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Analyzing Efficiency of Joint Operation of Gas Separator and Screw Pump on High-viscosity Gas-liquid Mixture

V. S. Verbitsky[a], A. V. Dengaev[a], E. U. Safiullina[b], M. V. Verbitsky[a], M. A. Suleymanov[a], V. V. Chugunov[c], D. R. Efremenko*[b]

[a] *Gubkin Russian State University of Oil and Gas, St. Petersburg Mining University, St. Petersburg, Russia*
[b] *Saint Petersburg Mining University, St. Petersburg, Russia*
[c] *Schlumberger Technology Company LLC, Russia*

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ABSTRACT

In this paper the application of centrifugal type gas separator as a part of submersible electric screw pumping unit is considered. A number of bench tests have been carried out to study the centrifugal gas separator on viscous gas-liquid mixture. Calculation of the dependence of delivery on the developed pressure of a single screw pump at the angular speed of rotation of the rotor 225 rpm for different gas content has been made. Also, characteristic curves of gas separators of groups 5 and 5A at different gas contents and different viscosity of gas-liquid mixture are obtained. A methodology for bench testing of gas separators has been developed, which takes into account the influence of gas-liquid mixture properties, changes in the angular speed of the electric motor shaft rotation, and natural separation parameters. The operating parameters of a gas separator of group 5A were determined experimentally, taking into account a residual gas content of 50%, in the range of angular speeds of 252 – 1000 rpm (4.2 – 16.7 Hz).

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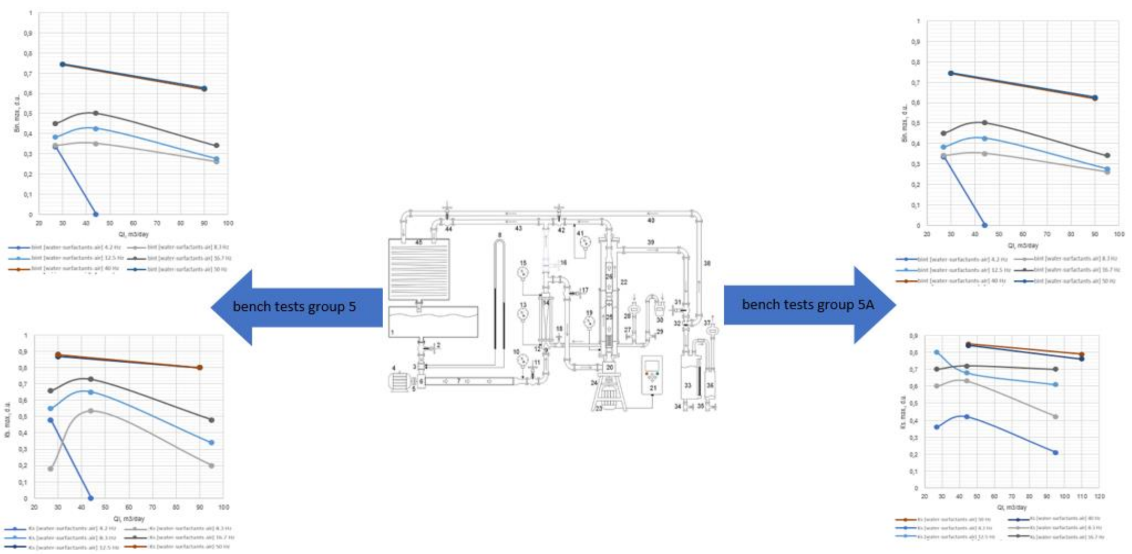
Graphical Abstract



*Corresponding Author Email: *daniil1801@mail.ru* (D. R. Efremenko)

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1. INTRODUCTION

Modern conditions of hydrocarbon field's exploitation are characterized by geological, technical and technological complications, leading to a decrease in the efficiency of hydrocarbon production by traditional methods and techniques. For example, the development of Russkoye oil and gas condensate field (OGCF) in Yamalo-Nenets Autonomous District, discovered in 1968, is associated with various complication factors, the main of which are: high oil viscosity values and low hydraulic conductivity values. Due to the fact that the field is characterized by exceptional complexity of its geological structure, it is multilayer, broken by tectonic disturbances into isolated blocks, the reservoirs are vaulted and massive (1). The productive horizons are characterized by a high degree of heterogeneity. Within the Cenomanian sediments (formation PK1-7) 16 deposits of high-viscosity oil have been identified (March 2008), the oil rim throughout the area has contact with the underlying water and with the gas cap. The natural mode of the deposits is elastic and inefficient gas and water pumping (2, 3).

The history of development of Russkoye oil and gas condensate field allows us to determine the influence of complicated factors on the efficiency of reserves development. Trial operation at the field began in 1975-76 in depletion mode, well products were lifted by sucker rod pumping units (SRPU) in a periodic mode with frequent stops for repair work due to the harmful effect of sand, which was carried out from the reservoir at insignificant underbalances in the reservoir. In 1978-1984 at experimental site of Russkoe OGCF in the water-oil zone, studies on injection of hot water into the reservoir and testing of the technology of intra formation burning (IFB) were carried out (4). Pilot field studies in the experimental area were not successful due to the fact that within 2 months in the producing wells received an increase in water cut, and in 7 days in the IDP area bursting of combustion products, as a consequence, a low coefficient of coverage of the reservoir as a result of the bursting of the burning center. The unsatisfactory results of the ODA led to the project being stopped and the research was resumed 20 years later, in particular, the ODA was conducted at four field sites with different development system parameters. Proshutinskiy et al. (4) conducted a detailed analysis of pilot plots No. 1-4 is presented, in particular, pilot plot No. 1 proved the effectiveness of hot water injection compared to cold water injection, having obtained water breakthrough on the fourth month after the start of cold-water injection. The ODA results allowed to determine the technology of hot water injection into the reservoir - the main technology of influence on oil-saturated areas of the deposit (5).

Vostochno-Messoyakhskoye, Van-Yeganskoye, Severo-Komsomolskoye fields can be referred to the fields - analogs of Russkoye field because of similar geological and physical characteristics, methods of complications control and choice of well operation method, mainly wells were operated by vane and screw pumps with electric drive (6, 7).

The operation of producing oil wells in Russkoe field is characterized by a complex factor of complications: low flow, heavy and high-viscosity oil, free gas breakthrough through geological faults and fractures, well watering ahead of schedule, formation temperature does not exceed 20°C, sand removal. The presented set of complications requires the development of non-standard solutions for effective lifting of well products to the day surface with minimal energy costs. Improving the efficiency of production wells operation by mechanized methods with various complication factors is an urgent task, including in determining the optimal method of oil production from wells penetrating oil rims of gas-oil and gas-condensate fields.

2. ON THE POSSIBILITY OF APPLICATION OF GAS SEPARATOR OF CENTRIFUGAL PRINCIPLE OF ACTION AS A PART OF SUBMERSIBLE ELECTRIC SCREW PUMPING UNIT

The popularity of the application of screw pumping units with electric drive can be associated with the technological necessity of working in complicated conditions when pumping viscous systems with the presence of solid phase and high gas content in the pumped product (8, 9). In Russia, screw pumps are not widely used due to their low reliability when operating in wells with low wellhead pressures, but the operating conditions of wells of Russkoye OGCF and analogous fields indicate the promising application of screw pumps, taking into account the increased efficiency of their operation with low wellhead pressures (5, 10).

Low reliability of screw pumps is due to the fact that, all other things being equal, an increase in the pressure drop across the stages (stator pitch) of a screw pump can lead to elastomer failure and large fluid leaks, with the pump efficiency decreasing (11). The calculated pressure drop in the stages of a screw pump depends on the compression fitting of the rotor and stator before the pump is run into the well, as well as on the properties of the elastomer, the stator pitch length and the properties of the gas-liquid mixture (12). If a screw pump is lowered to a great depth and it is necessary to provide low pressure at the pump inlet, as a result we get maximum pressure drop in pump stages when working on homogeneous liquid, and as soon as a gas-liquid mixture with high gas content (more than 50% by vol.) enters the pump, there are pulsations in the cavities between rotor and stator, compression fitting between adjacent cavities is broken, leakages occur in the decompression area of the pump, pump delivery decreases and during long operation of the pump in such a mode. To avoid negative scenarios in the operation of a screw pump unit, one of the solutions is to avoid the risk of free gas breakthrough at the pump inlet (ensuring that the gas content at the pump inlet does not exceed 50% by vol.), e.g. by means of a submersible gas separator.

It is known that the drive for electric screw pump units (ESPU), in one of the known variants, is a submersible electric motor (SEM) used as an electric drive for electric submersible pump units (ESPU), but the difference is that the ESPU operation requires half the angular speed of the shaft rotation. As a rule, the rotor angular velocity required for ESP operation is achieved by manufacturing a four-pole magnetic field drive with a synchronous speed of 1500 rpm or less (13). In contrast to ESPs operating at increased shaft speeds and contributing to the increase in head and delivery, increase in power consumption, for ESPs it is preferable to reduce the rotor speed to reduce the risks of reducing the performance characteristics of the pump due to wear, heating and ensuring the efficiency at the maximum level (14-16). Thus, of practical interest is the technological ability of the centrifugal principle gas separator operation at low speeds (in the arrangement with an electric screw pump) when pumping complex gas-liquid mixtures (17).

3. CHARACTERISTICS OF BOREHOLE SCREW PUMP OPERATION ON GAS-LIQUID MIXTURES

There are not many scientific works published in the open press, devoted to the analysis of the characteristics of downhole screw pumps on viscous gas-liquid mixtures in a wide range of gas contents. Studies of single screw pumps on viscous liquids have been reported in literature (18, 19), and on low-viscosity gas-liquid mixtures also reported (20-22).

In the literature (23) indicates that the single screw pump has a wide range of capabilities when working on gas-liquid mixture, but these studies relate only to model mixtures: "water-air", "water - surfactant - air", i.e. they did not consider the influence of free gas in the composition of high-viscosity gas-liquid mixture on the characteristics of the screw pump. Nevertheless, the research results indicate the effective influence of surfactants in the gas-liquid mixture, in particular, the screw pump operates with higher values of gas content under other equal conditions. Natural surfactants are present in well products, the composition and properties of which under certain thermobaric conditions lead to changes in the properties of the gas-liquid mixture and, as a consequence, on the operation of the downhole screw pump.

Rogachev and Alexandrov (24) carried out a generalized assessment of technical and economic efficiency of various methods of operation in a wide interval of changes in parameters: flow rate, well depth and gas factor. The result of the study is a map of effective application of mechanized oil production technologies in the coordinates "reservoir depth - gas factor", in which it is indicated that UEWS are able to operate with gas factor 120 - 400 m^3/t, respectively, at reservoir depths from 1000 to 2250 meters. They did not specify an important parameter for evaluating the efficiency of ESP application - viscosity of the gas-liquid mixture, and also did not specify the condition under which they conducted a comparative evaluation, for example, the influence of the operation of the pre-injection module as part of the pumping unit. It is known that ESP and ESPP can provide the same technical and technological characteristics in relation to the conditions of operation of one well, but at the same time, for example, a gas separator will be installed as part of ESP, while in the ESP arrangement there is no gas separator (25). Therefore, to choose the method of operation for hydrocarbon fields with hard-to-recover reserves, it is recommended to take into account not only the influence of the gas factor and the depth of equipment descent, but also the viscosity parameter of the gas-liquid mixture, energy indicators of the deposit (gas saturation, saturation pressure, reservoir pressure, etc.), peculiarities of the operation of mechanized units in conditions of multiphase systems pumping, including taking into account the influence of the efficiency of the pre-injection devices in the pumping units.

Nikolaev and Zaripova (26) qualitatively considered the issue of increasing the efficiency of screw pump installations in complicated operating conditions, conducted bench studies of the pressure characteristics of the screw pump taking into account the modeling of the screw pump operation on gas-liquid mixtures. The author points out that UEWP have significant limitations on the developing torque of the submersible motor and, therefore, operates with a gap or a small tension in the pair "rotor - stator", which predetermines the need to increase the rotor speed in accordance with the operating conditions of the system: "reservoir - well - pump - hoist", pressure-flow characteristics in this case correspond to the characteristics of dynamic pumps. The methodology for determining the ultimate pressure developed by a screw pump, taking into account the coefficients that take into account the properties of the pumped mixture (26):

$$P_0^{well} = k_p \cdot k_n \cdot k_{gas} \cdot k_\mu \cdot P_0 \quad (1)$$

where k_p- is the coefficient of ultimate pressure of the pump under operating conditions, r.m.s.;

$$k_p = -4.64 \cdot k_q^{well} + 5.76 \quad (2)$$

where $k_q^{well} = \frac{Q_i^{well} \cdot n_{nom}}{Q_i^{nom} \cdot n_{test}}$ – is the coefficient of deviation of pump delivery under operating conditions from nominal at bench rotor frequency, in relative units (R.U.); Q_i^{well}- screw pump flow rate in idle mode at bench tests, m^3/day;

$$Q_i^{well} = Q_i^{test} \cdot (1 - k_{elast}) \quad (3)$$

where k_{elast} – elastomer swelling coefficient in operating conditions, depends on the content of aromatic hydrocarbons in the liquid, carbon dioxide, hydrogen sulfide, pressure and temperature in the working chamber of the screw pump, elastomer composition and other parameters (27); Q_i^{nom} – nominal flow rate of the screw pump in idle mode at nominal rotor speed, m^3/day; n_{nom} – nominal rotor speed of the screw pump rotor, rpm; n_{test} – rotor speed at bench tests, rpm; k_n – rotor speed coefficient of the screw pump rotor under operating conditions:

$$k_\mu = 0.76 \cdot \left(\frac{2 \cdot \mu_{in}}{(\rho_{l.in.} + \rho_{l.out})}\right)^{0.159} \quad (4)$$

where μ_{in} – dynamic viscosity of liquid at the screw pump inlet, mPa*s; $\rho_{l.in.}$ and $\rho_{l.out}$ – density of liquid at the inlet and outlet of the screw pump, kg/m^3; P_0 – limit pressure of the screw pump at nominal rotor frequency, MPa; k_{gas} – coefficient of variation of pump ultimate pressure under operating conditions due to gas influence:

$$k_{gas} = 1 - \frac{\beta_{g.in} + \beta_{g.out}}{2} \quad (5)$$

where $\beta_{g.in}$ and $\beta_{g.out}$ – is the volumetric flow rate gas content of the gas-liquid mixture at the inlet and at the outlet of the screw pump, relative units;
Screw pump feed (21):

$$Q = Q_i \cdot \left(1 - \left(\frac{P}{P_0}\right)^\alpha\right) \quad (6)$$

where Q_i – screw pump delivery in idle mode, m^3/day;
P – pump pressure:

$$P = P_{out} - P_{in} \quad (7)$$

where P_{out} – screw pump outlet pressure, MPa; P_{in} – pressure at the screw pump inlet, MPa;
α – index of nonlinearity of pressure-flow characteristics of screw pump, depends on pump size, rotor speed and rotor tension and is determined by mathematical analysis (28).

The method proposed for calculating the pressure-flow characteristics of a screw pump on the one hand allows to calculate the ultimate pressure of a screw pump taking into account the deformation coefficients of the pump passport characteristic, on the other hand is complicated from the point of view of determining the coefficients: k_{elast} and α.

Let's consider an alternative method of determination of deformation coefficients of pressure-flow characteristics of a single screw pump according to test data (14). Tests of a single screw pump with kinematic ratio i = (5÷6), contour diameter of the cage D_c = 46 mm, length of the cage L = 700 mm, the screw surface of the cage T = 150 mm, eccentricity e = 2.45 mm, were carried out on a model mixture: "water-air", with maintaining pressure at the inlet of the screw pump 0.1 MPa (Figure 1).

The characteristics of the single screw pump are treated in dimensionless coordinates:

$$\varepsilon_{rel.init} = \frac{P_{out}}{P_{in}} \quad (8)$$

where $\varepsilon_{rel.init}$ – degree of pressure rises of the screw pump operating on homogeneous liquid without influence of free gas, r.e.m.; P_{out} and P_{in} – pressure at the outlet and at the inlet of the screw pump operating on homogeneous liquid, MPa (29);

$$\varepsilon_{rel} = \frac{P_{out.g}}{P_{in.g}} \quad (9)$$

where ε_{rel} – degree of pressure increases of the screw pump operating on gas-liquid mixture, r.e.m.; $P_{out.g}$ and $P_{in.g}$ – pressure at the outlet and at the inlet of the screw pump operating on gas-liquid mixture, MPa;

$$k_q = \frac{q_{l[\beta g>0]}}{q_{l[\beta g=0]}} \quad (10)$$

where k_q – is the coefficient of variation of screw pump delivery by liquid, R.O.D.; $q_{l[\beta g>0]}$ – screw pump delivery rate by liquid when pumping gas-liquid mixture, m^3/day; $q_{l[\beta g=0]}$ – screw pump delivery rate by liquid when pumping homogeneous liquid (without free gas), m^3/day;

$$\beta_{g.in} = \frac{Q_{g.in}}{Q_{g.in} + Q_{l.in}} \quad (11)$$

where $\beta_{g.in}$ – is the volumetric flow gas content at the screw pump inlet, r.e.m.; $Q_{g.in}$ – is the volumetric gas flow rate at the screw pump intake, m^3/day; $Q_{l.in}$ –

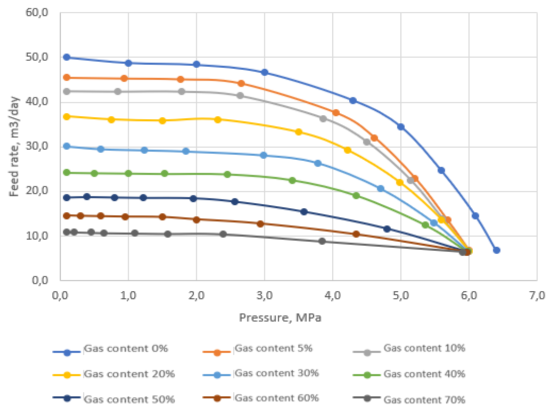

Figure 1. Dependence of delivery on developed pressure of single screw pump at rotor angular speed 225 rpm

volumetric flow rate of liquid at screw pump intake, m^3/day;

$$\beta_{g.out} = \frac{\beta_{g.in}}{\varepsilon_{rel} - \beta_{g.in}(\varepsilon_{rel} - 1)} \tag{12}$$

where $\beta_{g.out}$ – is the volumetric flow gas content at the screw pump outlet, r.e.m. On the basis of the obtained expressions $\beta_{g.in}$ and $\beta_{g.out}$ we calculate the average density of HLW in the screw pump:

$$\rho_{av} = \frac{1}{2}(\rho_{in} + \rho_{out}) \tag{13}$$

where ρ_{av} – average density of HLW, kg/m^3; ρ_{in} and ρ_{out} – density of HLW at the inlet and outlet of the screw pump, kg/m^3;

$$\rho_{in} = \rho_{l.in} - \beta_{g.in}(\rho_{l.in} - \rho_{g.in}) \tag{14}$$

where $\rho_{l.in}$ – density of liquid at the screw pump inlet, determined by the Cliperon equation, kg/m^3; $\rho_{g.in}$ – free gas density at the screw pump inlet, determined by the Cliperon equation, kg/m^3;

$$\rho_{out} = \rho_{l.out} - \beta_{g.out}(\rho_{l.out} - \rho_{g.out}) \tag{15}$$

where $\rho_{l.out}$ – density of liquid at the screw pump outlet, determined by the Cliperon equation, kg/m^3; $\rho_{g.out}$ – free gas density at the screw pump outlet, determined by the Cliperon equation, kg/m^3;

$$Q_{out} = Q_l + Q_{g.out} = Q_l + \frac{Q_{g.in}}{\varepsilon_{rel}} \tag{16}$$

where Q_{out} – is the volume flow rate of HLW at the screw pump outlet, m^3/day; Q_l – volume flow rate of screw pump liquid, m^3/day; $Q_{g.out}$ – free gas volume flow rate at the screw pump outlet, m^3/day. Let's determine the volumetric losses of gas-liquid mixture of screw pump due to decompression (influence of free gas), m^3/day:

$$\Delta Q = \Delta Q_l + Q_{g.in} \cdot \left(1 - \frac{1}{\varepsilon_{rel}}\right) \tag{17}$$

where $\Delta Q_l = Q_и - Q_{g.in} - Q_l$ – liquid volume losses, m3/day; $Q_{g.in}$ – free gas volume flow rate at the screw pump inlet, m3/day; Q_{teor} – geometric (theoretical) delivery of the screw pump, m^3/day;

$$Q_{teor} = 1440 \cdot V \cdot n \tag{18}$$

where V – pump working volume, m^3; n – rotor speed of the screw pump rotor, rpm;

$$V = z_2 \cdot S \cdot T \tag{19}$$

where z_2- number of turns of the rotor screw ($z_2 \geq 2$, for multi − turn screws); S – live section area of the pump working chamber, m^2; T – spacing of the screw surface of the cage, m;

$$S = 4e(D_c - 4e) \tag{20}$$

where e – eccentricity, m;
D_c – contour diameter of the cage, m;

$$n = \frac{n_{tac}}{2i_g} \tag{21}$$

where $n_т$ – tachometer reading, rpm; i_g – gear ratio of the gear unit.

According to the proposed method it is possible to determine the share of volume losses of liquid and gas-liquid mixture, the average density of gas-liquid mixture in the screw pump, the coefficients of pressure increase of the screw pump when operating on gas-liquid mixture and degradation of the pressure-flow characteristic of the screw pump due to the influence of free gas (coefficient of change of screw pump delivery). Figure 2 shows graphical dependences of experimental data processing (14) in the form of coefficients of change of delivery (Figure 2a) and coefficient of change of screw pump ultimate pressure (Figure 2b) according to the method (26) on gas content at the pump inlet, taking into account the degree of pressure increase (degree of gas compression) of the screw pump. The analysis of graphical dependences shows that with the decrease of the compression degree there is a deformation of screw pump characteristics. In particular, the screw pump feed rate decreases with decreasing compression ratio in the whole range of gas contents at the screw pump inlet (Figure 2a), and at compression ratio less than 40 the feed rate practically does not change in a wide range of gas contents (30). With increasing gas content at the screw pump intake there is a decrease in the pump delivery coefficient on liquid, for example, if we consider the operation of the screw pump in accordance with the recommended in the technical specifications parameter of permissible gas content - 50% vol. (31), then for εrel

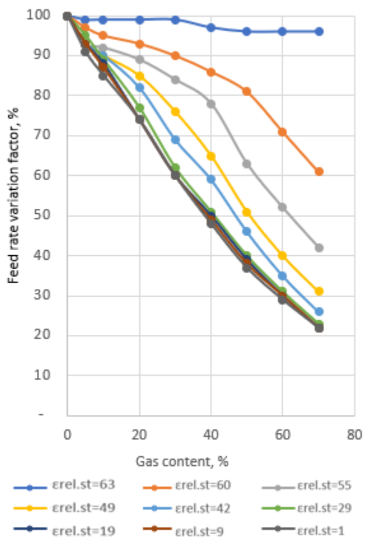

Figure 2a. Variation of coefficients of relative supply from gas content at the intake of a screw pump operating at rotor speed 225 rpm, taking into account the degree of pressure increases of the screw pump on homogeneous liquid

=63 the coefficient of change of delivery will be 96%, and for εrel=42, the coefficient of change of delivery is 51%. Thus, for a screw pump run into a well at a certain depth, when the pressure at the pump inlet is reduced so that εrel is reduced from 63 to 42, with a gas content of 50%, in the case of reduced pressure at the screw pump inlet, the delivery rate will be reduced by 51%. If the downhole screw pump installation is provided with a gas separator, it is possible to reduce the gas content at the screw pump inlet at a given εrel =42; thus increasing the value of the pump delivery variation coefficient.

Figure 3 shows crossplots of: volumetric flow gas content at the inlet and outlet of the investigated screw pump (Figure 3a) and the degree of pressure rise of homogeneous and multiphase liquids (Figure 3b).

As the compression ratio decreases, the volumetric flow gas content at the outlet of the screw pump increases relative to the volumetric flow gas content at the inlet of the screw pump (Figure 3a). Similarly, it can be seen that as the gas content increases, the degree of pressure rises when the screw pump is operating on a multiphase mixture decreases relative to the degree of pressure rise if the pump were operating on a homogeneous liquid. For example, for a volumetric flow gas content at the pump inlet of 50%, if $\boldsymbol{\varepsilon}_{rel}$ is reduced from 63 to 42, the gas content at the screw pump outlet, all other things being equal, will increase from 2 to 4.9% (Figure 3a), while the compression ratio will decrease by a factor of about 2 (Figure 3b).

The proposed methodology allows to carry out qualitative analysis of screw pumps operation on gas-liquid mixture in a wide range of gas content change at the intake, to determine the gas content at the pump outlet, compression ratio, screw pump feed degradation coefficient, average density of gas-liquid mixture and to evaluate the necessity of gas separator application.

To evaluate the application of a gas separator as part of a downhole screw pump unit, let us consider the results of unique bench experiments.

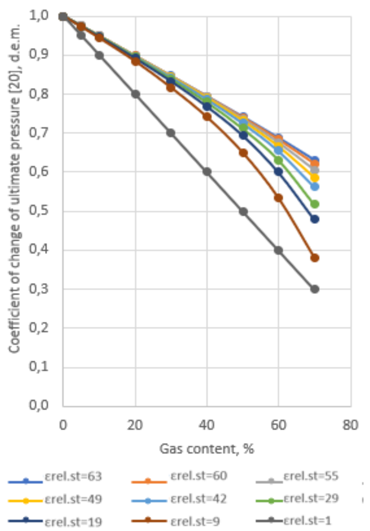

Figure 2b. Ultimate pressure according to the method from gas content at the intake of a screw pump operating at rotor speed 225 rpm, taking into account the degree of pressure increases of the screw pump on homogeneous liquid (32)

4. RESULTS OF BENCH TESTS OF CENTRIFUGAL GAS SEPARATOR ON VISCOUS GAS-LIQUID MIXTURE

At the department of development and operation of oil fields of Russian State University of Oil and Gas (RSU)

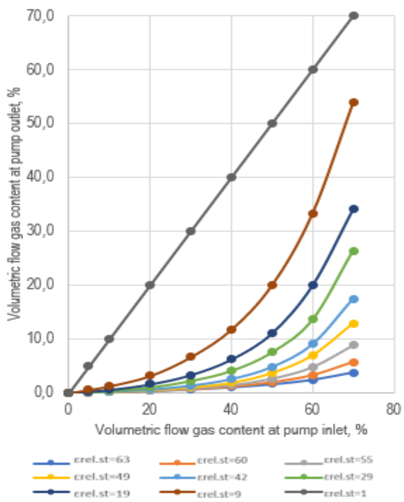

Figure 3a. Dependence of volumetric flow gas content at the inlet and outlet of the investigated screw pump of the screw pump operating at rotor speed 225 rpm

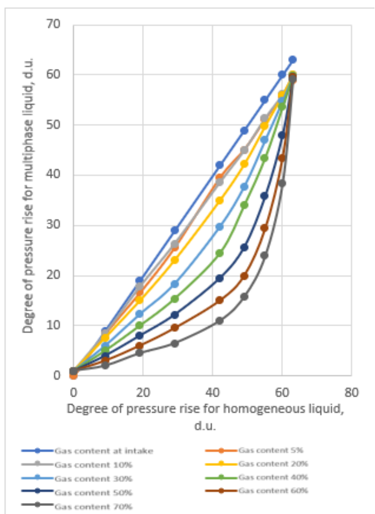

Figure 3b. The degree of pressure rise of homogeneous and multiphase liquids of the screw pump operating at rotor speed 225 rpm

named after I.M. Gubkin the research of centrifugal gas separators of group 5 and 5A on model mixtures was carried out: "water-surfactant-air", "oil-air" in the range of angular speeds of shaft rotation (motor current frequency) 252 - 1000 rpm (4.2 - 16.7 Hz). The research was carried out on a specialized stand simulating the operation of submersible pumping equipment in a well (Figure 4). The methodology of the experiment is as follows: the model liquid from Tank 1 passes through the gate valve 2 into the suction line, where the flow meter 3 is placed to measure the flow rate of the liquid. Then the liquid enters the receiving module 6 of the booster pump 7, driven by an electric motor 4. Torque from the electric motor shaft to the pump shaft is transmitted by means of elastic sleeve-finger coupling 5. A mechanical seal is installed in the intake module 6. The pressure developed by the booster pump is monitored by a pressure sensor 10. By the booster pump 7 the liquid is supplied to the nozzle 9 of the jet apparatus. The pressure in front of the nozzle is regulated by the gate valve 11. Due to the high velocity of the liquid at the outlet of the nozzle 9, a vacuum sufficient for pumping air out of the atmosphere is formed in the receiving chamber 12 of the jet apparatus. The vacuum can be monitored by a pressure sensor 13.

Through the open gate valve 18 the air is pumped out through the air line. The amount of air entering the receiving chamber 12 of the jetting device is measured by gas meter 30 (type G6) and regulated by valve 29. The time of passage of a certain volume of air through the meter 30 is measured by an electronic stopwatch. In case of air flow rate more than 10 m^3/hour instead of 30 and 29 used, respectively, gas meter 28 (type RG-40) and regulating valve 27. In the mixing chamber 12 of the jet apparatus there is an energy exchange of liquid and air flows, their active mixing, crushing of air bubbles. In the diffuser 14 of the ejector, kinetic energy of the mixed flow is converted into potential energy of pressure. The pressure at the diffuser outlet can be monitored by manometer 15. The resulting finely dispersed gas-liquid mixture flows through the open gate 17 into the receiving unit 20 of the production column model 22. The production column model consists of 130 mm inner diameter tubing and a transparent polished organic glass insert for visual observation. The shaft end seal assembly 20 isolates the bottom of the production string model and is the base of the entire structure. The gas separator 25 to be tested is mounted on it in arrangement with a centrifugal pump 26. Pressure at the inlet level of the tested gas separator 25 is measured by manometer 19. During the experiment, its absolute value is maintained at 0.2 MPa by adjusting the position of the gate valve 31 on the gas outlet line 39 of the annular space of the model production string 22. The gas-liquid mixture is injected by pump 26 into discharge line 43. The pressure in the outlet line is measured by a pressure gauge 41. By means of gate valve 42 it is possible to set the operating mode of the pump with the gas separator. After gate valve 42, the gas-liquid mixture flows through the open gate valve 44 into the shelf gravity separator 45, where air is separated from the liquid by separating the gas in a thin layer of the mixture. Then the liquid flows back into Tank 1.

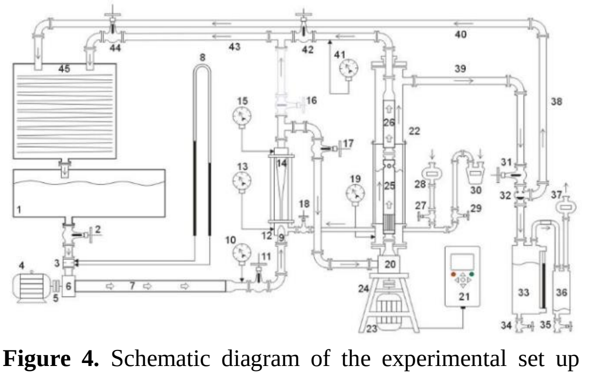

Figure 4. Schematic diagram of the experimental set up bench of centrifugal gas separators

The air separated by the gas separator together with the excessive amount of liquid taken away by the power stage of the gas separator is discharged into the annular space between the gas separator 25 and the model of the production column 22. The air and a portion of the liquid entrained by it are discharged into the shelf gravity separator 45 along the gas outlet line 39 through the regulating gate valve 31 and the three-way valve 32 along the line 38. There, air is separated from the liquid by separating the gas in a thin layer of the mixture. The liquid then drains into Tank 1. To measure the air and liquid discharged by the gas separator, a three-way valve 32 is used, which is switched at the moment of steady-state operation of the tested arrangement: "pump-gas separator". Liquid and air get into Tank 33, where they are separated. Air through the air line, through the buffer Tank 36 passes to the gas meter 37, where its volume is measured. Through the measuring glass of Tank 33, the volume of the discharged liquid can be determined. The measurement time at steady-state is recorded with an electronic stopwatch. Tank 36 prevents the liquid from entering the meter 37. Taps 34 and 35 are used to empty Tanks 33 and 36, respectively. Gate valve 16 is used at start-up to safely bring the experimental bench to the steady-state test mode. During the experiments the gate valve 16 is closed. The angular speed of the shaft rotation of the investigated centrifugal gas separator is changed by means of frequency converter 21.

As a model fluid in the experiments are used: 1) fine gas-liquid mixture "water-surfactant-air" (Disolvan 4411, concentration 0.05%), prepared with the help of ejector 14, is used for modeling of gas-oil mixture with water cut less than 50% (in some cases 60 - 70%) [15]; 2) viscous gas-liquid mixture "oil - air" (I-50A oil GOST 20799-88), is used for modeling the operation of submersible pumping equipment on viscous oils with breakthrough free gas. For the model mixture additional studies on a rotary viscometer (Rheotest RN 5.1) were carried out to determine the change in structural viscosity of I-50A oil at different shear gradients and temperatures. The results of research are presented in Figure 5. The scheme of the experimental bench is designed taking into account the circulation of the working fluid, with preliminary separation of residual gas. In the circulating scheme, the model mixtures will be heated due to the transfer of part of the electrical energy of the operating electric motors into thermal energy. To exclude the risk of working mixtures destruction, a flow-type heat exchanger was installed in the working fluid tank. In order to maintain a constant operating mode of the stand in the permissible range of viscosity change 150 - 200 mPa*s, we determined the permissible temperature range of the working fluid (oil I50A) 25 - 30 °C according to the graphs in Figure 5. Experimentally determined that the average time of the experiment on one mode should not exceed 20 minutes, during this time the temperature of the fluid reaches the value of 30 °C. When the critical temperature is reached, the stand is stopped for cooling of the working fluid with the cooling circuit switched on. The process of cooling the working fluid lasts on average 30 minutes.

The methodology of experimental data processing includes the following indicators:

1. Gas content at the gas separator inlet is the ratio of gas volume flow rate to the volume flow rate of the gas-liquid mixture entering the gas separator inlet (33):

$$\beta_{in} = \frac{Q_{g.in}}{Q_{g.in}+Q_{l.in}} \quad (22)$$

where $Q_{g.in}$ – is the volume flow rate of gas, reduced to receiving conditions (at the inlet to the gas separator), m^3/day; $Q_{l.in}$ – liquid volume flow rate, reduced to receiving conditions (at the inlet to the gas separator), m^3/day.

2. Residual gas content of the gas-liquid mixture flow from the gas separator to the submersible pump inlet. It is the ratio of the volumetric flow rate of the gas that has gone into the pump to the volumetric flow rate of the gas-liquid mixture that has gone into the pump (34, 35):

$$\beta_{rem} = \frac{Q_{g.rem}}{Q_{g.rem}+Q_{l.rem}} \quad (23)$$

where $Q_{g.rem}$ – volume flow rate of gas, reduced to the pressure at the pump inlet, gone to the pump, m^3/day; $Q_{l.rem}$ – volume flow rate of liquid gone to the pump, m^3/day.

3. Separation coefficient of the gas separator characterizes the ratio of the volume flow rate separated by the gas separator to the total volume flow rate of gas at the gas separator inlet:

$$K_s = \frac{Q_{g.in}-Q_{g.rem}}{Q_{g.in}} \quad (24)$$

The separation factor and residual gas content are correlated:

$$Q_{g.rem} = Q_{g.in}(1-K_s) \quad (25)$$

$$K_s = 1 - \frac{Q_{l.rem}\cdot\beta_{rem}\cdot(1-\beta_{in})}{Q_{l.in}\cdot\beta_{in}\cdot(1-\beta_{rem})} \quad (26)$$

4. The pressure developed by the pump-gas separator arrangement is calculated as the pressure difference between the gas separator inlet and the pump outlet:

$$P_{(p-g)} = P_{out.p} - P_{in.g} \quad (27)$$

where $P_{out.p}$ – pump outlet pressure, MPa; $P_{in.g}$ – pressure at the gas separator inlet, MPa.

5. Power consumption of the assembly N_{cons} (kW). It is measured by determining the load on the shaft of the driving motor.

6. Motor shaft angular speed n (rpm); motor current frequency f (1/s).

7. Assembly efficiency η (%). The ratio of useful work done by the assembly: "pump - gas separator" to the work done by the electric motor, taking into account friction losses in intermediate elements of the assembly (receiving module, bearings, local resistances, etc.) (36-38):

$$\eta = \frac{N}{N_{cons}} = \frac{N_l+N_g}{N_{cons}} = \frac{Q_l\cdot P_{(p-g)}\cdot 10^{-3}+Q_{g.in}\cdot P_{in.g}\cdot ln\frac{P_{out}}{P_{in.g}}\cdot 10^{-3}}{N_{cons}} \quad (28)$$

At the second stage of tests the characteristics of the investigated gas separators were studied on the model mixture "water-PAP-air" at low rotational speeds of the gas separators shaft (252 - 1000 rpm (4.2 - 16.7 Hz)).

At the first stage of research we studied the characteristics of the investigated gas separators on the model mixture "water-PAP-air" in the operating range of gas separators shaft rotation speed (2400 - 4200 rpm (40 - 50 Hz)). The purpose of research at the first stage is to determine the efficiency of gas separation, provided that 25% of free gas in the gas-liquid mixture arrives at the reception of the electric centrifugal pump. Figure 6 shows characteristic curves of gas separators of group 5

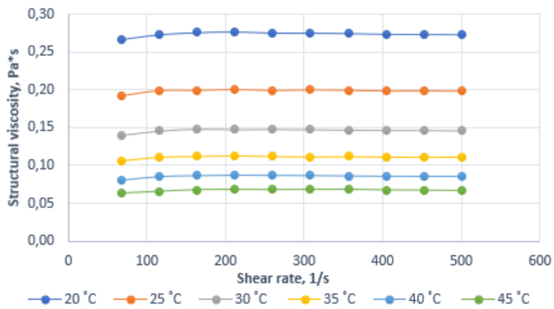

Figure 5. Rheological characteristics of dispersion medium (Oil - I 50A)

(Figure 6a) and group 5A (Figure 6b). Characteristic curves of gas separators are grouped by parameters: b_{max} and K_c depending on the feed, and an important circumstance is the absence of influence of angular speed of gas separators shaft rotation on their separation efficiency on low-viscosity liquid hydrocarbons.

This circumstance allows us to formulate a hypothesis that the investigated gas separators have a potential of operation at low angular velocities.

At the second stage of tests the characteristics of the investigated gas separators were studied on the model mixture "water-PAP-air" with low angular speeds of gas separators shaft rotation (252 - 1000 rpm (4.2 - 16.7 Hz)).

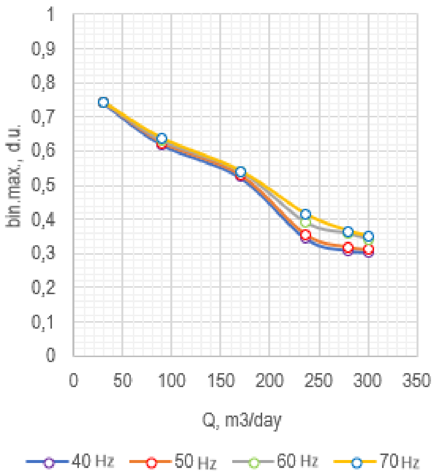

Figure 6a. Characteristic curves (permissible gas content at the intake with residual gas content - 25%) of gas separators: group 5, with nominal feed of 250 m^3/day [40 - 70 Hz, low-viscosity LPG]

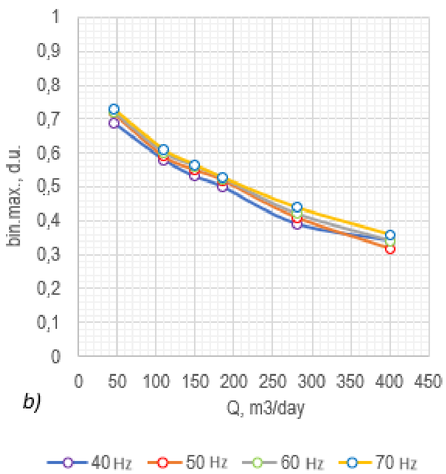

Figure 6b. Characteristic curves (permissible gas content at the intake with residual gas content - 25%) of gas separators: and group 5A, with nominal feed of 500 m^3/day [40 - 70 Hz, low-viscosity LPG]

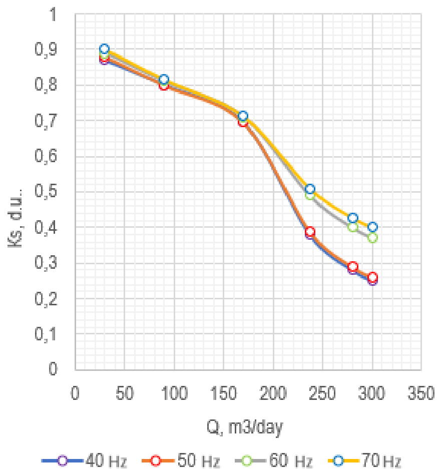

Figure 7a. Characteristic curves (maximum separation factor at residual gas content - 25%) of gas separators: group 5, with nominal feed of 250 m^3/day [40 - 70 Hz, low-viscosity LPG]

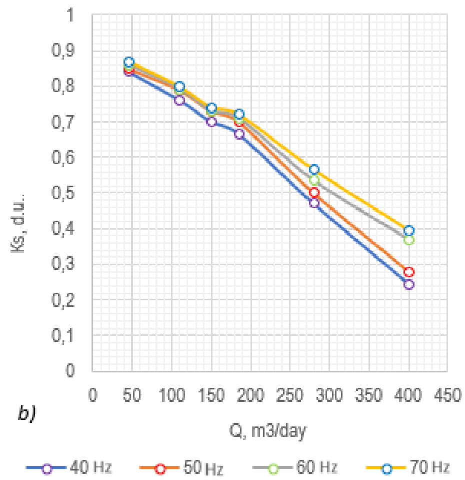

Figure 7b. Characteristic curves (maximum separation factor at residual gas content - 25%) of gas separators: group 5A, with nominal feed of 500 m3/day [40 - 70 Hz, low-viscosity LPG]

The analysis of the obtained results of gas separators research at reduced angular speeds showed that the gas separator of group 5 is not able to operate on low-viscosity model mixture at angular speeds below 500 rpm (8.3 Hz), while the gas separator of group 5A operates in a wide research range of angular speeds (Figures 8 and 9). It should be noted that the gas separators of groups 5 and 5A on low-viscosity model DST confirmed their performance, but with a significant decrease in efficiency parameters compared to the parameters of operation of gas separators with angular speed of 3000 r/min, in particular, the gas separator of group 5 with angular speed of 1000 r/min (16 Hz) works worse compared to the mode of rotation of 3000 r/min (50 Hz), on average, the separation efficiency is reduced by 30%. Further reduction of angular speed of rotation of the gas separator shaft of group 5 leads to the fact that at the value of angular speed of 252 r/min (4.2 Hz) separation efficiency decreases to zero, the entire flow of gas-liquid mixture moves into the pump, there is a failure of feeding of the arrangement: "pump-gas separator". A similar picture is observed for the gas separator of group 5A, except for the feed stall process at ultra-low speed (252 rpm (4.2 Hz)). - no stall occurs.

At the third stage of research we carried out a comparative analysis of the efficiency of operation of the investigated gas separators at low shaft rotation speed on viscous gas-liquid mixture (Figure 10). As a result of bench tests it was possible to determine that for the residual gas content of 50%, in relation to the

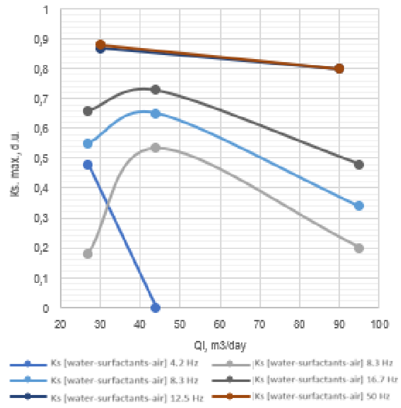

Figure 9a. Characteristic curves (maximum separation factor at residual gas content - 25%) of gas separators: group 5, with nominal feed of 250 m^3/day [4.2 - 16 Hz, low-viscosity LPG]

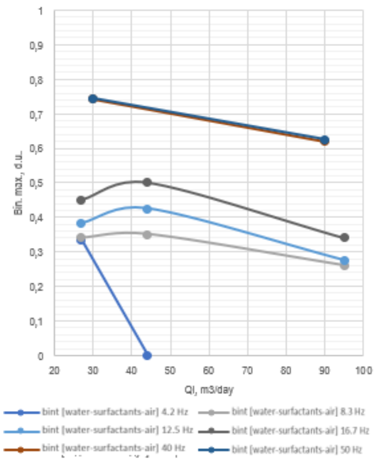

Figure 8a. Characteristic curves (permissible gas content at the intake with residual gas content - 25%) of gas separators: group 5, with nominal feed of 250 m^3/day [4.2 - 16 Hz, low-viscosity LPG]

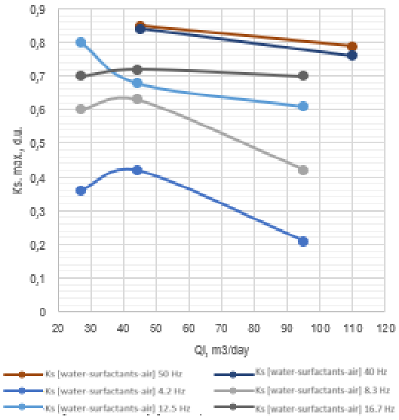

Figure 9b. Characteristic curves (maximum separation factor at residual gas content - 25%) of gas separators: group 5A, with nominal feed of 500 m^3/day [4.2 - 16 Hz, low-viscosity LPG]

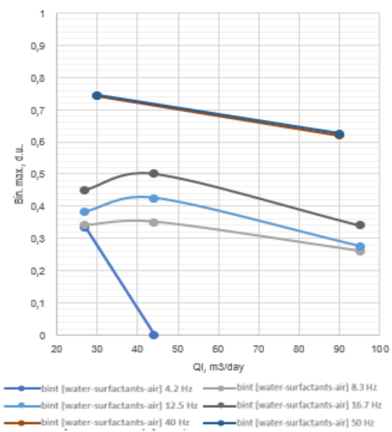

Figure 8b. Characteristic curves (permissible gas content at the intake with residual gas content - 25%) of gas separators: group 5A, with nominal feed of 500 m^3/day [4.2 - 16 Hz, low-viscosity LPG]

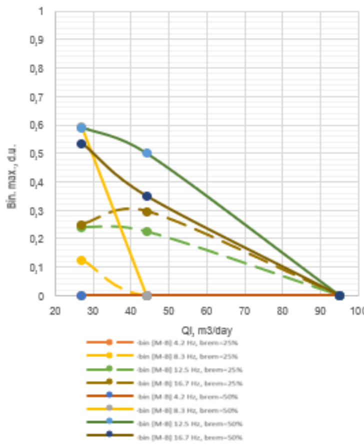

Figure 10a. Characteristic curves (permissible gas content at the intake at residual gas content - 25% and 50%) of gas separators: group 5, Ql.nom= 250 m^3/day [4.2 - 16 Hz, highly viscous LPG]

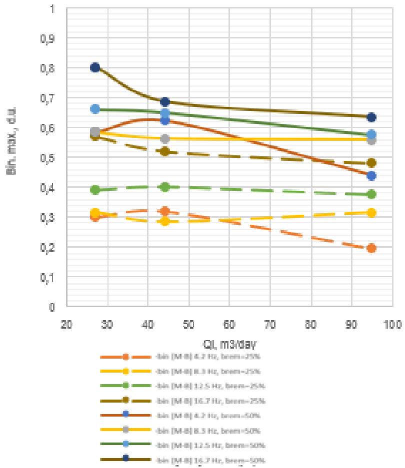

Figure 10b. Characteristic curves (permissible gas content at the intake at residual gas content - 25% and 50%) of gas separators: group 5A, Ql.nom= 500 m^3/day [4.2 - 16 Hz, highly viscous LPG]

requirement of permissible gas content at the screw pump inlet, the gas separator of group 5A works effectively in the range of angular speeds 252 - 1000 rpm (4.2 - 16.7 Hz), with the loss of efficiency in case of transition from the increased frequency of 16.7 Hz to the reduced frequency of 4.2 Hz on average by 16%.

The gas separator of group 5 showed unsatisfactory results of research and can be recommended for operation in combination with screw pumps in a limited mode: at low flow rates (up to 45 m^3/day), at angular speed of rotation exceeding 750 rpm (12.5 Hz), at values of gas content at the gas separator inlet exceeding 50%.

5. CONCLUSIONS

1) The aim of the research has been achieved - the characteristics of gas separators of group 5 and 5A on model gas-liquid mixtures of different viscosity have been experimentally obtained in relation to the conditions of well operation by screw pumps.
2) A comparative analysis of the characteristics of separation efficiency of gas separators at changing the angular speed of rotation of the motor shaft has been carried out.
3) Analysis of literature sources on the direction of research of screw pumps characteristics when operating on viscous gas-liquid mixtures indicates the lack of qualitative results.
4) On the basis of generalization of published materials of research of screw pumps operation on low-viscosity gas-liquid mixtures the potential of possible increase of efficiency of their operation at gas content over 50% at reception is determined. The efficiency potential is on the average - 20%. Achievement of the calculated efficiency potential can be ensured by using a downhole centrifugal type gas separator.
5) Methodology of bench testing of gas separators has been developed, taking into account the influence of gas-liquid mixture properties, change of angular speed of motor shaft rotation, parameters of natural separation; separation coefficients and efficiency coefficients of gas separators 5 and 5A have been experimentally determined on two model gas-liquid mixtures: low-viscosity (1 cPz) and high-viscosity (150 ÷ 200 cPz) in the interval of angular rotation speed values: 200 - 3000 rpm, for conditions of operation of marginal wells in the interval of pump delivery values on liquid: 25 - 100 m^3/day; at maintenance of constant values of pressure and temperature at the gas separator inlet.
6) Experimentally determined parameters of operation of gas separator of group 5A, taking into account residual gas content of 50%, in the range of angular speeds 252 - 1000 rpm (4.2 - 16.7 Hz). In case of transition from increased (16.7 Hz) to decreased frequency (4.2 Hz), a decrease in separation efficiency by 16 % on average was recorded.
7) The gas separator of group 5 showed unsatisfactory results of research and can be recommended for operation in combination with screw pumps in a limited mode: at low flow rates (up to 45 m^3/day), at angular speed of rotation exceeding 750 rpm (12.5 Hz), at values of gas content at the gas separator inlet exceeding 50%.
8) Gas separator of group 5 showed unsatisfactory results of operation on model viscous gas-liquid mixture and can be recommended for additional research of characteristics of gas separator of group 5 in arrangement with screw pump in limited mode: at low flow rates (up to 45 m^3/day), in a wide range of rotor speed 252 - 1000 rpm (4,2 - 16,7 Hz).

The purpose of the work is to substantiate the effectiveness of measures to reduce the impact of a high value of the gas factor during the operation of production wells. In the course of the study, the main complicating factors in oil production were considered, an analysis of modern technologies to combat the negative effect of free gas on Screw Pump installations was carried out, and equipment was selected for operating a well with a high gas-oil ratio (GOR).

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Persian Abstract

چکیده

این مقاله استفاده از یک جداکننده گاز از نوع گریز از مرکز را به عنوان بخشی از یک واحد پمپاژ الکتریکی پیچی شناور مورد بررسی قرار می‌دهد که تعدادی از آزمایش های رومیزی برای مطالعه یک جداکننده گاز گریز از مرکز با استفاده از یک مخلوط چسبناک گاز و مایع انجام شده .وابستگی جریان به فشار توسعه یافته یک پمپ تک پیچ با سرعت زاویه ای چرخش روتور سیم پیچی شده 225 دور در دقیقه برای محتویات مختلف گاز محاسبه شد .منحنی های مشخصه جداکننده های گاز گروه های 5 و ۵آ نیز در محتویات مختلف گاز و ویسکوزیته های مختلف مخلوط گاز و مایع به دست آمدند .روشی برای آزمایش رومیزی جداکننده های گاز با در نظر گرفتن تأثیر خواص مخلوط گاز و مایع، تغییرات در سرعت زاویه ای چرخش محور موتور الکتریکی و پارامترهای جداسازی طبیعی ایجاد شده است.