performances at P_j=71 bar and P_{op}=8 bar

No	$U_{g.av}$	$\Delta P_j/\Delta P_{op}$	P_j, bar	U_g	Q_g, m³/day
	1	2	3	4	5
1	0.9	0.205	20.9	1.51	83.3
2	1.0	0.201	20.7	1.67	91.9
3	1.5	0.183	19.5	2.42	133.5
4	2.0	0.164	18.3	3.12	171.6
5	2.5	0.141	16.9	3.72	204.8
5	3.0	0.118	15.4	4.24	233. 8
7	3.5	0.090	13.7	4.63	255.1
8	4.0	0.062	11.9	4.91	270.6

Table 4

Actual ejector parameters at P_{op}=71 bar and P_{rec}=8 bar

No	Q_g, m³/day	P_j, bar
1	269.0	11.7
2	248.1	15.2
3	196.2	17.2
4	150.9	18.9
5	90.2	20.7

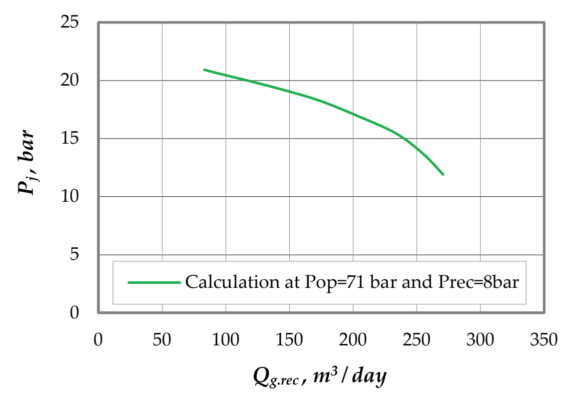


Fig. 6. Design performances of the ejector at P_{op}=71 bar and P_{rec}=8 bar

operating pressures, which were in the experiments 51.5, 61.5, 70.9, 81.0 and 90.8 bar.

Let us consider the use of the proposed method using one of the specific examples when calculating the performances of the ejector (the dependence of the outlet pressure P_j on the gas flow rate Q_g pumped out by the ejector under the conditions of its receiving chamber) for values of the operation liquid flow rate Q_{op}=55.1 m³/day, absolute pressure in front of the nozzle P_{op}=71 bar and at the entrance to the receiving chamber P_{rec}=8 bar.

To calculate the operating parameters of the ejector using the average integral performance, first according to the graph in figure 5 we find the corresponding values of $\Delta P_j/\Delta P_{op}$ for various values of $U_{g.av}$ and enter them in the first and second columns of table 2. For example, for the average integral injection coefficient $U_{g.av}$=2 according to the graph in figure 4, the relative dimensionless pressure drop $\Delta P_j/\Delta P_{op}$ is 0.164. Finding the value of $\Delta P_j/\Delta P_{op}$ based on the value of $U_{g.av}$ is shown in figure 5 red lines. Similarly, we find other values of $\Delta P_j/\Delta P_{op}$ for values of $U_{g.av}$ from 0.9 to 4 and enter them in the first and second columns of table 3.

Let us calculate for the mode corresponding to $U_{g.av}$=2 and $\Delta P_j/\Delta P_{op}$=0.164, the flow rate of the pumped gas Q_g and the pressure at the ejector outlet P_j.

Using formula (8), we calculate the absolute pressure at the outlet of the ejector P_j:

$$P_j = 8 + (71-8)\cdot 0.164 = 18.3 \text{ bar} \qquad (9)$$

Then we find U_g according to (3)

$$U_g = \frac{2(18.3-8)}{8\ln\frac{18.3}{8}} = 3.12 \qquad (10)$$

and gas flow rate Q_g pumped out by the ejector under the conditions of its receiving chamber according to formula (4)

$$Q_g = 55.1\cdot 3.12 = 171.6 \text{ m}^3/\text{day} \qquad (11)$$

We enter the calculated values into table 3. Similarly, the operating parameters are calculated and entered into table 3 – the gas flow rate Q_g pumped out by the ejector, and the mixture pressure at its outlet P_j for other values of $U_{g.av}$ and $\Delta P_j/\Delta P_{op}$.

After this, we construct, according to the data in table 3, the calculated performances of the ejector (the dependence of the pressure at the ejector outlet P_j on the flow rate of pumped gas Q_g) at P_{op}=71 bar and P_{rec}=8 bar (fig. 6). In this graph, the calculated ejector response is shown as a solid line.

To check the calculation results, let us compare them with the actual data (table 4) obtained during bench tests, when the same ejector was operating with an operation liquid pressure in front of the nozzle P_{op}=71 bar and at the entrance to the receiving chamber P_{rec}=8 bar.

Figure 6 shows a comparison of the calculated performances (solid line) and the actual operating modes of the liquid-gas ejector (marked with triangular signs) at P_{op}=71 bar and P_{rec}=8 bar.

As can be seen in the graph, there is a good agreement between the calculated and actual values.

Using the method described above, calculations of the ejector performances were also carried out (the dependence of the outlet pressure P_j on the gas flow rate Q_g pumped out by the ejector under the conditions of its receiving chamber) for the operation liquid flow rate Q_{op}=62.3 m^3/day, the absolute pressure in front of the nozzle P_{op}=91 bar and at the entrance to the receiving chamber P_{rec}=10 bar), as well as for Q_{op}=51.4 m^3/day, P_{op}=61 bar and P_{rec}=5 bar (tables 5 and 6).

The actual operating parameters of the ejector measured in experiments on the bench at P_{op}=91 bar and P_{rec}=10 bar are given in table 7, and at P_{op}=61 bar and P_{rec}=5 bar is in table 8.

Figure 8 shows a comparison of the calculated (solid lines) and measured in bench experiments operating parameters of the liquid-gas ejector at P_{op}=91 bar and P_{rec}=10 bar (actual modes are indicated by square signs) and at P_{op}=61 bar and P_{rec}=5 bar (actual modes marked with round signs).

Good convergence of the calculated and actual values is observed, and the developed method can be recommended for practical use in calculating the operating modes of liquid-gas ejectors in SWAG-technologies on the formation. This follows from the graphs in figures 7 and 8.

In addition to comparing the calculated and actual bench parameters of the ejector, a comparison was made of the calculated and field data of the operation of the liquid-gas ejector as part of a pump-ejector system for recycling associated petroleum gas and increasing oil recovery at the Samodurovskoye field (table 9).

Actual data from field tests of an ejector with a diaphragm nozzle diameter of 16.3 mm and a mixing chamber of 25.5 mm were taken from [41].

Calculated values of gas consumption $Q_{g.calc}$ pumped out by the ejector was calculated using the formulas given

Table 5

Calculation of ejector performances at P_{op}=91 bar and P_{rec}=10 bar

No	$U_{g.av}$	$\Delta P_j/\Delta P_{op}$	P_j, bar	U_g	Q_g, m^3/day
	1	2	3	4	5
1	0.9	0.205	26.6	1.53	95.1
2	1.0	0.201	26.3	1.68	105.0
3	1.5	0.183	24.8	2.45	152.4
4	2.0	0.164	23.3	3.14	195.8
5	2.5	0.141	21.4	3.75	233.5
5	3.0	0.118	19.6	4.27	266.3
7	3.5	0.090	17.3	4.66	290.3
8	4.0	0.062	15.0	4.94	307.5

Table 6

Calculation of ejector performances at P_{op}=61 bar and P_{rec}=5 bar

No	$U_{g.av}$	$\Delta P_j/\Delta P_{op}$	P_j, bar	U_g	Q_g, m^3/day
	1	2	3	4	5
1	0.9	0.205	16.5	1.73	89.1
2	1.0	0.201	16.3	1.91	98.1
3	1.5	0.183	15.2	2.76	141.7
4	2.0	0.164	14.2	3.52	181.1
5	2.5	0.141	12.9	4.17	214.2
5	3.0	0.118	11.6	4.71	242.0
7	3.5	0.090	10.0	5.06	260.1
8	4.0	0.062	8.5	5.27	270.7

Table 7

Actual ejector parameters at P_{op}=91 bar and P_{rec}=10 bar

No	Q_g, m^3/day	P_j, bar
1	92.1	26.8
2	142.3	25.3
3	179.3	23.9
4	210.2	22.7
5	235.7	21.3
6	265.9	19.6

Table 8

Actual ejector parameters at P_{op}=61 bar and P_{rec}=5 bar

No	Q_g, m^3/day	P_j, bar
1	252.5	9.8
2	196.1	13.9
3	149.8	15.5
4	95.9	16.9

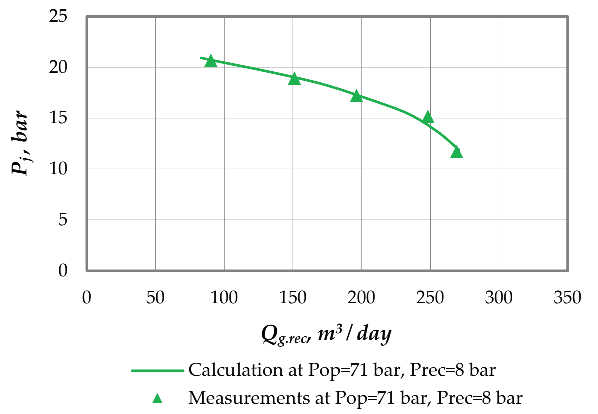


Fig. 7. Comparison of the calculated and measured in bench experiments operating parameters of the liquid-gas ejector at P_{op}=71 bar and P_{rec}=8 bar

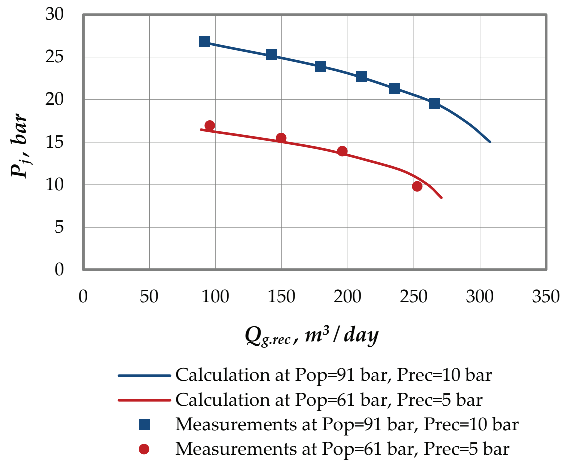


Fig. 8. Comparison of the calculated and measured in bench experiments operating parameters of the liquid-gas ejector at P_{op}=91 bar and P_{rec}=10 bar, P_{op}=61 bar and P_{rec}=5 bar

Table 9

Actual data from field tests of an ejector with a diaphragm nozzle diameter of 16.3 mm and a mixing chamber of 25.5 mm and calculated values of the pumped gas flow rate

No	P_{op}, bar	P_{rec}, bar	P_j, bar	Q_{op}, m^3/day	Q_g, m^3/day	$Q_{g.calc.}$, m^3/day	δ, %
1	90.6	3.0	22.3	1440	2836	2909	-2.6
2	101.0	3.3	25.2	1548	3364	3209	4.6
3	114.5	3.2	25.0	1632	3476	3414	1.8
4	121.0	3.2	26.5	1668	3481	3597	-3.3

above. For the ejector operating modes indicated in table 9, the average value of the average integral injection coefficient was 0.63, and the dimensionless relative pressure drop was 0.21. A comparison of the calculated and actual values of the gas flow rate pumped out by the ejector under the conditions of the receiving chamber showed that the maximum relative deviation of the calculated values from the actual values does not exceed 5%.

So, the technique allows, with sufficient accuracy for practical purposes, to calculate the pumped gas flow rate and outlet pressure in different modes, as testing has shown, in the range of absolute pressures at the entrance to the receiving chamber of the ejector from 3 to 10 bar and operating pressures in front of the nozzle from 61 to 121 bar. The technique is applicable not only in bench conditions, but also in field conditions.

It is also necessary to note the following circumstance. Since the method does not reflect the solubility of gas in water, it should not be used in the form presented above for cases of injection of water-gas mixtures containing carbon dioxide that is highly soluble in water (for example, during SWAG using flue or exhaust gases). For these variants of SWAG-technology the technique must be supplemented with formulas that take into account the solubility of gases in water under pressure.

Thus, the scientific significance of the work performed lies in the development of a graphical-analytical method for calculating the operating parameters of a liquid-gas ejector using the average integral performance, which ensures good convergence of calculated and actual data. Using the developed methodology, it is possible to quite simply, quickly and accurately determine the operating parameters of the ejector in a wide range of changing operating conditions in cases where the solubility of gas in liquid can be neglected.

The most preferred area for implementation of the proposed methodology is various variants of SWAG-technology with pumping of annular associated petroleum gas from producing wells [35, 43], when the values of annular pressures and pressures at the ejector intake are in the range from 5 to 10 bar.

Conclusion

The main results obtained in this work can be formulated in the following provisions.

1. The developed methodology for calculating the operating parameters of a liquid-gas ejector using the average integral performance makes it possible, as testing has shown, to determine with sufficient accuracy for practical purposes the values of the flow rate of the pumped gas and the pressure at the ejector outlet in a wide range of changing operating conditions. This greatly simplifies the selection of an ejector when configuring a pump-ejector system. The technique can be used both in bench and field conditions. The area of rational application of the technique is various variants of the SWAG-technology with pumping of annular APG from production wells.
2. The technique makes it possible to effectively use the technology of SWAG-technology with pumping gas from the annulus of producing wells while regulating the flow rates of the pumped gas and the pressure at the outlet of the jet apparatus. Ultimately this will allow increasing oil recovery through the introduction of SWAG-technology while simultaneously reducing annular pressures and increasing production well flow rates.
3. When injecting gases that are highly soluble in water, it is advisable to take into account the influence of the gas component solubility degree. This will allow us to continue research in the field of carbon footprint reduction technologies and enhanced oil recovery processes.

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References

1. Suleimanov, B. A., Rzayeva, S. C., Akberova, A. F., Akhmedova, U. T. (2022). Self-foamed biosystem for deep reservoir conformance control. *Petroleum Science and Technology*, 40(20), 2450-2467.

2. Suleimanov, B. A., Rzayeva, S. C., Akhmedova, U. T. (2021). Self-gasified biosystems for enhanced oil recovery. *International Journal of Modern Physics* B, 35(27), 2150274.

3. Suleimanov, B. A., Veliyev, E. F., Vishnyakov, V. V. (2022). Nanocolloids for petroleum engineering: Fundamentals and practices. *John Wiley & Sons*.

4. Veliyev, E. F., Aliyev, A. A., Poladova, G. Sh. (2023). Development of novel thermoactive polymer compositions for deep fluid diversion purposes. SPE-217642-MS. In: *SPE Caspian Technical Conference and Exhibition, Baku, Azerbaijan.*

5. Shakhverdiev, A. Kh., Denisov, A. V., Tumanova, V. D. (2021). New optimization criteria of waterflood patterns preventing premature water breakthrough in the context of water-oil displacement front instability. In: *7th Scientific Exploration Conference – Tyumen 2021: Natural Resources Management as a Cross-Functional Process.*

6. Shakhverdiev, A. Kh., Mandrik, I. E. (2007). Influence of technological features of hardly recoverable hydrocarbons reserves output on an oil-recovery ratio. *Oil Industry*, 5, 76–79.

7. Mansour, A., Gamadi, T., Emadibaladehi, H., Watson, M. (2017). Limitation of EOR applications in tight oil formation. SPE-187542-MS. In: *SPE Kuwait Oil & Gas Show and Conference, Kuwait City, Kuwait.*

8. Shakhverdiev, A. Kh., Arefiev, S. V., Pozdyshev, A. S., Ilyazov, R. R. (2023). On inclusion of high-watered reserves of oil-poor reservoirs in the category of hard-to-recover reserves. *Oil Industry*, 4, 34–39.

9. Shestopalov, Y., Shakhverdiev, A. (2021). Qualitative theory of two-dimensional polynomial dynamical systems. *Symmetry*, 13(10), 1884.

10. Shakhverdiev, A. Kh., Arefiev, S. V., Denisov, A. V., Yunusov, R. R. (2020). Method for restoring the optimal mode of operation of the reservoir – well system, taking into account the instability of the displacement front. *Oil Industry*, 6, 52–57.

11. Kovalenko, I. V., Koryakin, F. A. (2018). Estimating possibility of polymer flooding for reservoir PK1-3 of the Vostochno-Messoyahskoye field. *Oil Industry*, 9, 102-105.

12. Shakhverdiev, A. Kh., Panakhov, G. M., Abbasov, E. M., et al. (2006). Integrative efficiency of bed stimulation at intrastratal gas generation. *Oil Industry*, 11, 76–78.

13. Shakhverdiev, A. Kh., Panakhov, G. M., Abbasov, E. M., et al. (2010). The innovative technology of residual hydrocarbons reserves recovery by in-situ generation of carbon dioxide. *Oil Industry*, 6, 44–47.

14. Vishnyakov, V. V., Suleimanov, B. A., Salmanov, A. V., Zeynalov, E. B. (2019). Primer on enhanced oil recovery. *Gulf Professional Publishing.*

15. Drozdov, A. N., Gorelkina, E. I. (2022). Development of a pump-ejector system for SWAG injection into reservoir using associated petroleum gas from the annulus space of production wells. *Journal of Mining Institute*, 254, 191-201.

16. Suleimanov, B. A., Ismailov, F. S., Dyshin, O. A., Veliyev, E. F. (2016). Selection methodology for screening evaluation of EOR methods. *Petroleum Science and Technology*, 34(10), 961-970.

17. Suleimanov, B. A, Ismailov, F. S., Dyshin, O. A. (2014). Statistical modeling of life cycle of oil reservoir development. *Journal of the Japan Petroleum Institute*, 57(1), 47-57.

18. Muslimov, R. Kh. (2020). About the new paradigm of academician A.E. Kontorovich - development of the Russian oil and gas complex based on the experience of Tatarstan on the rational development of hydrocarbon resources. *Drilling and Oil*, 9, 6–14.

19. Shahrokhi, O., Sohrabi, M., Masalmeh, Sh. (2018). The impact of gas/oil IFT and gas type on the performance of gas, WAG and SWAG injection schemes in carbonates rocks. SPE-190338-MS. In: *SPE EOR Conference at Oil and Gas West Asia, Muscat, Oman.*

20. Kamali, F., Hussain, F. (2016). Field scale co-optimisation of CO2 enhanced oil recovery and storage through swag injection using laboratory estimated relative permeabilities. SPE-182261-MS. In: *SPE Asia Pacific Oil & Gas Conference and Exhibition, Perth, Australia.*

21. Sazonov, U. A., Mokhov, M. A., Mischenko, I. T., Drozdov, A. N. (2017). Development of jet-powered devices for energy effective oil and gas production technologies. *Oil Industry*, 12, 138–141.

22. Drozdov, A. N., Telkov, V. P., Egorov, Y. A., et al. (2008). Solution of problems of water-gas influence (WGI) on the layer using jet and electrical centrifugal pumping technology. In: *SPE Russian Oil and Gas Technical Conference and Exhibition. Society of Petroleum Engineers.*

23. Chen, P., Sowaidi, A. K. Al., Patel, H., et al. (2016). Assessment of simultaneous water and gas injection SWAG pilot in a giant offshore carbonate reservoir. SPE-183223-MS. In: *Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE.*

24. Drozdov, A. N., Telkov, V. P., Egorov, Yu. A., et al. (2007). Research of efficiency of high viscosity oil displacement by water-gas mixtures. *Oil Industry*, 1, 58–59.

25. Drozdov, A. N., Drozdov, N. A., Malyavko, E. A., et al. (2012). Investigation of SWAG injection and prospects of its implementation with the usage of pump-ejecting systems at existing oil-field infrastructure. SPE-160687-MS. In: *SPE Russian Oil and Gas Exploration and Production Technical Conference and Exhibition. Society of Petroleum Engineers.*

26. Shakhverdiev, A. Kh., Rybitskaya, L. P. (2003). Technological effectiveness assessment for impacts on hydrocarbons deposits. *Oil Industry*, 4. 65–68.

27. Shakhverdiev, A. Kh., Zakharov, I. V., Sulejmanov, I. V. (2004). Investigation of self-descriptiveness of parameters which determine stagnate and low drainage zones formation in hydrocarbon deposits. *Oil Industry*, 8, 64–68.

28. Shakhverdiev, A. Kh., Panakhov, G. M., Abbasov, E. M. (2002). Sinergetic effects at the system influence on deposit with thermo-rheochemical technologies summary. *Oil Industry*, 11, 61–65.

29. Strakhov, P. N., Belova, A. A., Markelova, A. A., Strakhova, E. P. (2021). Accounting for productive deposits heterogeneity in geological modeliling in order to improve an efficiency of water-alternated-gas injection. *Oil Industry*, 2, 46–49.

30. Abasov, M. T., Mandrik, I. E., Shakhverdiev, A. Kh. (2008). Multicriteria diagnostic methods for stochastic feature of oilfield development parameters. *Oil Industry*, 10, 66–69.

31. Lyubin, E. A. (2014). Evaluation of a technology for capturing petroleum vapors from Rvs-type storage tanks with the use of a pump-ejector plant. *Chemical and Petroleum Engineering*, 50, 288–293.

32. Rao, H. N., Wong, K. H., Karimi, I. A. (2016). Minimizing power consumption related to BOG reliquefaction in an LNG regasification terminal. *Industrial & Engineering Chemistry Research*, 55, 7431–7445.

33. Drozdov, A. N., Drozdov, N. A. (2020). Investigation of the ejector characteristics to improve the technology of pumping gas from the annular space during well operation by electrical submersible pump unit. *Oil Industry*, 2, 54–57.

34. Drozdov, A. N., Drozdov, N. A., Gorbyleva, Ya .A., Gorelkina, E. I. (2020). Application of jet devices in the oil field. *Moscow: Publishing house «Sputnik +».*

35. Dehkhoda, S. (2014). Experimental study of rock breakage with pulsed water-jet. ISRM-ARMS8-2014-173. In: *ISRM International Symposium - 8th Asian Rock Mechanics Symposium, Sapporo, Japan.*

36. Pestov, V. M., Yanovsky, A. V., Drozdov, A. N. (2019). Improving the technology for water-gas mixtures pumping into the reservoir. *Oil Industry*, 4, 84–86.

37. Drozdov, A. N., Zakenov, S. T., Karabaev, S. D., et al. (2020). Effect of nozzle-to-throat spacing on water-jet gas pump performance. *Oil Industry*, 8, 92–95.

38. Drozdov, A. N., Malyavko, E. A., Alekseev, Y. L., Shashel, O. V. (2011). Stand research and analysis of liquid-gas jet-pump's operation characteristics for oil and gas production. SPE-146638-MS. In: *SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA.*

39. Karabaev, S. D. (2021). Investigations of the liquid-jet gas pump's mixing throat lengths for well operations and associated petroleum gas utilization. *IOP Conference Series: Earth and Environmental Science*, 666(6), 062003.

40. Drozdov, A. N., Drozdov, N. A., Narozhnyy, I. M. (2021). Study of operating pressure effect on the performance of ejector for liquid-propellant rocket engine testing. *Advances in the Astronautical Sciences*, 170, 813-823.

41. Drozdov, A. N., Gorelkina, E. I. (2022). Investigation of the ejector`s characteristics for the system of injection of water-gas mixtures into the reservoir. *SOCAR Proceedings*, SI2, 25-32.

42. Verbitsky, V. S., Goridko, K. A., Fedorov, A. E., Drozdov, A. N. (2016). Experimental studies of electric submersible pump performance with ejector at pump inlet when liquid-gas mixture delivering. *Oil Industry*, 9, 106–109.

43. Kalinnikov, V. N. (2023). Development of technology for using annular oil gas from production wells for pumping water-gas mixtures into injection wells. PhD Thesis. *Moscow: Gubkin Russian State University of Oil and Gas (National Research University).*