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Improving the Operation of Pump-ejector Systems at Varying Flow Rates of Associated Petroleum Gas

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Application of pump-ejector systems for the utilization of associated petroleum gas reduces the negative environmental impact of its flaring, and also allows the implementation of a promising method of water-gas stimulation of the formation, which effectively increases oil recovery. Equally feasible is the use of pump-ejector systems in the operation of oil wells with a high gas factor, low bottomhole pressures to increase production rates and increase the turnaround period.

A significant change in the flow rate of associated petroleum gas over time is a serious problem for the efficient operation of pump-ejector systems for the utilization of associated petroleum gas. To ensure the rational operation of the pump-ejector system under the condition of a variable flow rate of associated petroleum gas, experimental studies of a liquid-gas ejector characteristics were carried out. The article presents the results of the research, obtained pressure-energy characteristics of the investigated jet apparatus at various values of the working stream pressure before the ejector nozzle. The possibility of adapting the operation of pump-ejector systems to changes in the flow rate of the pumped gas, regulated by the working pressure and fluid flow rate through the nozzle is revealed.

To successfully change the operation of the pump-ejector system, the possibility of frequency regulation of the pump shaft's rotation at changing gas flow rates in a small range of values is considered. With a large difference in the values of the possible flow rate of associated petroleum gas, it is recommended that frequency regulation should be supplemented by periodic short-term operation. The possibility of increasing the efficiency of the pump-ejector system when using salt solutions with a concentration that contributes to the suppression of bubble coalescence is noted.

***Key words*:** associated petroleum gas; pump-ejector systems; characteristic of liquid-gas ejector; frequency regulation; periodic short-term operation

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Introduction. One of the major problems of the oil industry is the irrational burning of associated petroleum gas (APG) in flares. About 150 billion m^3 of APG is burned annually in the world, while Russia is among the world leaders in APG flaring. In 2017 in our country 12.9 billion m^3 was burned in flares, or 13.1 % of total APG production [14]. There are many reasons for the irrational use of APG. Thus, low-pressure gas at the end stages of separation is often burned due to the unprofitable construction of expensive compressor stations for its utilization. At the same time, it is known that low-pressure gas can be utilized using simple and reliable pump-ejector systems that do not require high capital investments [3]. The composition of these systems includes jet apparatus (ejectors, jet pumps, liquid-jet compressors), pumps to drive ejectors, as well as separators, pipeline fittings, control-measuring instrumentation [5, 12]. In addition to utilization of APG into the gas pipeline or oil collector [3, 5, 11, 12], a promising option of associated gas utilization using pump-ejector systems is the water-gas stimulation of the formation [1, 4, 6, 16, 17]. As the field practice shows flow rates of flare gas requiring utilization vary considerably during field operation. Therefore, a relevant task is to develop a method of pump-ejector systems' operation, which ensures their efficient adaptation to a significant change in gas flow. This task is of great practical importance for the rational exploitation of oil wells equipped with electric submersible pumps ESP with ejectors when pumping gas with jet devices from the annulus space into the tubing string (TS).

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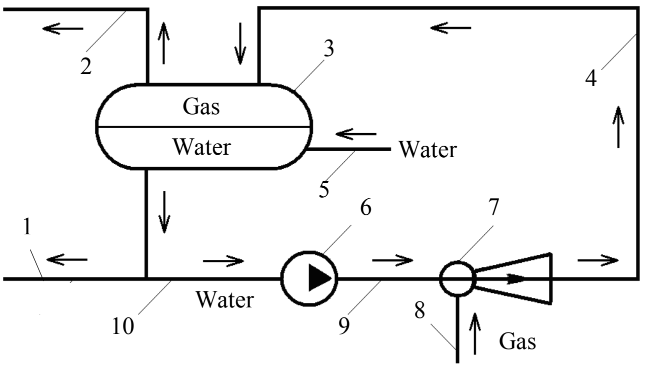

Fig.1. Principal scheme of the pump-ejector system

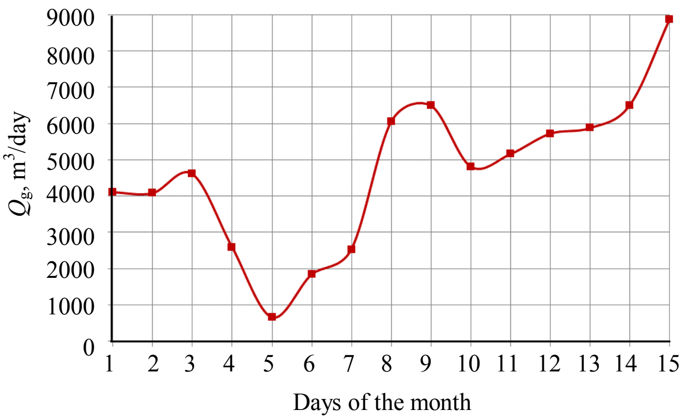

Fig.2. Dynamics of changes in daily flow rate of APG

Statement of the problem. One of the concepts of the pump-ejector system for low-pressure APG utilization by its injection into the gas pipeline is shown in Fig.1. The system includes an ejector 7, a pump 6, a separator 3, a suction line 10 of the pump 6, a discharge line 9 of the pump 6, a low-pressure gas pumping line 8, a water-gas mixture discharge line 4, a separated gas discharge line 2, a water supply line 5 and a water discharge line 1. The separator contains the working fluid. Fresh and mineralized water can be used as a fluid, as well as water-oil emulsions, oil, condensate, etc.

The system works as follows. Water from separator 3 enters the pump 6 inlet through suction line 10. Pump 6 injects water through line 9 into ejector nozzle 7, which pumps out associated gas through line 8 from the separation unit. After the ejector 7, the mixture with increased pressure is directed along the discharge line of the water-gas mixture 4 to the separator 3, where gas is separated from the water.

The gas in the discharge line 2 is then dried and sent to the gas pipeline. Since water is mixed with gas during circulation and as a result it partially evaporates, as necessary, the separator 3 should be fed with water through the water supply line 5. In addition, the water pumped through the closed loop of the system heats up when it passes through pump 1. Therefore, in those cases when heat transfer to the environment and heat transfer by the pumped medium are insufficient, it is advisable to reduce the temperature of the working fluid by supplying a certain amount of cooling water through line 5 to the separator 3 and discharging the same amount of heated water through line 1.

Methods for calculating the characteristics and selection of the most suitable flow path of the ejector for the specified operating parameters are given in [3, 5, 9]. However, variable flow rate of the pumped gas can seriously complicate the operation of the system.

As an example of significant changes in APG flow rates over time, Figure 2 shows actual field measurements of the daily flow rate of low-pressure associated petroleum gas Q_g at the end stage of separation, which is then burnt at the low-pressure flare of the «Samodurovskaya» initial water separation unit (IWSU) during the first half of October 2016.

The gas flow rates undergo significant changes during two weeks, and the minimum (650 m^3/day) and maximum (8880 m^3/day) flow rates differ from each other by 13.7 times. This is caused by non-stationary processes of development and exploitation of three oil fields (Samodurovskoe, Efremo-Zykovskoe and Spasskoe), the products of which are supplied to «Samodurovskaya» IWSU. The wells are stopped and started, current and complete repairs are made, and all this affects the flow rates of oil, gas and water supplied to the IWSU. In addition, the instability of flow rates is caused by the shutdown of wells for repairing field pipelines and the replacement of group metering units «Sputnik» and the subsequent commissioning of wells. A number of wells, including highly watered ones, are in periodic operation, which also contributes to the unsteady flow of fluid to the IWSU and, accordingly, to the change in low-pressure associated petroleum gas flow rates that must be utilized.

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Such a significant (more than 13 times) change in the flow rate of low-pressure APG in time is a serious problem for the efficient operation of pump-ejector systems and requires experimental studies for its solution.

In addition to the utilization of associated gas, pump-ejector systems allow expanding ESP application area in oil wells with complicated operating conditions. In addition, jet devices work much better compared to vane pumps when pumping gas and gas-liquid mixtures. At well exploitation, ejectors can successfully complement the electric submersible pumps [4]. However, it should be noted that the flow rates of associated petroleum gas pumped by the ejector out of the annular space into the tubing can vary significantly during the operation of the well. Consequently, for the rational exploitation of oil wells, a technology is also needed to use pump-ejector systems with variable flow rates of pumped associated gas.

Methodology. Special laboratory experimental studies of the liquid-gas ejector characteristics under significantly varying operating conditions were performed on a test bench, the description of which and the methodology for conducting experiments are given in [4]. Test bench contained a tank for liquid, a measuring tank, a shelf gravity separator, two head (submersible multistage centrifugal) pumps, a jet apparatus under study (an ejector), a system of distribution pipelines, control valves and gate valves, as well as control-measuring instrumentation. During the course of experiment the system of liquid circulation was closed-looped, for gas – open-looped. The liquid from the tank was injected with one or two head pumps into the jet apparatus, where it was mixed with the sucked gas. Mixed stream was directed from the jet apparatus to the shelf gravity separator. The separated liquid flowed from it into the tank, and the separated gas entered the atmosphere. Conducted study measured following values: the flow rate of liquid supplied to the working nozzle; flow rate of gas entering the receiving chamber; pressure values before the working nozzle, in the receiving chamber and at the outlet of the ejector diffuser; liquid temperature in the tank. Flow rates of liquid and gas, as well as the pressure values were regulated by gate valves or valves.

The characteristics of an ejector with a diaphragm nozzle with a diameter of 9 mm, a cylindrical mixing chamber with a diameter of 14 mm and a diffuser with an opening angle of 9º were investigated at the test bench. The length of the mixing chamber was 30 diameters. For the experiment, a diaphragm nozzle with rectangular edges was chosen. This form of a nozzle, as earlier studies showed [19], provides good conditions for the ejection of gas by a jet of liquid. Another advantage is the simplicity of the design and manufacture of such a nozzle.

Fresh water was used as a liquid, and air was used as a gas, which was sucked into the receiving chamber of the ejector from the atmosphere. The values of the working pressure P_{p} (pressure of the working fluid) before the nozzle and the flow rate of the working liquid Q_{p} were changed with the help of an adjustable gate valve.

According to the results of the research, the actual characteristics of the jet devices during the ejection of gas were constructed. Test bench, on which the experiment was carried out, allows investigation of the characteristics of various ejectors in a wide range of operating parameters when pumping liquid, gas, and also a gas-liquid mixture.

Discussion. According to the research results, the pressure and energy characteristics of the ejector were obtained – the dependence of the pressure ΔP_{c} created by the jet device and the efficiency of the ejector η on the flow rate of pumped gas $Q_{\text{g.ent}}$ while entering the receiving chamber of the ejector at different pressures of the working fluid P_{p} before the nozzle (Fig.3, 4)

Pressure

$$\Delta P_{\text{c}} = P_{\text{c}} - P_{\text{rc}},$$

where P_{c} – pressure at the jet apparatus outlet; P_{rc} – pressure in the receiving chamber.

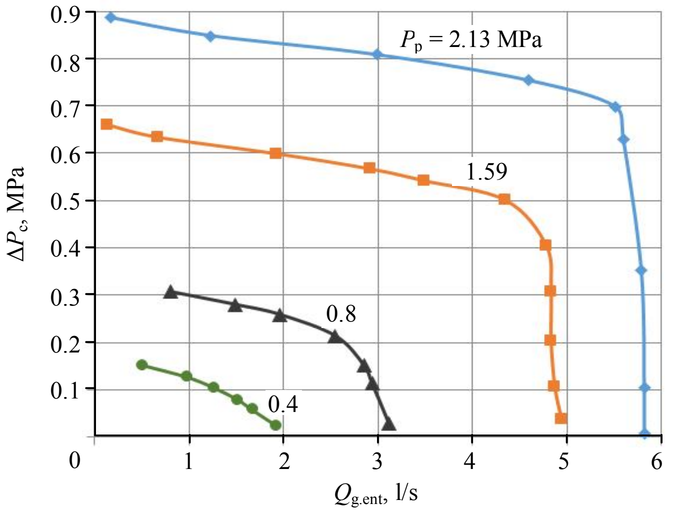

Fig.3. Dependencies of pressure ΔP_c created by jet apparatus on flow rate of pumped gas $Q_{g.ent}$ in the conditions of entry into the receiving chamber of the ejector (pressure characteristics) at different pressures of the working fluid P_p before the nozzle

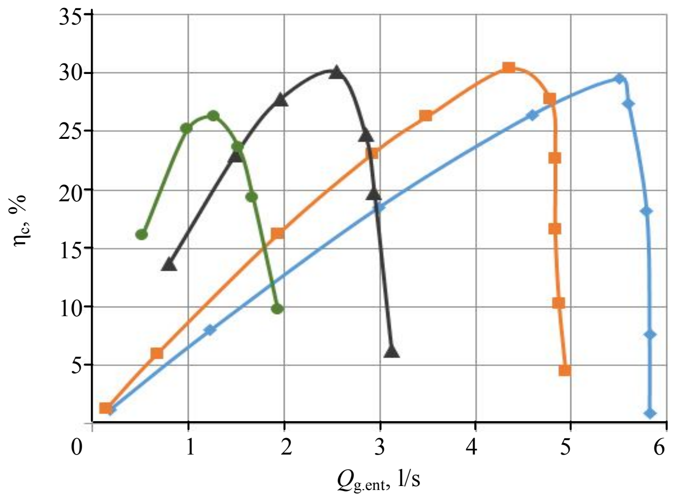

Fig.4. Dependences of a liquid-gas ejector efficiency η on the flow rate of pumped gas $Q_{g.ent}$ in the conditions of entry into the receiving chamber of the ejector (energy characteristics) at various pressure values of working fluid P_p before the nozzle
Values of P_p in the Fig.3

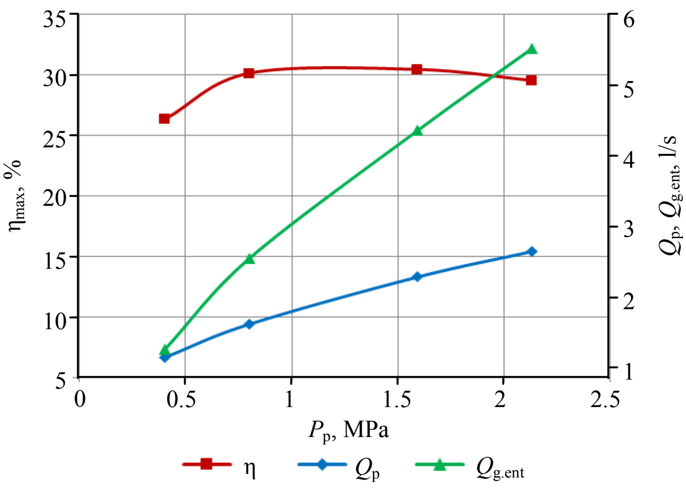

Рис.5. Dependences of maximum efficiency η_{max}, flow rate of working liquid Q_p and flow rate of pumped gas $Q_{g.ent}$ on the working pressure P_p before the nozzle for the investigated jet apparatus

The efficiency of the liquid-gas ejector

$$\eta = \frac{Q_{g.ent}\, P_{rc} \ln (P_c / P_{rc})}{Q_p (P_p - P_c)} .$$

Studies have shown that with increasing working pressure P_p, the pressure characteristics of the ejector change significantly. The pressure developed by the jet apparatus, and the flow rate of the pumped gas, increase remarkably, thus ejector's area of operation expands. During the course of experiment, the working pressure P_p before the nozzle increased from 0.4 to 2.13 MPa, i.e. about 5.33 times. The values of pressure ΔP_c, created by the jet apparatus in the modes of maximum efficiency, increased from 0.106 to 0.699 MPa, or almost 6.59 times. Flow rates of the pumped gas $Q_{g.ent}$ in the modes of maximum efficiency increased from 1.26 to 5.51 l/s – by 4.37 times. These values indicate that there are good opportunities for adapting the pump-ejector system to changes in flow rates of gas. Regulation of the system is possible by varying the working pressure before the ejector nozzle and the flow rate of working liquid through the nozzle (Fig.5).

Studies made it possible to establish that with an increase in the working pressure P_p, flow rates of both working liquid Q_p and pumped gas $Q_{g.ent}$ increase, and the degree of increase in the flow rate of gas is significantly higher than in the flow rate of the liquid. The values of η_{max} with increasing P_p grow at first, and after the value P_p = 1.59 MPa they decrease a little. At the same time, in the range P_p from 0.8 to 2.13 MPa, the changes η_{max} are insignificant (less than 0.9 %).

The possibility of successful control in the operation of the pump-ejector system, shown in the studies, by changing the working pressure before the ejector nozzle and the flow rate of working liquid through the nozzle, which allows pumping gas at significantly changing (several times) gas flow rates, can be best realized in practice by means of pump shaft's frequency regulation. This method provides much higher energy efficiency compared to flow control with a gate valve at the outlet of the pump (used in the process of the bench experiment described above). Control stations with frequency converters for pump drives are commercially available, so their use in practice as part of pump-ejector systems will not be difficult.

At the same time, studies showed that regulating the system only by changing the pressure before the ejector nozzle and the liquid flow rate through the nozzle is still not enough for adaptation in cases where the flow rates of the pumped gas change by more than 5 times. In fact, it is technically difficult to change (even by frequency regulation) the pressure developed by the system pump by 6 times or more. Therefore, for adaptation under conditions of a change in the flow rate of the ejected gas by more than 5 times (for example, 13.7 times, as at the «Samodurovskaya» IWSU), it is advisable to supplement the frequency regulation by the method of periodic short-term operation, similar to the method of operating wells described in [7].

At this method, periodic short-term switching on and off of the pump 6 is carried out, which drives the ejector 7 (see the diagram in Fig.1). The periods of operation of the pump 6 and the ejector 7 can be controlled by automatically regulating the pressure in the low-pressure gas suction line 8. When the pressure in line 8 rises above the preset value, the pump 6 is turned on, the ejector 7 pumps out the gas. After reducing the pressure in the low-pressure gas suction line 8 to a certain value, the pump 6 is turned off. During operation the pressure control values can be set so that the change in pressure in the low-pressure gas suction line 8 does not lead to pulses. It is advisable to start the pump using the soft start method. The pump and ejector parameters must be calculated based on the maximum expected gas flow rate. Thus, the system can provide gas pumping in the entire necessary range from the minimum to the maximum flow rate, even if they differ from each other by ten times.

It is possible to further increase the operational efficiency of the pump-ejector system shown in Fig.1 by using the results of studies presented in [20, 21]. It was experimentally established that there are regions of rational concentrations and composition of salts in which suppression of the coalescence of gas bubbles in a liquid is ensured due to the manifestation of repulsive forces between the bubbles, which are negatively charged in aqueous solutions of electrolytes. In addition, a noticeable improvement in the characteristics of liquid-gas ejectors with the addition of salt to water was revealed in [20], i.e. when gas is pumped out by a stream of salt water (in the region of rational concentrations of bubbles' coalescence suppression) in comparison with ejection of a gas by a stream of fresh water. Therefore, it is advisable to use water with the addition of electrolyte salts as the working fluid of the pump-ejector system, corresponding to the region of rational concentrations and composition of salt. It is important to note the following. Associated bottom water, separated at IWSU, as a rule, contains various dissolved salts. It was shown in [20] that the composition of the associated water of the Samodurovskoye field contributes to the suppression of bubble coalescence. Therefore, in such cases when nature itself is moving towards it, it is necessary to use associated water as a working fluid, the composition of which prevents the rapid coalescence of gas bubbles and increases the efficiency of gas pumping by the pump-ejector system.

The technology of pump-ejector systems can be used not only for the utilization of APG, but also for the operation of oil wells by ESP with jet devices.

As it is known, well operation by electric submersible pumps is the main method of oil production in Russia [4]. ESPs are also used in oil wells abroad rather widely. Of great importance in this case is the creation of technical solutions that can significantly increase the efficiency of well operation with ESP in complicated conditions. As noted by various foreign [15, 18] and domestic [2, 4, 8, 10, 13] researchers, one of them is the use of ESPs with jet devices. It is advisable to use such pump-ejector systems in the operation of oil wells to increase production rates and increase the

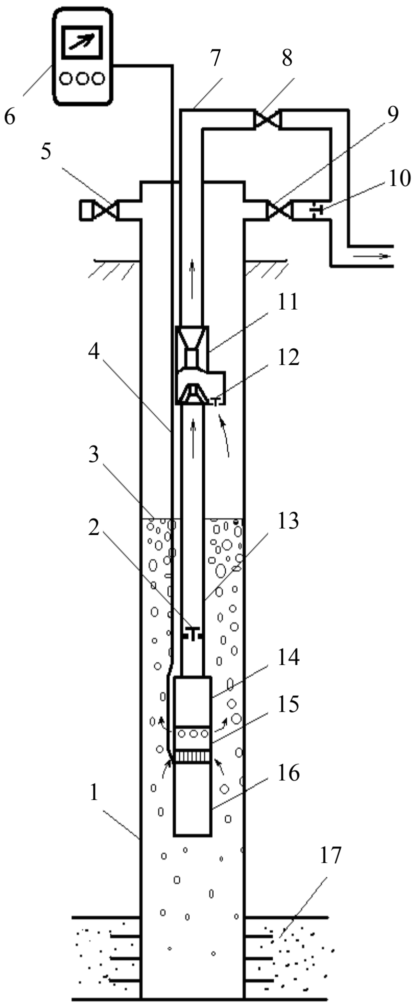

Fig.6. Scheme of the well equipped with submersible pump-ejector system

turnaround time, at production of oil with a high gas factor, low bottomhole pressure, as well as for developing idle wells and when extracting oil using ESPs with packers from wells with leaks in production strings.

At the same time, despite obvious advantages, the pump-ejector technology for operating oil wells is not widespread due to the difficulty in selecting the optimal parameters for the ESP and the jet apparatus [10]. The complexity of the selection in many cases is due to the fact that the flow rates of gas pumped by the ejector from the annulus into the tubing changes significantly during the operation of the well.

Under these conditions, the problem can be solved by using the technology of submersible well pump-ejector systems, similar to that recommended above for the utilization of APG and combining frequency regulation with periodic short-term operation. The scheme of a submersible pump-ejector system lowered into the well for the implementation of this technology is shown in Fig.6.

Submersible pumping unit is lowered into the well 1, drilled in the formation 17. It consists of an ESP 14, an input preinstalled device (standard input module, gas separator, dispersant, etc.) 15, a submersible motor 16 with hydroprotection and a thermomanometric well system TMS. ESP is lowered into the well on the tubing 13, with the backpressure pump valve 2 installed at the ESP output. Electricity is supplied to the motor 16 via cable 4. In the tubing string 13 there is a jet apparatus 11 with a backpressure valve 12 in the receiving chamber. Submersible pumping unit and jet apparatus are components of the pump-ejector system. Well 1 is equipped with wellhead 7 with gate valves 5, 8, 9 and a backpressure valve 10 from the annulus to the line. The installation is driven by a control station 6 with a frequency converter. Position 3 denotes a dynamic level.

Pump-ejector system is operated as follows. The ESP pumps out the fluid that enters the well 1 from the formation 17 and pumps it into the nozzle of the jet apparatus 11. At the same time, part of the free gas is separated at the inlet of the pump 3 due to natural (when the pump is equipped with a conventional input module or dispersant) and artificial (when the pump is equipped with a gas separator) separation into the annulus. The ejector 11 draws gas from the annulus above the dynamic level 3. After mixing the fluid and gas flows and increasing the pressure, the mixture is sent to the tubing string 13 and then rises along it to the surface.

Adaptation to significantly changing operating modes is carried out in this case both by adjusting the frequency of the current and, accordingly, the rotational speed of the pump shaft 15 using a control station with a frequency converter 6, and by periodically turning on and off the submersible pump unit. When the pump 14 is turned off, the backpressure valves 2 and 12 are closed, which does not allow fluid to flow from the tubing cavity 13 back to the well 1. During periods of shutdown of the pump 14, fluid accumulates in the wellbore 1, level 3 begins to rise, and gas passes through the backpressure valve 10 from the annulus to the flow line. The frequency of switching on and off of the pump 14 can be regulated and adjusted to the operating parameters of the well 1 based on the data of the thermomanometric well system TMS on pressure and temperature at the inlet of the submersible pump unit.

As in the case of the use of a ground-based pump-ejector system, the operating parameters of the submersible pump 15 and the jet apparatus 11 are calculated based on the maximum expected values of the flow rate of the well 1 and the gas flow rate. Thus, the difficult problem of selecting the optimal parameters of the ESP and jet apparatus is solved.

Conclusion. Experimental studies have shown the possibility of successfully regulating the operation of the pump-ejector system by changing the working pressure before the ejector nozzle and the flow rate of the working fluid through the nozzle, which makes it possible to pump out gas at significantly varying (several times) flow rates. At the same time, just regulating the operation of the system by changing the pressure before the ejector nozzle and the fluid flow through the nozzle is still not enough for adaptation in cases where the flow rates of the pumped gas change by 5 times or more. Therefore, for adaptation in conditions of higher changes in gas flow rates, it is advisable to supplement the frequency regulation by the method of periodic short-term operation. This technological solution is applicable both for pump-ejector systems for the utilization of associated petroleum gas, and for the rational operation of oil wells equipped with electric submersible pumps with ejectors.

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