Electrical submersible centrifugal pump units of the new generation for the operation of marginal and inactive wells with a high content of free gas and mechanical impurities

A Trulev¹, ⁵, V Verbitsky², S Timushev³ and P Chaburko⁴, ⁶
¹Rimera Group of companies, Moscow, Russian Federation
²Gubkin Russian State University of Oil and Gas, Moscow, Russian Federation
³Moscow Aviation Institute, Moscow, Russian Federation
⁴Bauman Moscow State Technical University, 5 Second Baumanskaya Street, Moscow, 105005, Russian Federation
⁵e-mail: aleksey.trulev@rimera.com
⁶e-mail: chaburko@bmstu.ru

Abstract. The paper is devoted to the development of innovative solutions for oil production in complicated conditions using submersible pumping systems. The conditions in which these systems should operate are described. A mathematical model used for computational fluid dynamic simulation is presented. Technical solutions, as well as their key features and advantages over existing systems are presented. The main conclusions are made.

1. Introduction
In recent years, there has been an emerging steady tendency towards the deterioration of the operating conditions of wells in the oil fields of the Russian Federation. This is due to the fact that the fields with favorable geological and field parameters enter the late stage of development, with a corresponding increase in the relative share of oil production from marginal fields with hard to recover reserves.

Active work is underway to intensify the inflow from the bottom hole zone, to increase oil withdrawals, with the result that most of the wells were transferred to operating modes with bottom hole pressures of 3–5 MPa. The growth rate of the mean time between failures for equipment has begun to decline. It became clear that at a large number of wells, electrical centrifugal pumps with the applicable endurance group are no longer able to ensure a further significant increase in parameter of time between failures, since they do not correspond to the changed operating conditions [1].

Submersible pumping equipment of serial production for well operation is often simply unable to work in such complicated conditions.

The share of marginal wells in the Russian Federation is about 30-40%, and most of them have complicating factors: high content of free gas, mechanical impurities, corrosion, scale. A pressing
issue is the introduction of an effective technology for their operation with nonfailure operation time of at least 600 days [3].

In line with this, the development, research and pilot implementation of innovative technologies for oil production in complicated conditions using submersible pumping systems becomes an actual problem.

2. Mathematical model

The calculation model is based on the Navier—Stokes (1) and continuity (2) equations:

\[
\frac{\partial \mathbf{V}}{\partial t} + \nabla \cdot (\mathbf{V} \mathbf{V}) = -\frac{\nabla P}{\rho} + \frac{1}{\rho} \nabla (\mu + \mu_t) (\nabla \mathbf{V}) \tag{1}
\]

\[
\nabla \cdot \mathbf{V} = 0 \tag{2}
\]

where

- \( \mathbf{V} \) – velocity vector;
- \( t \) – physical time;
- \( P \) – pressure;
- \( \rho \) – density;
- \( \mu \) – molecular viscosity;
- \( \mu_t \) – turbulent viscosity.

These equations are supplemented with the corresponding equations of the turbulence model. The calculations were performed using the standard \( k-\varepsilon \) (turbulent energy – dissipation rate) turbulence model [9], in which the turbulent viscosity is determined from relation

\[
\mu_t = 0.09 \cdot \rho \cdot \frac{k^2}{\varepsilon} \tag{3}
\]

The presented mathematical model was successfully used in [16–20].

3. Proposed solutions

The new complete set of equipment is proposed: a combination of a special design of stages, pump and elements of a system. New technical solutions are protected by patents for inventions, for example [8] – the conceptual development of the Rimera Group of companies and specialists of the Gubkin Russian State University of Oil and Gas (Gubkin University) under the “White well” project [10].

Impellers have an additional blade ring of a special design, which allows to optimize the axial force acting on the impeller, significantly reducing it, almost three times. Due to the combination of cells and channels in the additional blade ring, the gas-liquid mixture is effectively dispersed, therefore the permissible content of free gas is increased by 10% [14].

The stages are made of cast Ni-Resist, which in terms of combination of the corrosion resistance and wear resistance characteristics is superior to ZhGr (powder steel based on iron (Zh) and graphite (Gr)). Materials testing in the abrasive environment showed that with only abrasive exposed to the surface, the wear rate of materials’ samples had similar values. The wear rate increased almost three times for the sample of guide apparatus from ZhGr, which was previously tested in a corrosion-active environment. That is, if the working elements were previously exposed to an acid solution, their wear resistance in an abrasive environment is reduced. Adding 1.5% hydrochloric acid to the model fluid increases the wear rate of materials many times. In this case, the advantages of Ni-Resist as a material more resistant to the effects of “washouts” are fully manifested [4]. In many wells there is a corrosion complication. According to the unified technical requirements (UTR) of the oil company Rosneft (UTR 6), it is not allowed to use pumps with stages made of powder steels for equipment of an abrasion-resistant version (group N3).
Radial-stabilized pumps with a compression assembly configuration belong to the highest-class equipment for wear resistance [1]. This is the most reliable equipment among electrical submersible centrifugal pump (ESP) units. Traditionally they are made for high pump delivery flow rate starting from 200 m$^3$/day. The design has been improved. Today, JSC Alnas manufactures such pumps in series for delivery flow rate from 15 m$^3$/day; it has become expedient to manufacture low-flow pumps in compression version. The high service life of compression pumps allows them to work continuously for three to five years without dismantling, thereby significantly reducing the cost of repair and installation of ESP units [13].

One may note the reliable operation of pumps for 15, 25 m$^3$/day; for example, at OJSC “Surgutneftegas” the nonfailure operation time is over 4 years. On average, compared to traditional equipment, the operation time increases by more than three times [10], [12].

After bedding-in the support washers, all the axial force is absorbed by the axial support in the protector. As a result, the performance factor of compression pumps can be 10–15% higher than that of traditionally designed ESP units [2].

Compression pumps work reliably in the left area, with a high content of free gas, since the axial load is absorbed by the axial support in the protector. Floating up is not observed in the right area.

The assembly of the compression pump is extremely simplified by design, eliminating the complicated operation of shimming, when plates are installed between the shafts. For accurate alignment of the shafts, a fixture is used that eliminates the need for a measuring tool and helps to avoid human-caused errors.

In addition to this, the specialists of R&D center of the Rimera Group of companies developed a stage of the 5th overall dimensions with an optimum delivery flow rate of 20 with the width of the channels of the flow part equal to ones in the stage with a performance of 125 m$^3$/day [11], [12].

An analogue is an offer of Schlumberger – pumps with a wide operating range. The operation of wells with a production rate of 25 m$^3$/day is proposed to be driven by pumps with an optimal flow rate of 125 m$^3$/day. In this case, the nominal flow rate is 0.2 of the optimal one. According to API 610, the reliability and safety standard developed by the American Petroleum Institute for pumps with face seals for the petroleum and petroleum refining industry, the recommended operating mode of the pump ranges from 0.7 to 1.1 of the optimum delivery flow rate. Only short-term operation at the flow rate of 0.5–0.7 from the optimal one is allowed; when working outside the recommended range, reversed currents occur that lead to pressure pulsations and vibration, an increase in axial and radial force that acts on the impeller of each stage. Moreover, when operating at a delivery flow rate of less than 0.5 from optimal, the pressure characteristic degrades and a possibility of surging, gas lock formation and pump starvation emerges even if there is a small amount of free gas at the pump inlet [6].

New pumping unit elements intended for efficient operation at low flow rates include gas separators with interchangeable inducers and multiphase modules with a new work concept.

Gas separator is considered an unreliable element of a pumping unit due to hydroabrasive cutting of the body. The reason is the reversed currents that occur if the pump delivery flow rate is more than two times less than the calculated gas separator flow rate, the optimum flow rate of the inducer installed at the inlet [5]. For example, the flow part of the gas separator is designed for a delivery flow rate of 250 m$^3$/day, and the most demanded pump delivery flow rate ranges from 15 to 80 m$^3$/day. Reversed currents are a trap for mechanical impurities, the concentration of which increases rapidly. A rotating abrasive ring can cut through the body and other elements of the gas separator.

In cooperation with the specialists of Gubkin University, vortex and centrifugal gas separators with replaceable elements of the flow part for delivery flow rate ranges up to 50, 100 and 250 m$^3$/day were developed [11].

The traditional solution aimed to reduce the angle of the blades at the inducer inlet is not advisable, since it unnecessarily increases the diffusivity of the flow part and reduces the efficiency of the inducer operation [5].
It was proposed to reduce the diameter at the inducer inlet, while maintaining the optimal flow part, the angles at the inlet, and at the same time maintaining the component parts list.

It was also decided to split the supply part of the gas separator, in which the axial stage is installed, and the separation chamber by a special conical sleeve. In the separation chamber, a separation process takes place; on the periphery a rotating ring with partially separated liquid is formed. In the design this ring presses on the fixed axial support in the form of a conical sleeve, then a high pressure gradient occurs, due to which efficient gas separation is carried out. Previously, the specified ring pressed on the blades of the stage that supplies the gas-liquid mixture of lower density, which led to reversed currents, dispersion, etc.

For the commonality purpose, it is allowed to use one gas separator for the whole range of for delivery flow rates from 15 m$^3$/day to the maximum rate indicated above.

It should be noted that gas separators designed for low-flow units have less power, which saves energy.

Gas separators developed in cooperation with the specialists of Gubkin University exceed known analogues in terms of separation properties and wear resistance [12].

In the centrifugal forces field it is effective to separate not only free gas, but also mechanical impurities. For marginal wells with a gas-oil mixture, a special design has been developed that combines a gas and mechanical impurities separator within one module [15].

Conventional multiphase modules for low-flow units disperse and compress the liquid-gas mixture (LGM). But, starting with a certain content of free gas at the module inlet, the reverse process of coalescence, merging and enlargement of gas bubbles begins [6], which limits the functionality of the module.

A new concept of compressor dispersing stages (DPT) – the circulation of fluid in the impeller. During the operation, in each stage the LGM is dispersed at the impeller inlet, compressed in the flow part, and the gas is partially separated at the impeller outlet. Gas with the main flow is directed to the next stage inlet, and a part of the liquid is directed to the same impeller inlet. In the Moscow Aviation Institute (MAI) computational studies of three-dimensional turbulent unsteady flow in DPT of different designs were conducted.

Figure 1 shows the distribution diagrams of the total pressure in one of the planes of the flow part of the multiphase stage.

![Figure 1: Distribution diagrams of the total pressure in one of the planes of the flow part of the multiphase stage.](image)
This allows to more than twice reduce the content of free gas in the flow part of the impeller, to eliminate gas locks for off-design operating modes. The DPTs atomize and disperse bubbles of liquid-gas mixture, prepare a homogeneous, fine-dispersed structure of the flow, carry out its preliminary compression and delivery flow to the main stages of the pump. When a pump is operating together with a DPT, the maximum volumetric content of free gas at the inlet is allowed 15% higher compared to the use of a pump without DPT.

For the operation of wells with a high content of free gas and mechanical impurities, protectors of a new generation with a dynamic labyrinth have been developed. The compensating element may be of the diaphragm or piston type.

The design has two gas bells (figure 2).

Figure 2. Sketch of the upper part of the protector with a dynamic labyrinth.

The advantages over the serial analogues:
- the gravity labyrinth to protect the upper face seal is replaced by a dynamic labyrinth (gas bell), which has absolute reliability, since moving face seals operating in adverse conditions are replaced with a fixed seal that is not subject to wear;
- the estimated separation efficiency of the dynamic labyrinth is 300 times higher than of the gravity one, since the centrifugal acceleration at the outer radius of the dynamic sleeve is corresponding number of times higher than the free fall acceleration;
• if there is even a small amount of free gas, which is always present in the reservoir fluid, a gas region forms under the bell, separating the face seal not only from mechanical impurities, but also from the reservoir fluid;
  • the lower gas labyrinth in the nipple protects the piston module from mechanical impurities and scale, thereby eliminating the probability of piston seizure;
  • a pumping device in the form of a labyrinth-screw pair provides that the oil pressure in the area of the face seal exceeds the pressure of the reservoir fluid by 7 meters of water column, which is necessary for the movement of the piston and reliable sealing [7];
  • the mounting height of the piston type protector is reduced by 40% compared to the analogue, the cost of repair is reduced due to the smaller number of parts;
  • the presence of a filter-heat exchanger and inducer in the area of the bearing assembly allows cooling the thrust bearing;
  • the face seal is not hydraulically connected to the compensating element, therefore, when lowering, starting or stopping the engine, the face seal does not contact the formation fluid, it works in an enclosed oil area;
  • in comparison with diaphragm type analogues, the effect of “thermos” is eliminated, heat removal is better, penetration of dissolved gas, which degrades the physical properties of the submersible electric motor oil and forms foam during the transition to the free state, through the diaphragm is impossible.

About 70% of all fields in Russia have two or more oil-bearing reservoirs, which are located in parallel planes at different depths.

A unit for dual production, taking into account the features of marginal reservoirs operation, has been developed. The unit is one-string, with one pump.

A reservoir switching valve is used, which allows alternate production from each reservoir.

The unit alternately pumps out the reservoir fluid from the upper and lower reservoir, for a relatively small amount of pressure change, while maintaining a given pressure drawdown for each reservoir. The pump works in continuous operation mode.

Accounting of samplings and measurement of the main parameters for each of the developed reservoirs in accordance with the requirements of RD 153-39.0-109-01 in the field of drill-hole hydrodynamic research and downhole logging is performed when one of the reservoirs is shut off.

Schlumberger uses two units to operate two reservoirs. These units are installed in the same well. Accordingly, the radial overall dimension of each unit should be less than in the case of using one unit.

In comparison with the above described option, the use of one unit allows to significantly save on the cost of equipment, installation and electricity, since the performance factor of one unit is higher.

There is an opportunity to complete unit with serial centrifugal, sucker-rod or progressive cavity pumps.

The unit has a versatility of application, both for dual production and dual injection.

The opportunity of using the algorithm of operation with varying pressure amplitude in the reservoirs from 1 to 250 atmospheres according to a given program and the possibility of changing the operation program, without removing the unit from the well, are implemented.

New innovative submersible equipment allows, in cooperation with scientists from Gubkin University and MAI, to develop a fundamentally new wave technique for fields exploitation with controlled impact on the reservoir, with the aim of increasing oil recovery for the subsequent introduction of new oil production technology by service departments of Rimera Group of companies and by Yuganskneftegeofizika company.

When the pump stops during operating in constant mode and especially in the short-term operation mode, with a backpressure valve installed at the pump outlet, there is a possibility that the gas will fill the pump through the inlets and the formation fluid will flow out into the annular space. This happens just in the same way that gas is collected in a glass with the bottom up-directed, if the glass is installed in a liquid-gas mixture. In this case, there will be considerable difficulties in starting the pump, since the pressure developed by it is proportional to the density of the working medium, and the gas density
is three orders of magnitude lower than the liquid density. The problem is particularly urgent for low-flow pumps. In cooperation with specialists from Gubkin University and RN-Uganskneftegas company, shut-off and gas exhaust modules are being developed that can successfully solve this problem.

Under the integration project “White well”, a comprehensive selection of material for the entire suspension and electrical submersible equipment is carried out for specific operating conditions. A technique that intended for the selection of material taking into account the content of corrosive components in the formation fluid has been developed in the Pervouralsk New Pipe Plant (PNTZ).

4. Conclusions

The innovative solutions proposed in the paper increase the efficiency of oil production in complicated conditions, which is proved by computational fluid dynamic simulation, as well as by operational testing.

Published under licence in Materials Science and Engineering by IOP Publishing Ltd.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

References

[1] Yakimov S B 2016 On the prospects for the use of radially stabilized compression centrifugal pumps to improve the efficiency of operation of wells of the AV field group of the Samotlor reservoir (О перспективах использования радиально стабилизированных вихревых насосов для повышения эффективности эксплуатации скважин пластов группы AV Самотлорского месторождения) Territory “NEFTEGAZ” (6) pp 78–86

[2] Loginov V F 2016 Compression pumps for oil production in complicated conditions (Компрессионные насосы для нефтедобычи в осложненных условиях) Oil and gas journal (6) pp 54–56

[3] Kosilov D A 2015 Improving the efficiency of the management of the mechanical stock of the well in the current macroeconomic conditions. Mechanized production (Повышение эффективности управленческого механизированного фонда скважин в текущих макроэкономических условиях) Proceedings of the specialized section of the conference of Rosneft Oil Company (Moscow) pp 8–11

[4] Smirnov N I, Smirnov N N and Gorlanov S F 2010 Scientific basis for increasing the resource of ESP units for marginal wells (Научные основы повышения ресурса УЭЦН для малодеячных скважин) Engineering practice (Inzhenernaya praktika) (7) pp 18–21

[5] Borovskiy B I and Petrov V I 11975 High speed vane pumps (Высокооборотные лопаточные насосы) (Moscow, Mashinostroyeniye Publ.)

[6] Drozdov A N 1982 Development of methods for calculating the characteristics of a submersible centrifugal pump for the operation of wells with low pressure at the entrance to the pump (Развитие методик расчета характеристик погружных вихревых насосов при низком давлении на входе в насос). Thesis for the degree of PhD

[7] Golubev A I 1986 Seals and sealing technology (Уплотнения и уплотнительные устройства) Handbook 449 p

[8] Patent of the Russian Federation No. 2449176 for an invention: Step of a submersible multistage centrifugal pump Application filed on July 12, 2010 published on April 27 2012

[9] Wilcox D. C. 1994 Turbulence modeling for CFD (DCW Industries, Inc) 460 p

[10] Trulev A V 2015 New equipment of CJSC Rimera for wells with complicated operating conditions, Proceedings of the conference on mechanized production Oil and Gas Vertical (Neftegazovaya Vertikal)19
[11] Trulev A V 2015 New equipment of OJSC Alnas for wells with complicated operating conditions *Engineering Practice (Inzhenernaya praktika)* (12) pp 71–73

[12] Trulev A V, Sabirov A A, Sibirev S V, Verbitsky V S and Timushev S F 2017 Submersible ESP units with wide channels in the flow part for the production of formation fluid from marginal wells with a high content of mechanical impurities *Engineering Practice (Inzhenernaya praktika)* (1–2) pp 60–63

[13] Trulev A V 2017 Submersible ESP unit of new generation. Innovative solutions for combatting complicated conditions in case of the marginal field, *Oil and Gas Journal Russia* (4) pp 30, 34

[14] Trulev A V 2017 New submersible centrifugal pumps with gray cast iron stages and between bearing design *Engineering Practice (Inzhenernaya praktika)* (5) pp 74–76

[15] Trulev A V and Grachev V V 2018 Bench tests of a submersible gas and mechanical impurities separator in model mixtures *Gas Industry (Gazovayapromyshlennost')* (8) pp 20–24

[16] Lomakin V O 2015 Investigation of two-phase flow in axial-centrifugal impeller by hydrodynamic modeling methods *Proceedings of 2015 International Conference on Fluid Power and Mechatronics, FPM 2015, November 24* pp 1204–1206 DOI: 10.1109/FPM.2015.7337302

[17] Lomakin V O, Kuleshova M S and Bozh’eva S M 2016 Numerical Modeling of Liquid Flow in a Pump Station *Power Technology and Engineering* January 1 49(5) pp 324–327 DOI: 10.1007/s10749-016-0623-9

[18] Lomakin V, Cheremushkin V and Chaburko P 2018 Investigation of vortex and hysteresis effects in the inlet device of a centrifugal pump *Global Fluid Power Society PhD Symposium, GFPS 2018*, September 25 2018 DOI: 10.1109/GFPS.2018.8472374

[19] Lomakin V O, Kuleshova M S and Kraeva E A 2015 Fluid Flow in the Throttle Channel in the Presence of Cavitation *Procedia Engineering* 106 pp 27–35 DOI: 10.1016/j.proeng.2015.06.005

[20] Gouskov A M, Lomakin V O, Banin E P and Kuleshova M S 2017 Minimization of Hemolysis and Improvement of the Hydrodynamic Efficiency of a Circulatory Support Pump by Optimizing the Pump Flow path *Biomedical Engineering* November 1 51(4) pp 229–233 DOI: 10.1007/s10527-017-9720-9