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Investigation of Gas Natural Separation Process Unsteady Features by Means of an Experimental Rig and Mathematical Modeling

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Abstract. Natural gas separation is an important process in wells equipped with electric submersible pumps (ESP) that affects the efficiency of the "wellbore-pump-tubing" system. Nowadays, the amount of knowledge about this process requires critical analysis and further improvement. The paper presents the results of studying the unsteady features of the process of separation of gas bubbles into the annular space in the near-intake domain of the well model with conditionally radial inlet. The results of the experimental bench tests, as well as the results of numerical simulation in dynamic multiphase flow simulator are analyzed. The experiments were carried out on a test rig with the inner diameter of the casing model 80 mm and the outer diameter of the intake module 64 mm, taking into account the possibility of measuring liquid and gas flow rates, as well as high-speed video recording of the processes occurring in the near-intake domain of the well model. Unsteady features of gas-liquid mixtures flow with the help of video frames in the near-intake domain for model mixtures "Water-Air" and "Water-Surfactant-Air" are shown. It is revealed that at small time intervals (<1 s) the regimes with slug-churn flow patterns are characterized by significant nonstationarity. The results of numerical simulation indicate that such unsteady behavior can lead to oscillatory operation of the well and ESP.

On the basis of critical analysis of the obtained research results the following promising directions are formulated: a study of theoretical basis of separation in the near-intake domain of a well; field and bench experiments; a numerical modeling of natural gas separation into the annular space of a well equipped with ESP.

Keywords: natural separation of gas, electric submersible pump, oil well, experimental research, multiphase flow, gas-liquid mixture, multiphase flow regime, transient process

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Introduction

A design of optimal operation modes for wells equipped with ESP systems and resolution of energy consumption issues in contemporary oil and gas operations are at present a current trend in the development of artificial oil production in both Russian oilfields and numerous oil and gas facilities worldwide. A number of scientific and research works, as well as field practice show the need to improve the methods of engineering calculations in the area of artificial lift operation of production wells, including the methods for determining the efficiency of gas separation in the near-intake domain of the submersible pumping equipment (natural separation and total gas separation, including the operation of the gas separator) (Ivanov et al., 2024a; Pashali, Zeygman, 2022).

This paper aims to study and describe the unsteady features of the natural gas separation (NGS) process based on bench studies and numerical modelling.

The tasks set out in this paper are:

- The review of Russian and world scientific publications concerning the processes of natural gas separation at submersible equipment intake with a conditional-radial intake is essential for the systematization of fundamental knowledge about this physical phenomenon.
- It is vital to identify any gaps of knowledge that exist regarding the natural gas separation process at ESP intake.

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This will allow us to clarify the existing theoretical concepts and formulate recommendations for experimental, field and theoretical studies.

• The description of non-stationarity of the natural gas separation process based on the visualization through the high-speed video recording and verification of the obtained empirical representations by the modelling of this process under steady-state operating modes of well and ESP in a dynamic multiphase flow simulator.

Overall summary of the knowledge of the process of natural gas separation at the ESP intake

The natural gas separation efficiency (NGSE) in wells equipped with ESPs depends on many factors: geometrical characteristics of a well and near-intake space; location of intake device relative to a perforation interval; physical and chemical properties of produced fluids (PVT properties); technological parameters of a well operation; gas-liquid mixture (GLM) flow structure; pump operation mode and other parameters (Ivanov et al., 2024a). The natural gas separation efficiency K_{ns} can be determined using equation (1):

$$K_{ns} = NGSE = \frac{q_g^{an}(P_{\text{int}}, T_{\text{int}})}{q_g^{total}(P_{\text{int}}, T_{\text{int}})}, \quad (1)$$

where $q_g^{an}(P_{\text{int}}, T_{\text{int}})$ is a volume flowrate of free gas entering a well annulus as a result of the natural separation under thermobaric conditions of ESP intake, m^3/day (cubic meters per day); $q_g^{total}(P_{\text{int}}, T_{\text{int}})$ is a total volume flowrate of free gas at ESP intake (before separation) under thermobaric conditions of ESP intake, m^3/day; P_{int} is ESP intake pressure, MPa; T_{int} is ESP intake temperature, ^{o}C.

The conducted analysis of published studies enabled the systematization of knowledge regarding the process of natural gas separation at submersible equipment intake with a conditionally radial intake. The knowledge was then classified according to the types of studies, i.e. field studies, lab bench experiments and computational fluid dynamic modelling (3D CFD). Furthermore, the distinctive features presented in Table 1 were identified for each study.

Table 1 shows the reviewed scientific studies cover a wide area of knowledge about the process of natural gas separation in the near-intake domain of production ESP well, which were summarized in the form of infographics in Fig. 1. The ranges and values of the investigated parameters that effect on the efficiency of natural gas separation are as follows.

1. The values for the diameters of production casings, tubings and ESP are specific to each case study and are not generalizable, i.e. the authors do not usually investigate the effect of annular space area in a single study.

2. The effect of a well inclination angle was investigated over a wide range of values (5^{o}, 15^{o}, 30^{o}, 45^{o}, 60^{o}, 90^{o}).

3. Technological parameters of well operation were studied in wide ranges:

- water cut (0÷100%);
- pump intake pressure (up to 8 MPa);
- liquid flowrate (up to 477 m^3/day);
- free gas volume fraction in the flow before the separation of gas (or free gas content in the flow before the separation of gas) β_g – equation (2). Herewith, the maximum value of free gas content is bounded by 70.9% (mentioned explicitly), which indicates that it is possible to study regimes at β_g > 70.9%.

$$\beta_g = \frac{q_g(P,T)}{q_g(P,T) + q_l(P,T)}, \quad (2)$$

where $q_g(P,T)$ – free gas volume flowrate at pressure P and temperature T, m^3/day; $q_l(P,T)$ – liquid flowrate at pressure P and temperature T, m^3/day.

4. Physical-chemical properties of fluids have been researched quite widely:

- liquid viscosity has been investigated over a large range of values (1÷100 mPa·s) (Lackner, 1994; Okafor et al., 2021, 2024);
- the influence of liquid density (870 and 1000 kg/m^3) was investigated (Okafor et al., 2021, 2024), whereas in field studies liquid density takes different values;
- the studies were carried out at different values of surface tension at the "liquid-gas" interface (0.032, 0.042, 0.067, 0.072 N/m) (Okafor et al., 2021, 2024; Ivanov et al., 2024a).

However the influence of various parameters on the natural gas separation efficiency remains insufficiently studied: the shape and size of the intake port holes (Okafor et al., 2021, 2024) and hydraulic characteristics of the intake filter (Urazakov et al., 2021); the annular area and outer diameters of the tubing and ESP (Okafor et al, 2021, 2024; Ivanov et al., 2024a); the presence of solid particles in the multiphase flow (Nikonov et al., 2024); gas-liquid flow structure; periodic mode of well operation with ESP; non-standard ESP designs (e.g., with housing and liner) and abnormal operation modes (e.g., flowing through the annulus (Goridko, 2023)).

In order to further development of the knowledge of the natural gas separation process at ESP intake, it is necessary:

1. The execution of new experiments in the previously undiscovered ranges of fluid properties, technological and geometrical parameters.

2. The accumulation of experimental data of the influence of gas-liquid flow structures on K_{ns} is also to be undertaken.

3. The investigation and description of non-stationarity of the natural separation process of different time scales will also be a key focus.

a. Influence of periodic ESP operation modes on the K_{ns} value;

b. Impact of non-stationary phenomena of gas phase movement, dispergation, coalescence on the K_{ns} value, existing both at steady-state and periodic operating modes of ESP wells.

4. Study the influence of the solid particles suspended in multiphase flow on the efficiency of natural gas separation (Nikonov et al., 2024).

5. Improvement and tuning of various theoretical models of K_{ns} calculation by adaptation and validation on experimental and field data.

1	– Field experiments
2	– Lab experiments
3	– 3D modelling – Computational Fluid Dynamics (CFD)
E	– Empirical correlation for the calculation of K_{ns}
M	– Mechanistic correlation for the calculation of K_{ns}

Reference	Type	Description
(Mischenko, Gurevich, 1969)	1	1. Analytical algorithms are presented for the processing of well field studies aimed at the measurement of gas flowrates through the tubing and annulus. 2. Based on the results of the field information processing, the dependencies of the natural separation efficiency K_{ns} on the liquid flowrate q_l and the ESP and well geometric characteristics were obtained (f_{ESP} – pump/intake cross-sectional area; f_{CASING} – total cross-sectional area of the casing). 3. Field test parameters ranges: • Water Cut n_{WC} = **(17–90)%**; • Pump Intake Pressure P_{int} = (**0.8–7.2**) **MPa**; • Liquid Flowrate q_l = (**110–352**) **m^3/day**; • Casing OD **168 mm**; • Tubing OD **51 и 63 mm**. 4. Conclusion: K_{ns} decreases as the liquid flowrate increases and the f_{ESP} / f_{CASING} ratio decreases.
(Mischenko, Gurevich, 1970)	E	Based on the field data, an analytical model was developed to calculate the K_{ns}. The model takes into account the technological parameters of well operation and its geometric characteristics: • q_l – Liquid Flowrate; • q_g – Free Gas Flowrate at Pump Intake Conditions; • υ_r – vertical relative velocity of gas in the casing at pump intake conditions; • $F_{CASIGNG}$ – Total Cross-Sectional Area of the Casing; • F_{INTAKE} – Pump Intake Area
(Lyapkov, Gurevich, 1973)	1 E	1. Wells in the Romashkinskoye, Arlanskoye, Shkapovskoye and Tuimazinskoye fields were surveyed. 2. The analytical dependence for calculating K_{ns} based on field studies is presented. 3. Conclusion: υ_r and K_{ns} depend on the water cut and foaming properties of the fluid.
(Ghauri, 1980)	1	1. Field comparison of separation efficiencies for wells with different values of internal casing diameter (D_{CASING} = **139.7 и 177.8 mm**). 2. It has been experimentally determined that D_{CASING} = 177.8 mm is characterized by a higher separation efficiency as well as a lower failure rate of the downhole pumping equipment (DPE) compared to D_{CASING} = 139.7 mm.
(Lea, Bearden, 1982)	2	1. The experimental data were obtained during the bench tests of the model Water-Air mixture in the vertical model of the plexiglass pipe with the internal diameter D_{CASING} = **177.8 mm** and the diameter of the ESP housing D_{ESP} = **130 mm**. According to the results of experimental data processing, the dependence of K_{ns} on technological parameters was determined in the following value ranges: • Pump Intake Pressure (**0.17–0.2 MPa**); • Liquid Flowrate (**55–340**) **m^3/day**; • Free Gas by Volume at Pump Intake β_g = **0–17%**. 2. As the liquid flowrate increases at the intake conditions, a decrease K_{ns} is observed, and as the free gas flowrate increases at the intake conditions, an increase K_{ns} is observed.
(Lyapkov, 1987)	E	A simplified analytical correlation is presented for the calculation of K_{ns}, depending on the: • Superficial Fluid Velocity at Intake Conditions $\overline{\upsilon}$; • Free Gas by Volume at Pump Intake β_g; • Gas Drift Velocity at Pump Intake Conditions υ_{GD}. υ_{GD} depend on water cut n_{WC} (for n_{WC} ≤50% υ_{GD} = 0.02 m/s; for n_{WC} >50% υ_{GD} = 0.17 m/s).

Table 1. Generalization of studies of the natural gas separation process in wells equipped with ESPs according to different researchers' data

(Alhanati, 1993)	2 E	1. The results of bench tests carried out on a vertical laboratory unit on a model Water-Air mixture with constant parameters: casing diameter D_{CASING} = **177.8 mm**, ESP outer diameter D_{ESP} = **102 mm**, fluid properties, are presented. Slug-churn flow regime was taken into account. 2. According to the results of experimental data processing, the dependence of K_{ns} on technological parameters was determined in the following value ranges: • Liquid Flowrate (**98–153**) **m^3/day**; • Pressure (**0.74–1.59**) **MPa**; • Temperature (**34–39**) **^{o}C**; • GLR (**17.8–35.6**) **std.m^3/std.m^3**, • Free Gas by Volume β_g = **61–70%** 3. K_{ns} decreases with increasing liquid flowrate at intake conditions, increasing pressure, and decreasing GLR (results consistent with Lea, Bearden, 1982). 4. A simplified analytical formula for calculating K_{ns} based on the Drift Flux model is presented. The formula depends on the superficial fluid velocity at intake conditions and the terminal vertical gas velocity υ_∞. Assumption: no gas slippage in the radial direction near the pump intake. 5. The presented formula needs to be improved in terms of the influence of pressure on the efficiency of natural separation.
(Sambangi, 1994)	2	1. The results of bench tests carried out on a vertical laboratory unit on a model WaterAir mixture are presented. 2. According to the results of experimental data processing, the dependence of K_{ns} on technological parameters was determined in the following value ranges: • Liquid Flowrate q_l = (**95.4–477**) **m^3/day**; • Pressure (**0.68–2.04**) **MPa**; • GLR (**8.9–53.4**) **std.m^3/std.m^3**
(Lackner, 1997)	2	1. The results of bench tests carried out on a vertical laboratory unit on a model Mineral Oil-Air mixture are presented. Liquid viscosity range μ_l = (**1–50**) **mPa*s** at **37.8 ^{o}C**. 2. According to the results of experimental data processing, the dependence of K_{ns} on technological parameters was determined in the following value ranges: • Liquid Flowrate q_l = (**95.4–429**) **m^3/day**; • Pressure (**0.68–2.04**) **MPa**; • GLR (**8.9–53.4**) **std.m^3/std.m^3**. 3. The use of hydrocarbon liquid (mineral oil) leads to a decrease in the terminal vertical gas velocity υ_∞ used in the Alhanati analytical formula. These results in a slight decrease K_{ns} for the hydrocarbon fluid compared to the model Water-Air mixture.
(Serrano, 1999)	2 E	1. The results of bench tests carried out on a vertical laboratory unit on a model Water-Air mixture with different angles of inclination of the well model relative to the horizon (vertical position (**90^o**), inclined position (**30^o, 60^o**)) are presented. Constant parameters: casing inner diameter D_{CASING} = **127 mm**, ESP housing diameter D_{ESP} = **95 mm**, fluid properties. 2. The influence of the flow structure on the efficiency of natural separation was studied (bubble flow modes were considered). 3. According to the results of experimental data processing, the dependence of K_{ns} on technological parameters was determined in the following value ranges: • Liquid Flowrate q_l = (**159–318**) **m^3/day**; • Pressure (**0.34–1.02**) **MPa**; • Free Gas by Volume β_g **<20%.** 4. K_{ns} decreases as both liquid and gas flowrates increase. A change in pressure has a negligible effect on K_{ns}. 5. A modified Alhanati formula is presented for estimating the fraction of free gas in the flow at the pump intake up to 20%. Assumption: no gas slip in radial direction near the pump intake.
(Harun et al., 2000, 2001)	M	1. A simplified model for calculating K_{ns} in vertical wells is presented, taking into account experimental data from Alhanati, Sambangi and Serrano. The model takes into account phase slippage near the intake for different flow structures (bubble and churn). The need for additional experiments to tune the model at low (<159 m^3/day) and high (>477 m^3/day) liquid flowrates and for different well geometry was noted. 2. A mechanistic model for calculating K_{ns} in deviated wells is presented with considering Serrano experimental data. The model takes into account phase slippage near the intake for different flow structures (bubble, slug and churn). The need for additional experiments to tune the model at well inclination angles different from the Serrano experiments and for free gas fraction >20% was noted.

Table 1. Generalization of studies of the natural gas separation process in wells equipped with ESPs according to different researchers' data

(Lissuk, 2001)	1 E	1. An analytical formula for the calculation of K_{ns} based on field studies in wells of the Vatinskoye, Tuimazinskoye and Yarino-Kamennolozhskoye fields is presented. The formula depends on the superficial fluid velocity at intake conditions $\overline{\upsilon}$ and the vertical relative velocity of gas in the casing at pump intake conditions υ_r. 2. Field test parameters ranges: • Water Cut n_{WC} = **(40–90) %**; • Pump Intake Pressure P_{int} = **(3.8–7.0) MPa**; • Liquid Flowrate q_l = **(24–352) m^3/day**; • Casing OD **168 mm**. 3. A decrease K_{ns} is observed as the liquid flowrate increases at the intake conditions and an increase K_{ns} is observed as the relative gas velocity increases at the intake conditions. 4. K_{ns} is independent of the type of intake to the DPE of the gas-liquid mixture (conditional-axial or conditional-radial intake). 5. K_{ns} depends on the foaming properties of the liquid and the structure of the GLM flow.
(Liu, Prado, 2001)	M	1. A mechanistic model for calculating K_{ns} that accounts for experimental data from Tulsa University Artificial Lift Projects (TUALP). The model is based on the calculation of the trajectories of gas bubbles in the vicinity of the intake, taking into account the trajectory of liquid motion and the balance of forces acting on the gas bubble in a two-dimensional coordinate system. The model accounts for phase slip in the vicinity of the intake. 2. The need to develop an equation for estimating gas bubble sizes for tuning the K_{ns} calculation model is noted.
(Mischenko, 2003)	E	1. Generalized analytical formula for calculating K_{ns} based on studies by various authors (at Tuimazinskoye, Arlanskoye, Shkapovskoye, Romashkinskoye fields). The formula depends on the superficial liquid velocity at intake conditions $\overline{\upsilon}$ and the vertical relative velocity of gas in the casing at pump intake conditions υ_r. 2. Field test parameters ranges: • Water Cut n_{WC} = **(0–96) %**; • Pump Intake Pressure P_{int} = **(0.8–7.95) MPa**; • Liquid Flowrate q_l = **(3.96–321) m^3/day**; • Casing OD **146** and **168 mm**.
(Marquez, Prado, 2003; Marquez, 2004)	M	1. A simplified model for calculating K_{ns} is presented, taking into account experimental data from TUALP. The model takes into account the liquid trajectories and phase slippage in vertical and radial directions in the vicinity of the intake. 2. A mechanistic model for calculating K_{ns} that accounts for experimental data from TUALP. The model is based on the calculation of the trajectories of gas bubbles in the vicinity of the intake, taking into account the trajectory of liquid motion and the balance of forces acting on the gas bubble in a two-dimensional coordinate system. The model accounts for phase slip in vertical and radial directions in the vicinity of the intake. 3. An experimental equation (based on TUALP data) for estimating gas bubble size (Interface Characteristic Length) is proposed for use in calculating gas bubble trajectories in mechanistic correlation K_{ns}. 4. The necessity of new experiments for tuning the presented models is noted (for small gas and liquid flowrates, as well as for different liquid viscosity). 5. The necessary to modify the mechanistic model of K_{ns} calculation to take into account: the location of the intake module (above/below the perforation); the presence of a separator; different angles of well inclination; eccentric location of the ESP intake module in the well.
(Elichev et al., 2009)	1	1. Field studies were conducted to evaluate the applicability of the mechanistic model of the K_{ns} Marquez R. calculation on real wells of several fields of RN-Purneftegaz LLC in Western Siberia. 2. The mechanistic model of Marquez R. describes well the field data obtained.
(Shakirov, 2011)	1 E	1. Analytical correlation for K_{ns} calculation based on Lyapkov-Gurevich model taking into account field studies at 6 Russian oil fields. The formula depends on liquid flowrate q_l and water cut n_{WC}. 2. Field test parameters ranges: • Water Cut n_B = **(0–96) %**; • Pump Intake Pressure P_{int} = **(0.8–8.0) MPa**; • Liquid Flowrate q_l = **(4–320) m^3/day**; • Casing ID **132** and **155 mm**.

Table 1. Generalization of studies of the natural gas separation process in wells equipped with ESPs according to different researchers' data

(Pashali, 2011)	3 M	1. Mechanistic correlation for calculating K_{ns} in wells with ESPs set below the perforation interval based on the mechanistic model of Marquez R. 2. Numerical modelling is used to show the influence of the free gas volume fraction in the flow on the K_{ns} value for ESPs below the perforation.
(Volkov, 2016)	M	Mechanistic correlation for calculating the K_{ns} at well start-up based on Marquez R. mechanistic model (taking into account fluid flows from the formation and casing into ESP intake module).
(Vieir et al., 2021)	2	1. The results of bench-scale experiments performed using a model bench (ESP Skid) on a model Water-Air mixture are presented. High-speed video of different flow regimes (bubble and slug flow structures) through a transparent casing was performed. 2. Experimental parameters ranges: • Inclination angle of the well model (**5°, 15°, 30°, 45°, 60°**); • Superficial Fluid Velocity $\overline{v}$ = (**0.1–1**) **m/s**; • Free Gas by Volume at Pump Intake β_g = (**10–50**) **%**. 3. Alhanati model poorly describes the obtained results due to the fact that the model does not take into account phase slip in the radial direction and is also designed for vertical wells.
(Urazakov et al., 2021)	3	1. Numerical 3D modelling was carried out to study the influence of hydraulic characteristics of the intake module (without filter, with frame-wire filter) on the efficiency of natural separation. 2. When the hydraulic parameter of the filter (**0.24–0.06**) decreases, K_{ns} decreases.
(Ivanov et al., 2024a)	2	1. The paper presents the results of bench experiments carried out at constant mode of ESP operation to evaluate the influence on K_{ns} of the structure of the GLM flow; equivalent diameter of the annular space d_{EQ}; foaming properties of the fluid. 2. Ranges of experimental test parameters: • Liquid Flowrate q_l = (**13.4–68.1**) **m^3/day**; • Free Gas by Volume into Pump β_g = (**11.1–70.9**) **%**. 3. Measurements of gas flowrates and high-speed video imaging in the vicinity of the intake of the well model through a plexiglass casing were carried out on a vertical model stand on the model mixtures Water-Air and Water-Surfactant-Air at fixed parameters: internal diameter of the casing D_{CASING} = **80 mm**, external diameter of the intake screen of the pump D_{ESP} = **64 mm**, overpressure at the intake (**0.04–0.05 MPa**). 4. Empirical dependence corrections for the size estimation (interface characteristic length) of gas bubbles under intake conditions for the K_{ns} calculation by the Marquez R. mechanistic model for bubble and slug-churn structures of the GLM flow are presented.
(Okafor et al., 2021; Okafor, Verdin, 2024)	3	1. Numerical 3D modelling was carried out to study the influence of different parameters on the efficiency of natural separation: • Surface Tension σ (**0.020, 0.032, 0.067 N/m**); • Liquid Density ρ_l (**870 and 1000 kg/m^3**); • Liquid Viscosity μ_l (**1, 10, 100 mPa*s**); • Casing Inner Diameter (**161.5** and **228.6 mm**); • Tubing Outer Diameter (**89** and **140 mm**); • Number of Intake Port Holes (**6, 9, 12 ea.**); • Pressure (**1.59** and **2.93 MPa**). 2. The bench from Alhanati's research was used as a basis. The 3D model was tuned to the experimental parameters of the separation efficiency points K_{ns} from Alhanati's work. Most of the studied regimes were characterized by a churn flow structure. 3. Conclusions: surface tension has a small effect on K_{ns}; a slight decrease K_{ns} is observed with decreasing liquid density; a decrease K_{ns} is observed with increasing viscosity; an increase K_{ns} is observed with increasing casing inner diameter and decreasing tubing outer diameter; total pump intake area affects K_{ns}. 4. The need for additional numerical studies to investigate the process of natural separation at bubble and slug flow structures is noted. It is necessary to modify the existing methods of K_{ns} calculation to take into account the influence of liquid viscosity. It is necessary to study the effect of changing the outer diameter of the tubing and ESP, as well as the geometry of the intake port holes on the K_{ns} using a physical bench.

Table 1. Generalization of studies of the natural gas separation process in wells equipped with ESPs according to different researchers' data

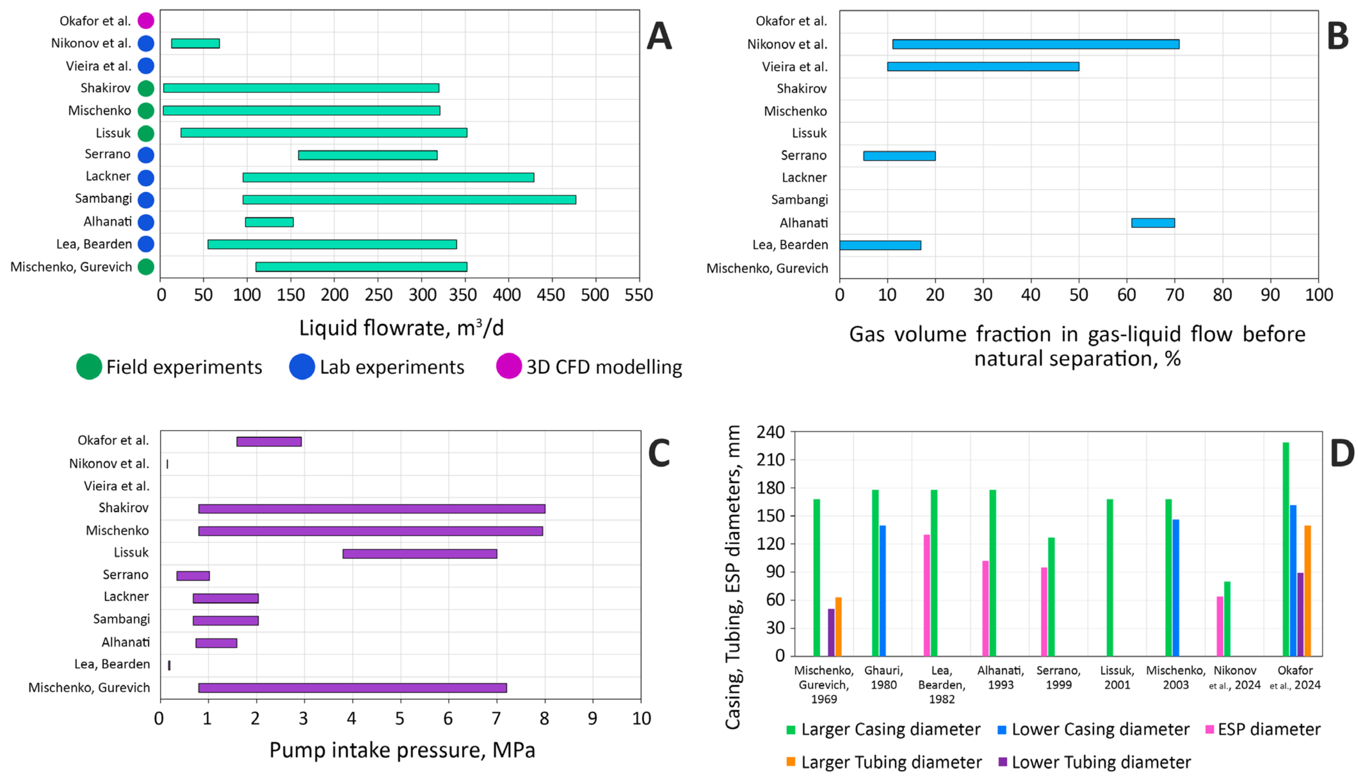

Fig. 1. Infographics of the investigated ranges of parameters that effect on the efficiency of natural separation, according to different authors: a – liquid flowrate; b - free gas content in the flow before separation; c – pressure at the ESP intake; d – diameters of casing, tubing, ESP

In a considerable number of scientific papers, the authors employ K_{ns} calculation models that utilize the parameter of relative gas velocity in the near-intake domain of the annulus space υ_r, which is dependent on a variety of physical parameters:

$$\upsilon_r = \upsilon_g - \upsilon_l = f(q_l, q_g, \rho_l, \rho_g, \mu_l, \sigma, D_{CAS}, d_{ESP}, d_{bub} ...), \quad (3)$$

where υ_g – true gas velocity, m/s; υ_l – true liquid velocity, m/s; q_l – liquid volume flowrate under thermobaric conditions of ESP intake, m³/day; q_g – free gas volume flowrate under thermobaric conditions of ESP intake, m³/day; ρ_l – liquid density, kg/m³; ρ_g – gas density, kg/m³; μ_l – liquid viscosity, mPa·s; σ – surface tension at the "liquid-gas" interface, N/m; D_{CAS} – inner diameter of the production casing, m; d_{ESP} – ESP outer diameter, m; d_{bub} – gas bubble diameter under thermobaric conditions of ESP intake, m.

The analytical models indirectly consider the influence of fluid properties and well geometry on K_{ns} by using υ_r. However, the calculation process is complicated by the dependence of υ_r on the gas bubble diameter. A detailed study of existing empirical relationships for estimating υ_r shows that they need to be adjusted to specific geological and physical conditions. The current approach to estimating K_{ns}, denoted by υ_r, is challenging to apply in engineering calculations and necessitates modernization.

The experimental studies of the natural gas separation efficiency

The paper describes the results of the natural gas separation process investigations conducted at National University of Oil and Gas "Gubkin University" (Department of Oil Field Development and Operation) by means of the experimental setup (Fig. 2), which replicates a constant (steady-state) operating mode of an electric submersible pump with a conditionally radial intake of gas-liquid flow into the intake device. The experiments considered steady-state co-current regimes of gas-liquid flows in wide ranges of technological parameters values. The determination of the investigated parameters was carried out by means of the following procedures:

1. Instrumental measurement of gas flowrates through the tubing and annular space;
2. High-speed video recording of the near-intake domain of the well model through a plexiglass casing using a video camera "Phantom Miro eX4" (Vision Research company, USA) with frame rate up to 1800 fps.

Four model mixtures were used in the experiments: "Water-Air" (WA), "Water-Surfactant-Air" (WSA), "Water-Air-Solids" (WAS) and "Water-Surfactant-Air-Solids" (WSAS). Technical water was used as a liquid for all model mixtures. The surface tension at the liquid-gas interface was 0.072 N/m for WA mixtures, and 0.042 N/m for WSA (the demulsifier "Disolvan 4411" with a volume concentration of 0.05% was used as a surfactant)[1]. In the model mixtures WAS and WSAS irregularly shaped quartz sand particles with an average diameter of 0.2–0.6 mm with a concentration of 1000 mg/l were used as a solid phase.

The experimental setup has the following geometrical features: inner diameter of the casing D_{CAS} = 80 mm, outer

[1]Values of surface tension of the model mixtures "Water-Surfactant-Air" and "Water-Air" are taken on the basis of A.N. Drozdov's PhD dissertation (Drozdov, 1983).

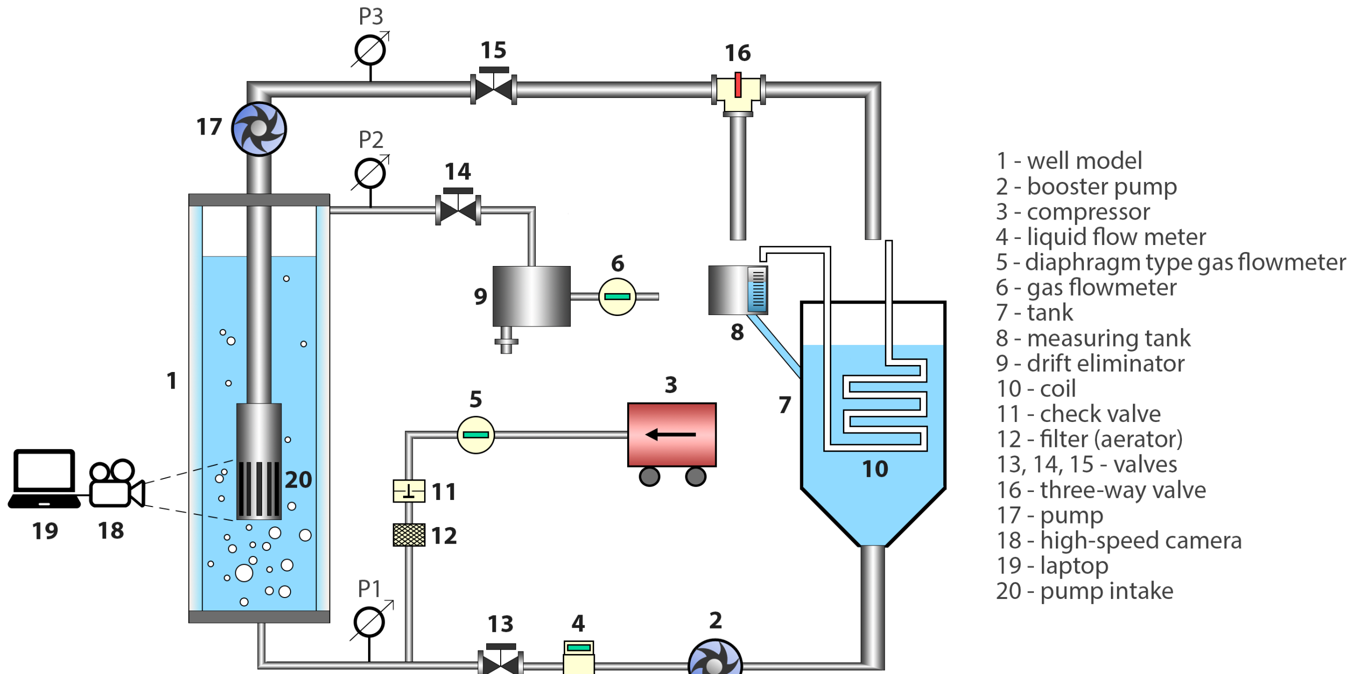

Fig. 2. Schematic illustration of the experimental setup

diameter of the intake screen d_{intake} = 64 mm. In all experiments the same overpressure of 0.04–0.05 MPa was maintained at the intake of ESP. The methodology of the experiments is described in details in articles (Ivanov et al., 2024a; Nikonov et al., 2024).

The relationships between the natural gas separation efficiency and the liquid flowrate obtained as a result of processing the instrumental measurements of gas flowrates through the tubing and annular space are presented in Fig. 3 for all investigated regimes. In spite of the fact that approximation of actual measurements by a quadratic function has a higher coefficient of determination, in this comparative analysis it is more obvious and easier to use linear trends for each model mixture, which are characterized with rather high coefficients of determination ("Water-Air" → R^2 = 0.956; "Water-Surfactant-Air" → R^2 = 0.969; "Water-Air-Solids" → R^2 = 0.919; "Water-Surfactant-Air-Solids" → R^2 = 0.977).

Fig. 3 shows that a decrease of surface tension at the liquid-gas interface leads to a small decrease of NGSE (up to 5%) in the investigated ranges of technological parameters values. In the article (Nikonov et al., 2024), based on the processing of video files of current research, it is shown that for the regimes of the model mixture "Water-Surfactant-Air" the average diameters of gas bubbles (0.91 mm) are smaller than for "Water-Air" (1.89 mm). Due to smaller average gas bubble sizes for the model mixture "Water-Surfactant-Air", it will be characterized by smaller vertical relative velocities of gas bubbles in the gas-liquid flow in the near-intake domain of the annular space, which will lead to decrease of the K_{ns} values in comparison with the K_{ns} values for the model mixture "Water-Air" under close values of operating parameters. This observation and explanation of the process corresponds to the studies of various authors, however, for its confirmation within the conducted experiments it is necessary to estimate the values of relative gas velocity for the investigated regimes by means of video processing.

The presented linear NGSE trends for the model mixtures "Water-Air-Solids" and "Water-Surfactant-Air-Solids" require further detailed analysis. A detailed analysis of relative gas velocities based on video processing, as well as an investigation of the influence of the presence of solid phase in model flow on the natural gas separation efficiency are planned to be presented in the future.

Experimental data processing

In the course of video processing, two-phase flow patterns were visually determined for each regime of the investigated model mixtures "Water-Air" and "Water-Surfactant-Air". The following flow patterns were observed:

1. For the WA mixture at $\beta_g \leq 30\%$, bubble flow; at $\beta_g \geq 35.4\%$, slug-churn flow;
2. For the WSA mixture at $\beta_g \leq 33.1\%$, bubble flow; at $\beta_g \geq 39.3\%$, slug-churn flow.

Table 2 presents the values of the main technological parameters (liquid flowrate q_l, gas flowrate before separation q_g, free gas volume fraction in the flow before separation β_g under thermobaric conditions of intake device) and K_{ns} of different regimes of the model mixtures WA and WSA recorded on video.

During the investigation of video recordings of flow regimes of model mixtures "Water-Air" and "Water-Surfactant-Air" it was observed that the regimes 0-WA, 0-WSA, 1-WSA are characterized by long time intervals, during which a regime of "zero separation" is observed when all free gas enters the intake screen due to sufficiently large liquid flowrates (which correspond to large values of Reynolds number (Ivanov et al., 2024a)). In this case, the capture of small bubbles from the near-intake domain of the annulus is due to small sizes of the gas bubbles, their uniform distribution in the liquid (dispersed bubble pattern of the flow) and sufficient force of the liquid flow dragged into the pump.

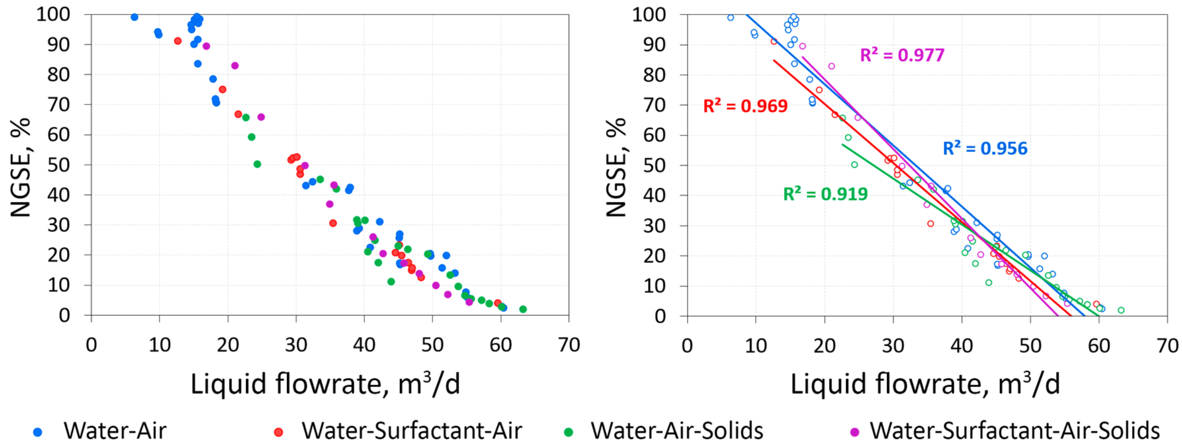

Fig. 3. Measured NGSE values for the model mixtures «Water-Air», «Water-Surfactant-Air», «Water-Air-Solids», «Water-Surfactant-Air-Solids»

Regime No.	q_l, m^3/day	q_g, m^3/day	β_g, %	K_{ns}, %
0-WA	64.3	12.0	15.8	1.1
1-WA	54.3	18.2	25.1	2.7
2-WA	53.0	22.8	30.0	25.0
3-WA	52.0	28.4	35.4	31.1
4-WA	45.8	29.6	39.2	34.5
5-WA	39.1	31.6	44.7	50.4
6-WA	23.4	32.3	58.0	70.2
7-WA	13.4	32.7	70.9	96.9
0-WSA	68.1	8.5	11.1	0.6
1-WSA	62.5	13.0	17.2	0.9
2-WSA	50.6	19.3	27.6	8.3
3-WSA	49.4	24.4	33.1	25.9
4-WSA	48.7	31.6	39.3	30.9
5-WSA	32.4	30.4	48.4	55.9
6-WSA	18.3	33.7	64.8	77.2

Table 2. Characterization of video-recorded regimes for the model mixtures WA and WSA

Fig. 4 shows a visual comparison of different model mixtures at slug-churn flow regime for 6-WA and 6-WSA (at close values of technological parameters). The model mixture "Water-Surfactant-Air" with slug-churn pattern is characterized by more pronounced heterogeneity in the sizes of gas bubbles. The average diameter of gas bubbles ($d_{b.avg}$) for the 6-WSA regime is 0.9 mm. For the 6-WA regime of the "Water-Air" model mixture the average diameter of bubbles is 2.4 mm.

One feature of slug-churn flow regimes is the fluctuation of true velocity of gas bubbles in time. A frame-by-frame visualization of this feature for the model mixture "Water-Air" with a frequency of one frame in 10 milliseconds is presented on Fig. 5. When the large gas slug appears in the frame, the small bubbles uniformly distributed in the fluid flow around it slow down in relation to their average velocity. This can be shown by the position of the bubble marked by the pink circle on Fig. 5. (the angle of inclination of the line passing through the pink circles on three contiguous frames decreases until the gas slug collapses – the bubble seems to be hanging). Further, after the gas slug collapses near the pump intake screen an increase of velocity greater than the mean value for both the bubbles around the slug and the bubbles below it is noted. This can be observed from the position of the bubble marked by the orange circle (the inclination angle of the orange line is larger than that of the pink line at the beginning of the storyboard). This unsteady feature can be explained by the fact that there is a downward flow of liquid around the large gas slug, which prevents the small bubbles from moving upward (Brill, Mukherjee, 2006). When the gas slug collapses, the liquid near it tends to take its place, which helps to accelerate the bubbles around the slug.

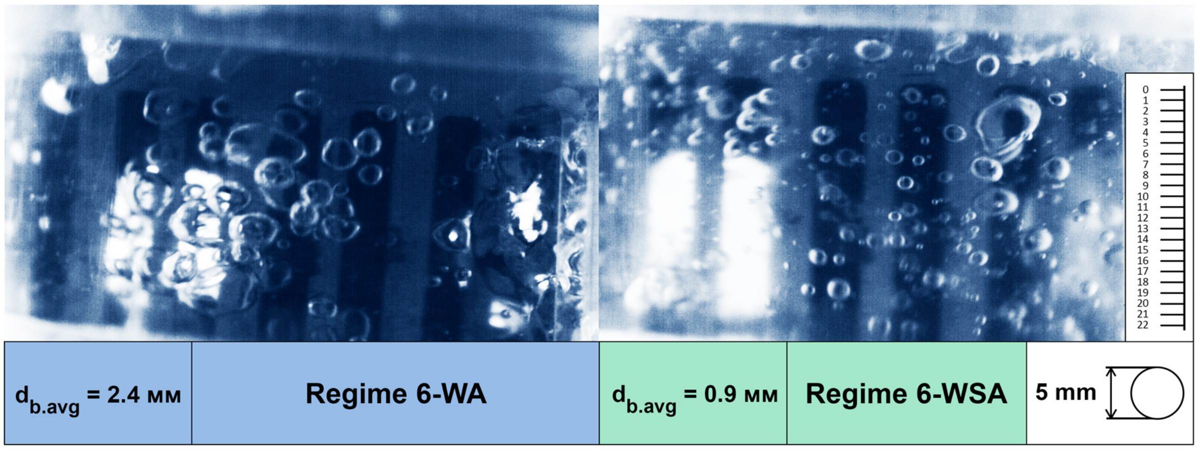

Fig. 4. Visual comparison of gas-liquid flows of the model mixtures WA and WSA for regimes with similar technological parameters and slug-churn flow structure (6-WA and 6-WSA)

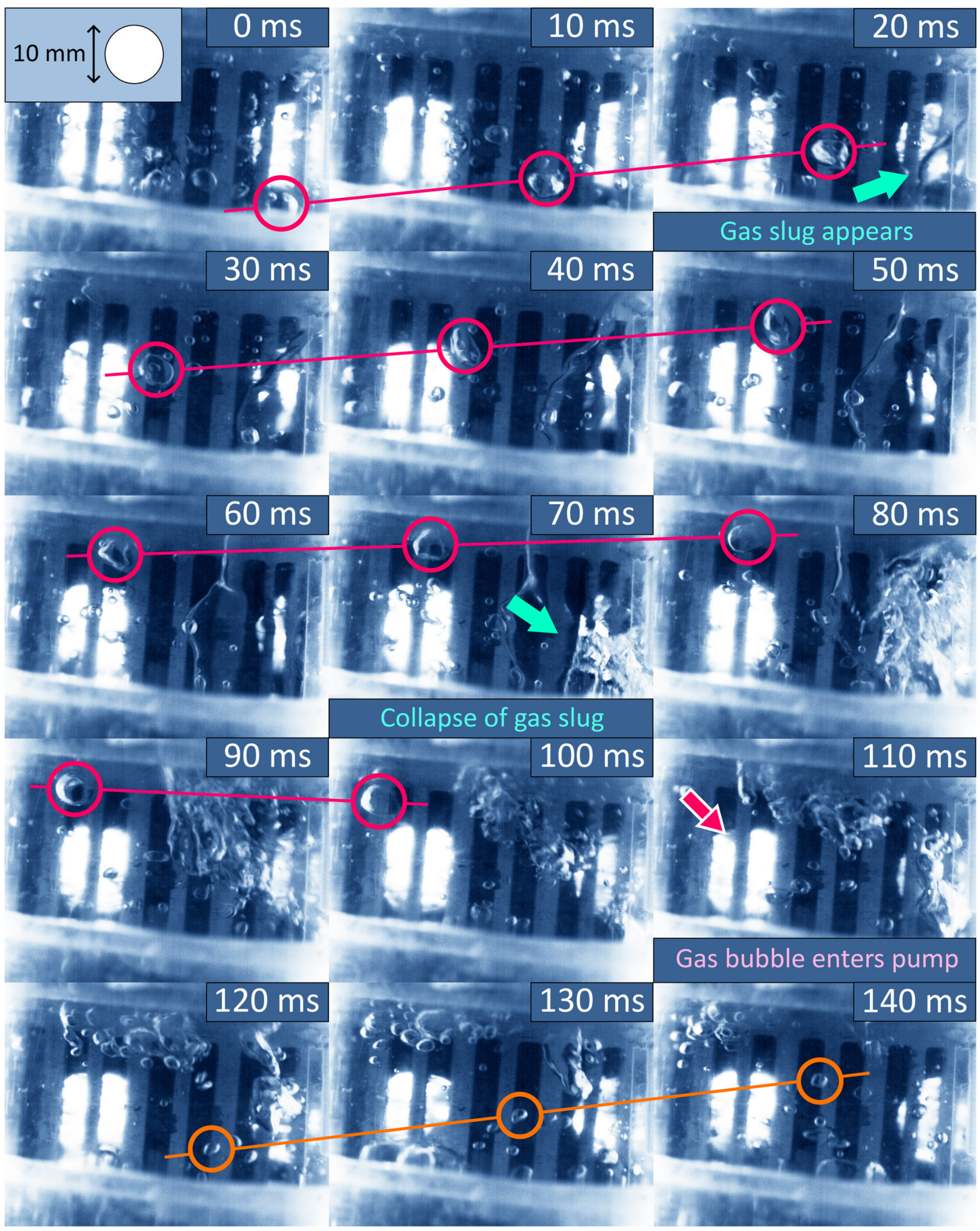

Fig. 5. Frame-by-frame dynamics of gas bubble velocity fluctuations, when the gas slug appears in the frame for the 3-WA regime with a step of 10 ms

Another feature observed in some of the regimes was a return of gas bubbles from the annular space above the intake screen to the intake domain, causing some of the returned bubbles to enter the intake screen, reducing the separation efficiency. Other bubbles re-separated into the annular space. Fig. 6 shows the frame-by-frame dynamics of the motion of gas bubbles returned from the annular space for the slug pattern of the model mixture "Water-Air" with a frame rate one frame in 5 milliseconds. Green color indicates the gas bubbles returned from the annular space. Pink color indicates the bubbles returned from the annulus that will enter the intake screen within 1-3 frames. For the "Water-Air" and "Water-Surfactant-Air" mixtures, this feature was observed for all regimes with the slug-churn flow pattern. Such behavior can be caused by unsteadiness of the processes occurring in various elements of the system "reservoir – wellbore – pump – tubing", including the part of the well model above the pump intake screen – the annular space. However, video recordings of the processes occurring in the annular space above the intake device, measurements of the liquid level position and measurements of the instantaneous fluid flowrates through the pump were not conducted as part of current research. In addition, the return of gas bubbles from above at the slug-churn flow regimes can be associated with the presence in the intake domain of a large gas slug that is not caught in the frame, which creates a downward flow of liquid with gas bubbles distributed in it around itself.

Fig. 7 shows the dynamics of changes of the instantaneous values of the natural gas separation efficiency for the model mixtures "Water-Air" (regimes 1-WA and 3-WA) and "Water-Surfactant-Air" (regimes 2-WSA and 4-WSA). Visually, modes 1-WA and 2-WSA are characterized by a bubbly flow (β_g = 25.1% and 27.6%, respectively), modes 3-WA and 4-WSA are characterized by a slug flow (β_g = 35.4%

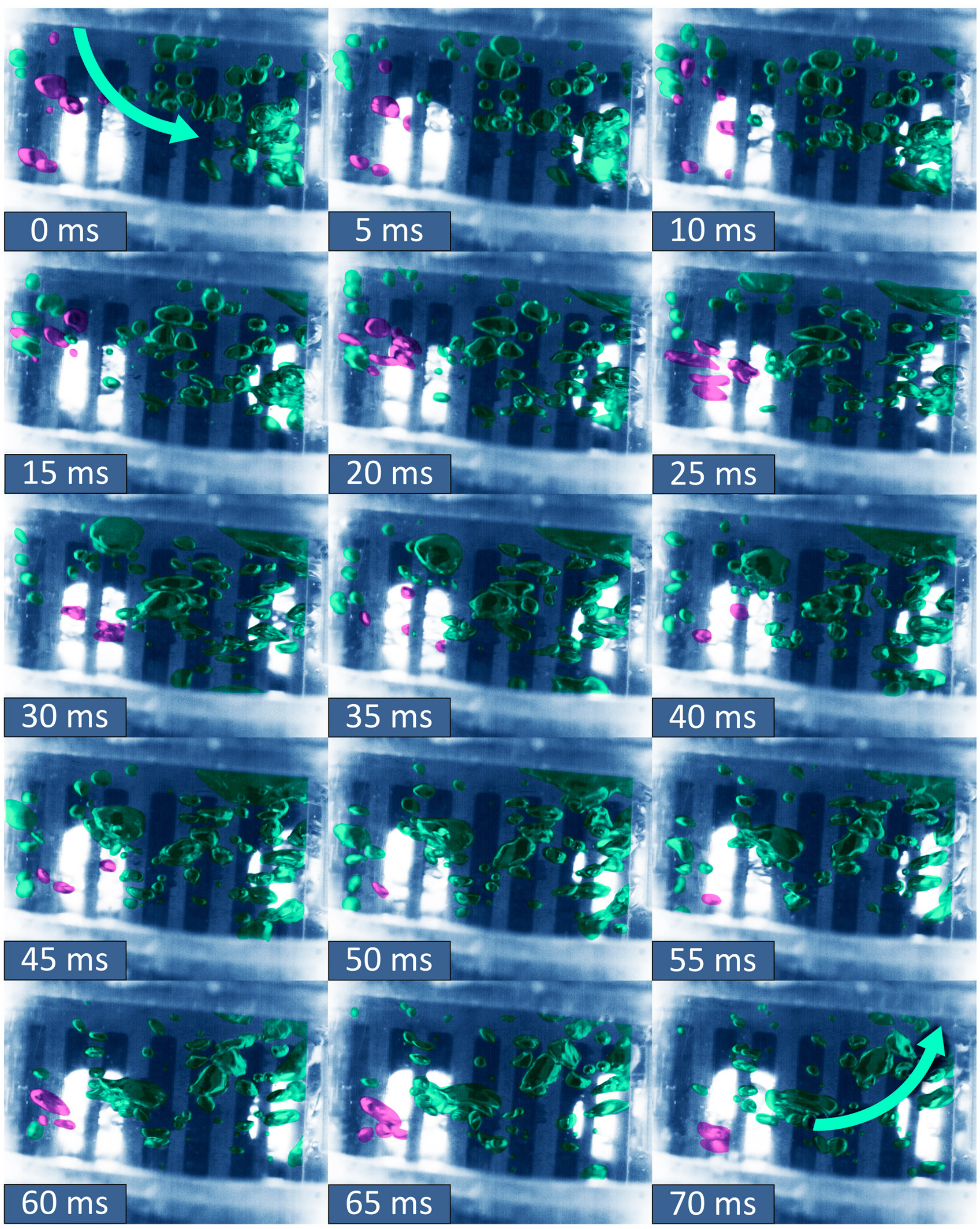

Fig. 6. Frame-by-frame dynamics of the motion of gas bubbles returning from the annulus for the 6-WA regime with a step of 5 ms

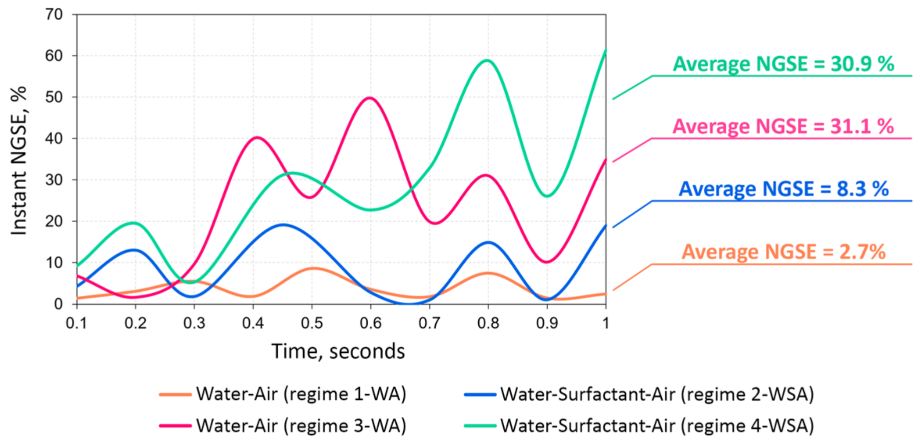

Fig. 7. Dynamics of instantaneous NGSE for model mixtures “Water-Air” and “Water-Surfactant-Air”

and 39.3%, respectively). The average values of natural separation efficiency, liquid and gas flowrates before separation, and free gas volume fractions in the flow before separation for these regimes are given in Table 2. The plots presented in Fig. 7 were obtained by processing the video recordings of these regimes. In the course of video processing, the accumulated volumes of gas bubbles entering the intake device and venting through the annulus were measured using a millimeter scale with a time step of 0.1 s. There are no significant differences in the dynamics of the instantaneous K_{ns} values for different model mixtures within the same flow structures. For the bubble flow structure for both model mixtures small absolute fluctuations of 5–10% in relation to the average K_{ns} values are observed. Regimes with bubble flow can be characterized as sufficiently stable in time. For the slug flow for both model mixtures, significant absolute fluctuations of K_{ns} up to 20–30% are observed. Such unstable behavior of the regimes with slug flow structure can explain the unsteady features described earlier. Periodic instantaneous increase of free gas fraction in the flow entering the intake device can lead to unsteady pump operation, instantaneous deformation of its head-flow (performance) curve (HFC), which can result in fluctuations of liquid level above the pump in the annulus.

Further, we describe the results of modeling of experimental regimes in the OLGA[2] simulator, which helps us to explain the visually observed features described above.

Numerical modeling of the experimental regimes

As part of the natural separation process investigation, the obtained set of experimental regimes was modeled using the dynamic multiphase flow simulator OLGA in order to explain the processes occurring in the near-intake domain, which were not explored in the laboratory experiments. For this purpose, two variants of model-analogs of the real physical setup were created in the simulator (Fig. 8). A difference between the model-analogs is concluded in different types of nodes (*Internal node* – has a finite volume, *Junction node* – has zero volume), where the separation of the total gas-liquid flow into two different flows (flow in the annular space above the intake screen; flow into the pump) takes place. Fig. 8 shows a description of the model-analogs. Numbers mark characteristic elements of the model:

1. Wellhead of the well model (*Tubing* and *Annulus*);
2. *ESP* – pump model; *ESP_CONTROL* – control station model;
3. The module responsible for calculating the accumulated NGSE, consisting of two transmitters measuring the accumulated gas production ACCQGST through the intake and through the annulus, as well as an algebraic controller *Ksep_accumulated* with a calculation equation. This module is necessary in cases of unstable system operation when the instantaneous NGSE is inconvenient to analyze;
4. The module responsible for calculating the instantaneous NGSE, consisting of two transmitters measuring the instantaneous gas flowrates QG through the intake and through the annulus, and the algebraic controller *Ksep_instant* with a calculation equation;
5. The module responsible for calculating the free gas volume fraction in the gas-liquid flow before separation, consisting of two transmitters measuring instantaneous liquid QL and gas QG flowrates in front of the pump intake (at the top of the *Wellbore* branch), and an algebraic controller *Bg* with a calculation equation;
6. Mass water and air sources (*SOURCE-WATER* and *SOURCE-AIR*) at the bottom of the model wellbore;
7. Two versions of the gas-liquid flow separation node (*Internal node* and *Junction node*).

Fig. 9 and Table 3 show the results of three variants of calculations:

1. Calculations with *Junction node*;
2. Calculations with *Internal node* with automatically calculated volume (adjusting the volume of the *Internal node* did not improve the convergence of the calculation and experiment);
3. Calculations using *Internal node* with automatically calculated volume + Adjustment of natural separation efficiency using additional gas removal system.

The calculation results sufficiently depend on the volume fraction of free gas β_g in the gas-liquid flow in the near-intake domain of the annular space of the calculation model, so the modeling results were also adjusted to match the experimental and calculated values of β_g (relative errors of no more than 3.3% were obtained). The calculation of β_g was carried out

[2] Slb.com. OLGA. Dynamic Multiphase Flow Simulator. 2021. https://www.software.slb.com/products/olga

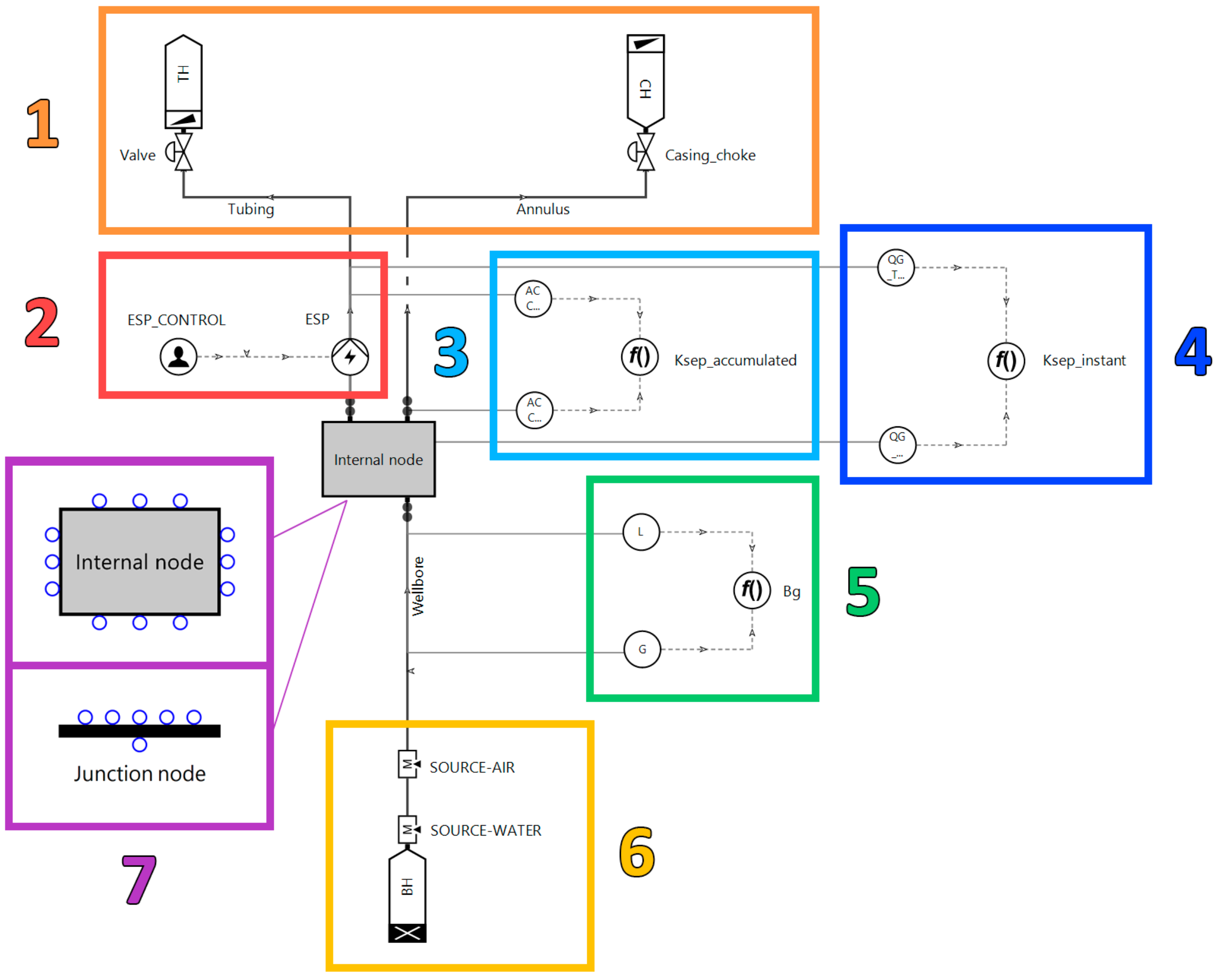

Fig. 8. Model of the physical setup for the investigation of experimental regimes in the OLGA simulator

using block 5, marked in Fig. 8. Table 3 also presents the calculations of relative errors for three sets of calculated values of NGSE (δ_{Kns}, %) and β_g ($\delta_{\beta g}$, %) in relation to the experimental data (equations (4) and (5)).

$$\delta^i_{Kns} = \frac{\left|K^{Ei}_{ns} - K^{Ci}_{ns}\right|}{K^{Ei}_{ns}} \cdot 100\%, \quad (4)$$

$$\delta^i_{\beta g} = \frac{\left|\beta^{Ei}_{g} - \beta^{Ci}_{g}\right|}{\beta^{Ei}_{g}} \cdot 100\%, \quad (5)$$

where δ^i_{Kns} – relative error for the natural gas separation efficiency, %; $\delta^i_{\beta g}$ – relative error for free gas volume fraction before separation, %; K_{ns}^{Ei} – the natural gas separation efficiency from the experiment for the i-th regime, %; K_{ns}^{Ci} – the natural gas separation efficiency from the OLGA calculation for the i-th regime, %; β_g^{Ei} – free gas volume fraction before separation from the experiment for the i-th regime, %; β_g^{Ci} – free gas volume fraction before separation from the OLGA calculation for the i-th regime, %.

The calculations obtained using the model with *Junction node* have the worst convergence of all obtained results. The calculation points obtained with *Internal node* without tuning show a reasonably good convergence with experiments at fluid flowrates > 20 m^3/day. At lower liquid flow rates (less than 20 m^3/day), significant discrepancies between calculated and actual NGSE (35–45%) are observed.

The articles (Ivanov et al., 2024b; Yushchenko et al., 2024) present a mathematical approach for tuning the separation process in the dynamic simulator OLGA.

This approach implies setting the NGSE value to the calculation input, which should be previously estimated using analytical models. The proposed method can be used both for tuning the total separation in the presence of a gas separator in the ESP system and for tuning the process of natural gas separation. Fig. 9 shows the results of calculations using this approach (*Internal node* + Tuning) characterized by the best convergence with the experiment. Further calculations were performed using this tuning method.

To understand the physics of unsteady processes occurring in the annular space, calculations with a small step of graphical data output were carried out in the OLGA model. For data output in the simulator, a point output step similar to the video processing step of 0.1 s was chosen to compare the calculated NGSE dynamics with the dynamics determined from the video. Fig. 10 shows a comparison of the instantaneous natural gas separation efficiency obtained by calculation in the simulator (*Internal node* + Tuning) and by video file processing, for regimes 1-WA and 3-WA. The calculated dynamics of the natural gas separation efficiency is close to the dynamics obtained from video files, thus it allows further analysis of calculations.

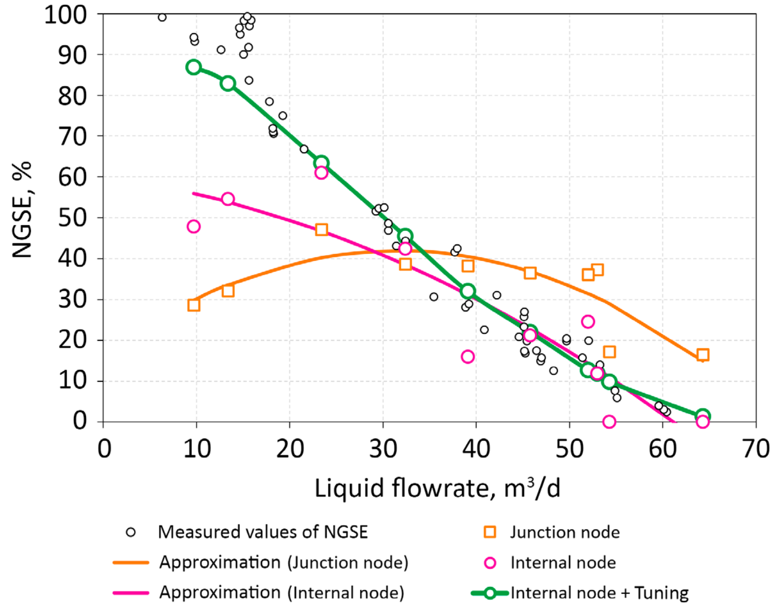

Fig. 9. Different variants of NGSE calculation in OLGA simulator

Regime No.	Experiment		Internal node				Internal node + Tuning				Junction node			
	β_g, %	K_{ns}, %	β_g, %	$\delta_{\beta g}$, %	K_{ns}, %	δ_{Kns}, %	β_g, %	$\delta_{\beta g}$, %	K_{ns}, %	δ_{Kns}, %	β_g, %	$\delta_{\beta g}$, %	K_{ns}, %	δ_{Kns}, %
1	15.8	1.0	16.1	1.9	0	-	16.2	2.5	1.2	20.0	16.2	2.5	16.5	1550.0
2	25.1	9.5	24.6	2.0	0	-	25.6	2.0	9.8	3.2	24.7	1.6	17.2	81.1
3	30.0	11.0	31.0	3.3	11.8	7.3	29.6	1.3	11.9	8.2	31.0	3.3	37.3	239.1
4	35.4	12.5	36.3	2.5	24.5	96.0	34.5	2.5	12.7	1.6	36.1	2.0	36.1	188.8
5	39.2	21.5	39.9	1.8	21.2	1.4	38.9	0.8	22.0	2.3	39.2	0.0	36.5	69.8
6	44.7	32.5	45.3	1.3	15.9	51.1	44.4	0.7	32.0	1.5	45.2	1.1	38.2	17.5
7	80.0	45.0	78.8	1.5	42.4	5.8	79.6	0.5	45.5	1.1	78.9	1.4	38.6	14.2
8	58.0	66.0	59.1	1.9	61.0	7.6	57.0	1.7	63.4	3.9	57.6	0.7	47.1	28.6
9	70.9	92.0	70.8	0.1	54.6	40.7	69.5	2.0	82.9	9.9	70.8	0.1	32.1	65.1
10	66.5	99.0	66.0	0.8	47.8	51.7	66.1	0.6	86.9	12.2	65.6	1.4	28.6	71.1
Avg. δ %				**1.7**		**32.7**		**1.5**		**6.4**		**1.4**		**232.5**

Table 3. Comparison of experimental-measured and calculated data

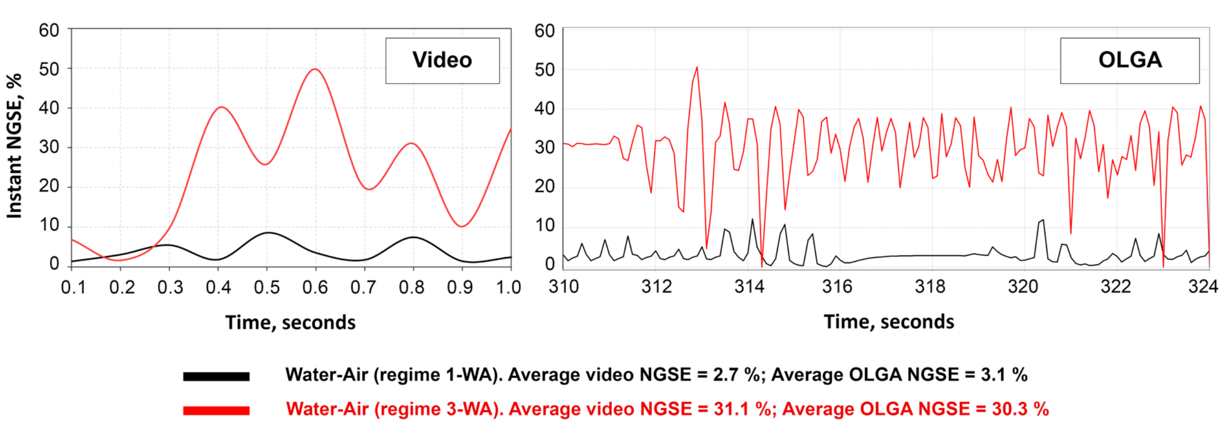

Fig. 10. Comparison of instantaneous NGSE determined by video and calculated in OLGA

Fig. 11 shows the dynamics of instantaneous liquid flowrates through the pump (under operating conditions) and instantaneous K_{ns} for regimes 1-WA and 3-WA. Fluctuations of instantaneous liquid flowrates through the pump are observed. For 1-WA regime from 53.9 to 55.7 m^3/day (average value 54.3 m^3/day). For mode 3-WA from 51.2 to 54.2 m^3/day (average value 52 m^3/day).

As previously stated, the 1-WA regime is characterized by a bubbly flow, with the 3-WB regime characterized by a slug flow, that determines the amplitude of fluctuations of the instantaneous free gas volume fraction in the gas-liquid flow in front of the intake device. Due to the lower values of the residual free gas volume fraction in the flow through the pump for the 1-WA regime (β_g^{int} ~ 24.5%) compared to the 3-WA regime (β_g^{int} ~ 27.5%) as well as due to the more stable in time flowrate of gas entering the pump, the instantaneous liquid flowrate through the pump for the 1-WA regime is also more stable in time.

When the instantaneous liquid flowrate though the pump is less than the average value, a part of the liquid entering the well model flows into the annulus, thus simplifying the gas separation process. At the moment of instantaneous increase of the liquid flowrate through the pump greater than the average value, a part of the liquid from the annulus space above the intake is dragged into the pump, resulting in a short-time counter-current regime of liquid and gas flow in the annular space, complicating the gas separation process. Fig. 12 shows the instantaneous values of the superficial gas velocity in the annular space above the pump. The regime 3-WA is characterized by significant fluctuations of gas velocity, with reaching negative values (gas flow is directed downward to the intake screen), that indicates the periodic occurrence of the "zero separation" regime, when the downward velocity of liquid in the annulus space is so high that all gas is carried away by the downward flow into the intake module. That may explain the processes noted in the processing of video files,

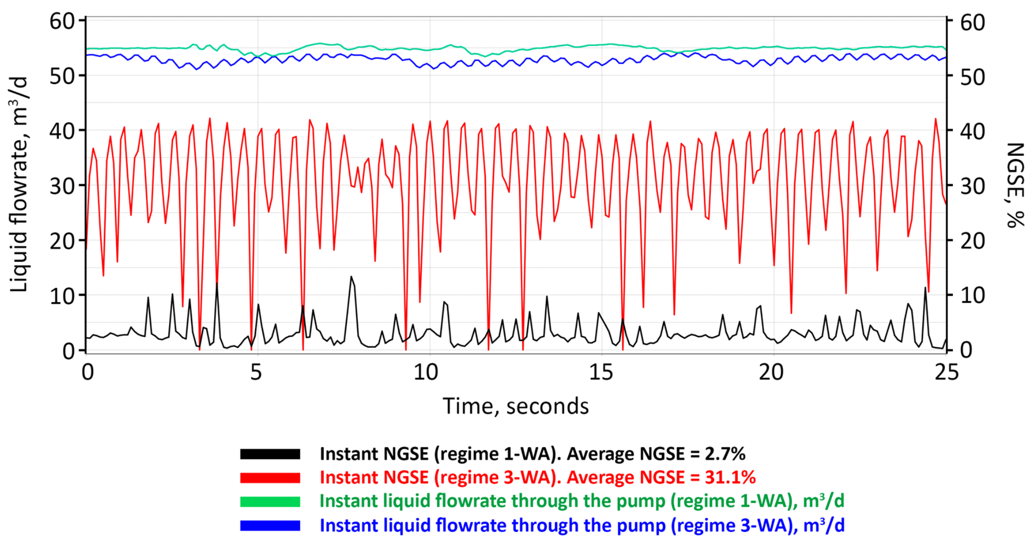

Fig. 11. Dynamics of the instantaneous natural gas separation efficiency and liquid flowrates through the pump for regimes 1-WA and 3-WA, calculated in simulator OLGA

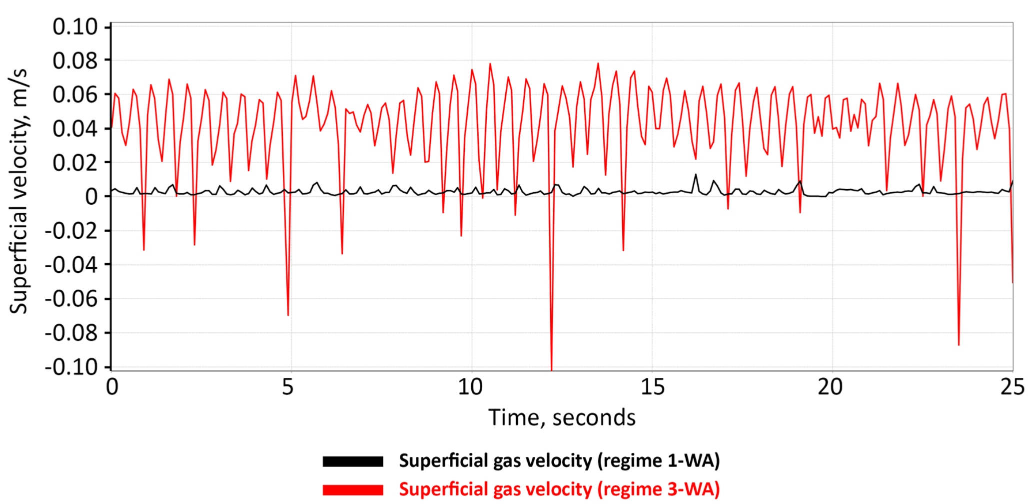

Fig. 12. Dynamics of superficial gas velocities in the annular space above the intake module for regimes 1-WA and 3-WA, calculated in the simulator OLGA[3]

[3]Fig. 11 and 12 show different time periods to make the demonstrative data clearer

associated with the periodic return of gas bubbles from the annulus to the near-intake domain.

Fig. 13 shows the dynamics of fluctuations of instantaneous values of NGSE, liquid flowrate through the pump q_l and residual volume fraction of free gas through the pump β_g^{int} after separation for regime 6-WA (with slug-churn flow regime), calculated in the simulator. The pulsational character of the pump operation is observed. This regime is characterized by significant fluctuations of NGSE, that leads to time fluctuations of residual volume fraction of free gas in the flow entering the pump. Periodically, the critical value of free gas volume fraction in the pump is exceeded ($\beta_g^{int} > \beta_g^{int.crit}$; $\beta_g^{int} \sim 60$–65%), that leads to a short-term regime of "gas-lock".

Discussion of the results

Similar behavior (Fig. 13) can be observed in real wells with increased free gas volume fraction at ESP intake. In (Bedrin et al., 2008) the analysis of actual operation of wells with different technologies, providing ESP operation with increased free gas volume fraction due to the inclusion of a special device or a special design of pump, is presented. Fig. 14 shows the actual dynamics of technological parameters (gas-oil ratio, liquid, oil and gas flowrates) of a well with ESP in one of the designs to provide operation with high free gas fraction at the pump intake, obtained through field tests using a multiphase flowmeter. The example in Fig. 14 is similar to the experimental regime 6-WA by the value of the parameter the volume fraction of free gas in the flow at the intake device before separation ($\beta_g \approx 60\%$). Significant fluctuations of well process parameters are observed for small periods of time (< 15 minutes). The authors of the article (Bedrin et al., 2008) also connect this instability with short-term excesses of critical gas fraction in the pump during operation and with the structure of multiphase mixture flow in the pump and wellbore (slug and churn flow patterns). Such fluctuations of technological parameters are associated with specific fluctuations of motor current – "current saw".

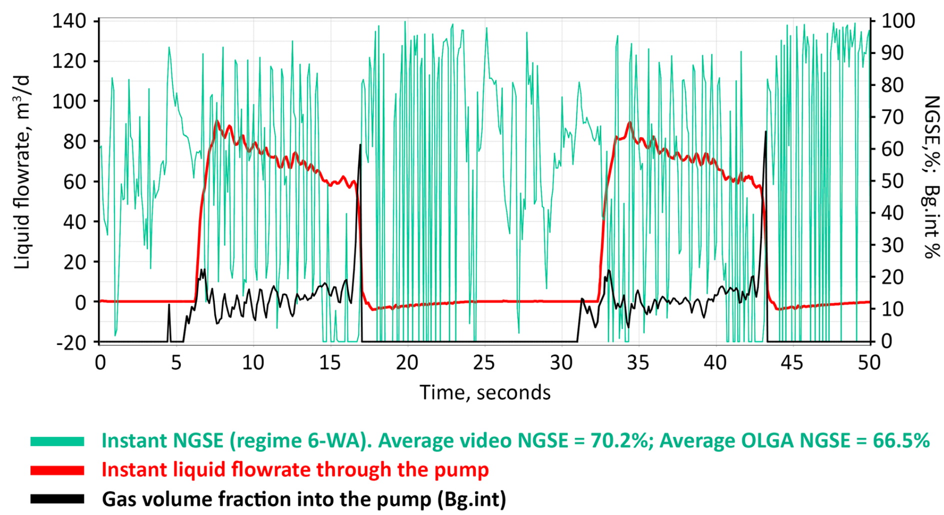

Fig. 13. Dynamics of fluctuations of instantaneous values of NGSE, liquid flowrate through the pump ql and residual free gas volume fraction through the pump βgint for the 6-WA regime calculated in the simulator OLGA (the change of the NGSE calculated in the OLGA simulator corresponds to the assumptions of the calculation model, as well as the theoretical foundations of separation processes for the conditionally axial and conditionally radial entrance to the intake device, as set out in the book by I.T. Mishchenko (2003))

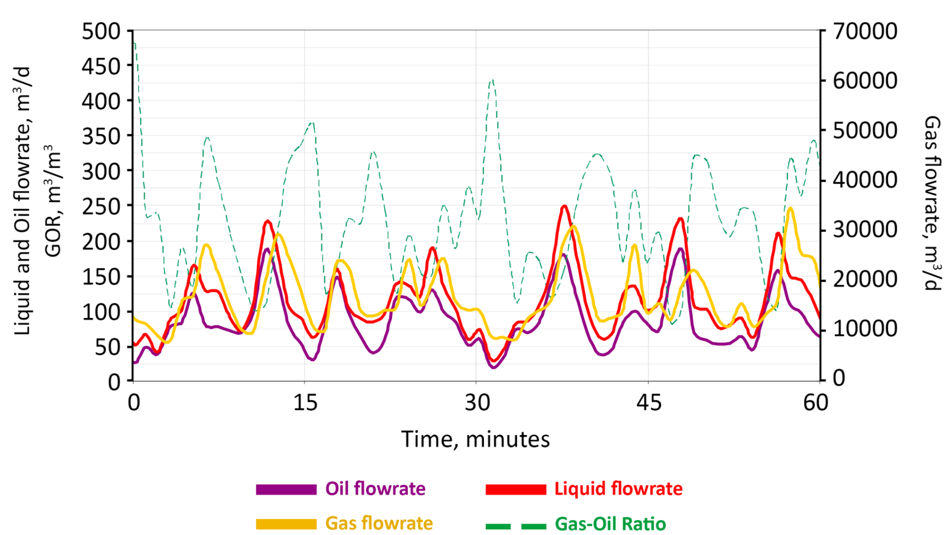

Fig. 14. Example of time fluctuations of gas-oil ratio, oil, liquid and gas flowrates in a well during operation of submersible equipment with high free gas fraction at the pump intake (circa 60%) according to (Bedrin et al., 2008)

It is worth to note that most of the existing analytical techniques for calculating NGSE, presented in Table 1, are steady-state. This means that they are able to determine only the average value of the natural gas separation efficiency over a rather long time interval due to the fact that these methods were adjusted to the accumulated values of NGSE obtained during various studies. At the same time, in order to reproduce the dynamics shown in Fig. 13 and Fig. 14, it is necessary to take into account unsteady features of the natural gas separation process (Fig. 5, Fig. 6) and related features of the pump pulsational operation, described in this paper, in analytical methods for calculating NGSE.

On the basis of comparison of the results of laboratory experiments and numerical modeling in the simulator OLGA the following conclusions can be drawn:

1.1 Constant regimes of ESP operation with bubble or slug structure of gas-liquid flow at the intake module can be considered as “quasi-stationary” at long time intervals.

1.2 The operation of the whole system is nonstationary on small time intervals (< 1 s). Instantaneous efficiency of natural gas separation with slug-churn flow structure can vary in a significant range (on the example of modeling of 6-WA regime), that can affect the instantaneous performance of ESP operation and lead to pulsational character of the pump operation.

2.1 The use of *Junction node* for calculation of the natural separation in OLGA simulator gives significant discrepancies with experimental data.

2.2 Efficiency of natural separation, calculated in OLGA simulator using *Internal node* without tuning, has good convergence with experimental data with liquid flowrates more than 20 m^3/day, but at lower liquid flow rates there are significant discrepancies with the experiment.

2.3 To adjust the process of separation (natural or total, taking into account the presence of a gas separator) in the model of a well with ESP in the OLGA simulator, it is recommended to use the approach used in this article and described in details in the articles (Ivanov et al., 2024b; Yushchenko et al., 2024). This approach shows the best convergence of calculations with experimental data in the investigated ranges of technological parameters, however, it requires preliminary calculations using analytical methods, which at the moment need to be adjusted to the experimental data in the unexplored ranges of various parameters.

Conclusions and recommendations

The main conclusions are as follows:

1. A comprehensive review of the extant scientific literature has been undertaken, with a view to systematizing the knowledge base relating to the process of natural gas separation in wells equipped with ESPs. Consequently, factors that necessitate further comprehensive investigation have been identified. Primarily, these factors pertain to a detailed understanding of the natural gas separation process physics into the annular space at the conditionally radial intake. Moreover, these factors are also relevant in order to improve the quality of engineering calculations of the operating mode of an ESP well.

2. It has been demonstrated that the process of natural gas separation is unsteady over short timescales, irrespective of the operational mode of the well (steady-state or periodic).

3. The present paper describes and illustrates the non-stationarity of the separation of natural gas. This is achieved by means of visualizing the process using high-speed video recording of the near-intake area of the well model and by explaining the empirical representations obtained by modelling the process in steady-state ESP operation modes in the dynamic multiphase flow simulator OLGA. The constraints that are shown and the recommendations for modelling of the natural separation in this dynamic simulator are described.

The following recommendations are proposed for further study of the subject of the gas separation in wells equipped with ESP

1. In the context of contemporary developments in Russian oil and gas industry, there is an urgent need to develop advanced methods for predicting the performance of wells equipped with ESP. This is particularly crucial for accounting for the non-stationary aspects of gas-liquid mixture flow during transient processes, such as well start-up, periodic modes of operation, pulsational operation of ESP and others. In order to calculate the instantaneous efficiency of the natural gas separation, it is necessary to develop a non-stationary analytical correlation, taking into account gas bubble sampling of different sizes. The research results presented in this paper can be applied in a scientific environment to determine the efficiency of the gas separation process in the non-stationary mode of operation of the production system “reservoir-wellbore-pump-tubing”.

2. The task of computational fluid dynamic modelling (CFD), which allows to study in details the process of natural gas separation, including at periodic modes of ESP operation, taking into account the flow structures of gas-liquid mixtures both at the ESP intake and directly in the working elements of the centrifugal pump, is actual. The results of CFD modelling are, on the one hand, a good tool for planning and conducting bench and field experiments, on the other hand, they can be used for verification of physical experiments and determination of the influence on K_{ns} of the required investigated parameters in uncovered ranges.

3. It is necessary to conduct field studies in wells at different regimes, taking into account the measurement of parameters affecting the natural gas separation efficiency; to adjust analytical correlations on the results of field studies and to plan bench experiments to refine the analytical correlations.

4. The scientific interest lies in conducting complex bench experiments in previously unexplored ranges of technological, geometric and physical-chemical parameters of the “reservoir-wellbore-pump-tubing” system for the following purposes: adjustment of analytical correlations for calculation of relative gas velocity in gas-liquid flow; calculation of the natural gas separation efficiency; creation of a database of technological modes of near-intake domain operation in the well model; definition of the sizes of gas bubbles necessary for adjustment of the analytical correlation of the relative gas velocity calculation; study of natural gas separation conditions when a multiphase gas-liquid mixture containing solid particles of different nature moves in the near-intake space of the well.

Supplementary files

In the appendix: frame-by-frame dynamics of gas bubble velocity fluctuations when a gas plug appears in the frame for mode 3-WA; frame-by-frame dynamics of gas bubbles returning from the annular space for mode 6-WA.

References

Alhanati F.J.S. (1993). Bottomhole Gas Separation Efficiency in Electrical Submersible Pump Installation. Ph.D. dissertation. The University of Tulsa.

Bedrin V.G., Khasanov M.M., Khabibullin R.A., Krasnov V.A., Pashali A.A., Litvinenko K.V., Elichev V.A., Prado M. (2008). High GLR ESP Technologies Comparison, Field Test Results. SPE-117414-MS. *SPE Russian Oil and Gas Technical Conference and Exhibition*, Moscow, 16 p. https://doi.org/10.2118/117414-MS

Brill J.P., Mukherjee H. (2006). Multiphase Flow in Wells. Moscow-Izhevsk: Institut kompyuternykh issledovaniy, 384 p. (In Russ.)

Drozdov A.N. (1983). Development of a methodology for calculating the characteristic of a submersible centrifugal pump during operation of wells with low pressures at the pump inlet. Candidate of Technical Sciences dissertation. MINKH i GP im. I.M. Gubkina. (In Russ.)

Elichev V.A., Khabibullin R.A., Krasnov V.A., Litvinenko K.V., Prado M.G. (2009). Performance Analysis of ESP Systems in High-GLR Wells: From Lab Experiments to Practical Field Applications. SPE-120628-MS. *SPE Production and Operations Symposium*, Oklahoma City, 9 p. https://doi.org/10.2118/120628-MS

Ghauri W.K. (1980). Production Technology Experience in a Large Carbonate Waterflood, Denver Unit, Wasson San Andres Field. *Journal of Petroleum Technology*, 32(09), pp. 1493–1502. https://doi.org/10.2118/8406-PA

Goridko K.A. (2023). Influence of varying properties of gas-liquid mixture along the pump length on the characteristics of electric submersible pump system. Candidate of Technical Sciences dissertation. RGU nefti i gaza (NIU) imeni I.M. Gubkina. 246 p. (In Russ.)

Harun A.F., Prado M.G., Serrano J.C., Doty D.R. (2000). A Simple Model To Predict Natural Gas Separation Efficiency in Pumped Wells. SPE-63045-MS. *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, 10 p. https://doi.org/10.2118/63045-MS

Harun A.F., Prado M.G., Serrano J.C., Doty D.R. (2001). A Mechanistic Model to Predict Natural Gas Separation Efficiency in Inclined Pumping Wells. SPE-67184-MS. *SPE Production and Operations Symposium*, Oklahoma City, 9 p. https://doi.org/10.2118/67184-MS

Ivanov V.A., Khabibullin R.A., Yushchenko T.S., Demin E.V., Verbitsky V.S. (2024b). Development of dynamic well model in short-term periodic mode of electric submersible pump operation. Teaching guide. Moscow: RGU, 89 p. (In Russ.)

Ivanov V.A., Verbitsky V.S., Khabibullin R.A., Goridko K.A., Nikonov E.I. (2024a). Experimental studies of natural separation efficiency at the intake of electric submersible pump. *Neftegaz.RU*, 8(152), pp. 78–84. (In Russ.)

Lackner G. (1997). The Effect of Viscosity on Downhole Gas Separation in a Rotary Gas Separator. *Ph.D. dissertation*. The University of Tulsa.

Lea J.F., Bearden J.L. (1982). Effect of Gaseous Fluids on Submersible Pump Performance. *Journal of Petroleum Technology*, 34(12), pp. 2922–2930. https://doi.org/10.2118/9218-PA

Lissuk M. (2001). Development of a methodology for calculating the pressure at the intake of an electric submersible pump. *Candidate of Technical Sciences dissertation*. RGU nefti i gaza im. I.M. Gubkina (In Russ.)

Liu B., Prado M.G. (2004). Modeling Downhole Natural Separation Using a Bubble Tracking Method. *ASME*, 8 p. https://doi.org/10.1115/PVP2004-2844

Lyapkov P.D. (1987). Selection of submersible centrifugal pump system for well. Teaching guide. Moscow: MING, 71 p. (In Russ.)

Lyapkov P.D., Gurevich A.S. (1973). About the relative velocity of the gas phase in the wellbore before entering the downhole pump. *Neftepromyslovoe delo*, 8. pp. 6–10. (In Russ.)

Marquez R., Prado M.G. (2003). A New Robust Model for Natural Separation Efficiency. SPE-80922-MS. *SPE Production and Operations Symposium*, Oklahoma City, 11 p. https://doi.org/10.2118/80922-MS

Marquez R. (2004). Modeling Downhole Natural Separation. *Ph.D. dissertation*. The University of Tulsa.

Mischenko I.T. (2003). Borehole oil production: Textbook for universities. Moscow: RGU nefti i gaza im. I.M. Gubkina, 816 p. (In Russ.)

Mischenko I.T., Gurevich A.S. (1969). Gas separation at the intake of a submersible centrifugal pump. *Neftepromyslovoe delo*, 3, pp. 7–10. (In Russ.)

Mischenko I.T., Gurevich A.S. (1970). Gas separation at the intake of submersible equipment operating in an oil well. *Neftyanoe khozyaystvo = Oil industry*, 3, pp. 52–56. (In Russ.)

Nikonov E.I., Verbitsky V.S., Goridko K.A., Shishulin V.A., Suleymanov M.A. (2024). The Study of Solid Particles Effect on the Gas Bubble Dispersion Dynamics of Complex Gas-Liquid Mixtures at the Intake Screen of Submersible Pump. *SOCAR Proceedings*, 2, pp. 61–70. http://dx.doi.org/10.5510/OGP20240200967

Okafor C.C., Verdin P.G., Hart P. (2021). CFD Investigation of Downhole Natural Gas Separation Efficiency in the Churn Flow Regime. SPE-204509-MS. *SPE Gulf Coast Section Electric Submersible Pumps Symposium*, Texas, 21 p. https://doi.org/10.2118/204509-MS

Okafor C.C., Verdin P.G. (2024). 3D computational fluid dynamics analysis of natural gas separation efficiency in multiphase pumping wells with heterogeneous flow regime. *Engineering Applications of Computational Fluid Mechanics*, 18(1), 22 p. https://doi.org/10.1080/19942060.2024.2395452

Pashali A.A. (2011). Algorithms and mathematical models for optimization of well operation modes under high gas-oil ratios. Candidate of Technical Sciences dissertation. Ufimskiy gosudarstvennyy neftyanoy tekhnicheskiy universitet. (In Russ.)

Pashali A.A., Zeygman Yu.V. (2022). Increasing Efficiency of Gas Natural Separation in Oil Production Wells Equipped by Electrical Submersible Pumps. *Neftyanoe khozyaystvo = Oil industry*, 5, pp. 94–97. (In Russ.) https://doi.org/10.24887/0028-2448-2022-5-94-97

Sambangi S.R. (1994). Gas Separation Efficiency in Electrical Submersible Pump Installation with Rotary Gas Separator. MSc thesis. The University of Tulsa.

Serrano J.C. (1999). Natural separation efficiency in electric submersible pump systems. MSc thesis. The University of Tulsa.

Shakirov A.M. (2011). An Accurate Model to Predict Natural Separation Efficiency based on Common Data. MEALF-00098. *Middle East Artificial Lift Forum*, Bahrain, 8 p.

Urazakov K.R., Tugunov P.M., Alimetov Sh.A. (2021). Simulation of Gas-Liquid Flow at the Intake of Electric Centrifugal Pumping Units with Wire-Frame Filter. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*, 332(11), pp. 68–77. (In Russ.) https://doi.org/10.18799/24131830/2021/11/2879

Vieira S.C., Custodio D.A.S., Verde W.M., Biazussi J.L., de Castro M.S., Bannwart A.C. (2021). Experimental Investigation of Gas-Liquid Separation for Two-Phase Flow within Annular Duct of an ESP Skid. *Journal of Petroleum Science and Engineering*, 198, 29 p. https://doi.org/10.1016/j.petrol.2020.108130

Volkov M.G. (2016). The Metodology Calculation Natural Gas Separation Efficiency During Well Startup. *Neftegazovoe delo*, 14(4). pp. 45–49. (In Russ.) https://ngdelo.ru/files/ngdelo/2016/4/ngdelo-4-2016-p45-49.pdf

Yushchenko T.S., Demin E.V., Ivanov V.A., Khabibullin R.A., Volkov A.V. (2024). Case Studies and Operation Features of Transient Multiphase flow in low-flow wells with multistage fracturing and extended horizontal wellbore operated with ESP in PSA mode. *Petroleum Research*, 9(4), pp. 657–672. https://doi.org/10.1016/j.ptlrs.2024.06.005

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