

Experimental studies of the efficiency of high-speed ESPs

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Abstract: The purpose of the present research paper is to estimate the energy efficiency of ESP-operated low production rate wells (up to 100 m³/d).The data on pumps energy efficiency, including the high-speed ESPs, were consolidated and analyzed. The bench test of high-speed ESPs and comparison with field tests allowed to determine the efficiency adjustment factors and establish functional dependencies of energy parameters on shaft rotation speed;theobtainedcorrelations were suggested for recalculation of nominalvalues in bench tests. The paper also indicates that the average efficiency for the high speed ESPs is 12-17% higher in absolute values and 40-68% higher in relative values, compared with the efficiency of pumps with a nominal rotation speed of 3000 rpm. The suggested approach can be expanded as a methodology for wells with more complex operational conditions and more complex pump systems.

1 Introduction

In today's oil and gas production environment, enhancement of a company's operations efficiency becomes extremely important. In addition, the growing electricity tariffs on the market has set a trend for a steady increase in the share of electricity costs in the company's total operational expenses. Significant efforts are made to optimize the company's costs. Thus, every year, the issue of maintaining the energy efficiency of oil production becomes more and more critical.

Presently, the total power consumption for lifting fluids for Russian oil companies is 55-62% of the total energy consumption, while for water injection it is 22-30%, and for oil and gas treatment and transportation it amounts to 8...23%. The remaining oil production processes are less energy-consuming [1]. Electric submersible pumps (ESPs) produce 75% of all oil in Russia and are installed in more than 60% of the Russian well stock. Therefore, the ESP energy efficiency is a crucial factor.

In the present paper we investigate methods of estimating energy efficiency of wells with low flow rate (up to 100 m³/d) operated by ESPs. Energy efficiency is measured by

the pump efficiency factor, which is equal to the ratio of useful hydraulic capacity generated by ESP to the consumed electric power.

2 ESP system useful capacity losses

The ESP system consists of the following components installed and connected in series: surface operating unit - step-up transformer - cable line - downhole electric motor - other elements (motor seal; gas separator; gas handler, etc.) - pump (Fig.1). Thus, the total efficiency can be split into individual efficiency factors attributed to various components of the ESP system and indicating the total ESP energy efficiency. Figure 2 shows the classification of energy losses in ESP components, including hydraulic and electric losses. The electric losses include losses in the cable and the MLE, surface operating unit, transformer, downhole motor; the hydraulic losses include losses on tubing friction, flow line backpressure at the wellhead, losses in ESP stages [2].

Surface Operating Unit

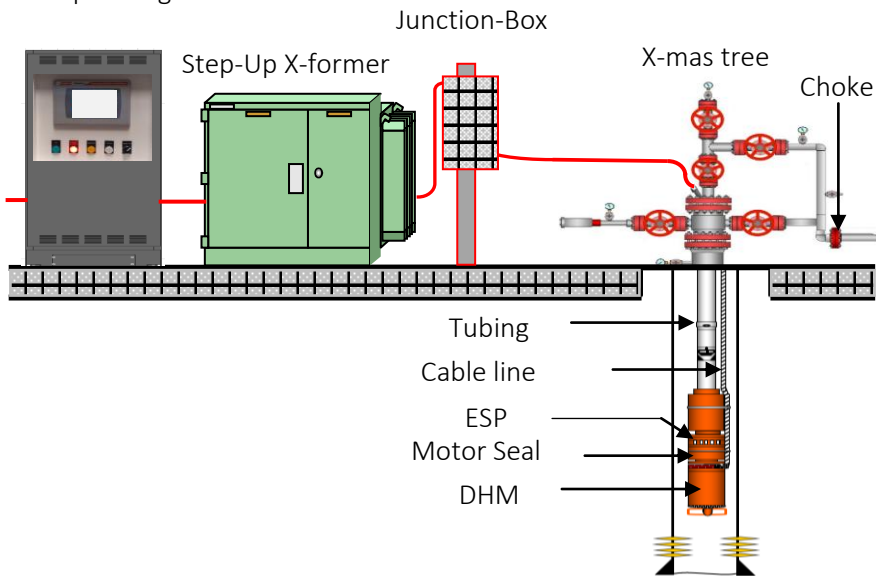


Fig. 1. Main ESP components.

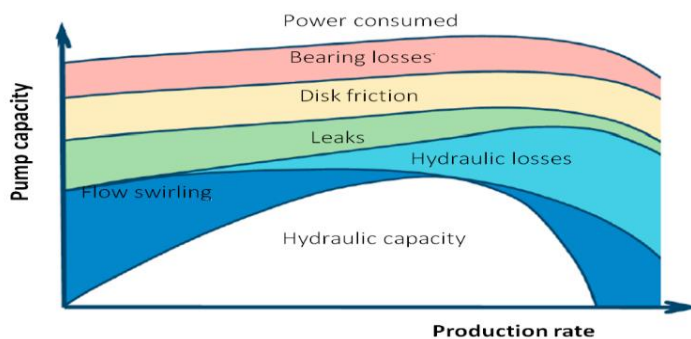


Fig. 2. ESP energy losses.

The downhole electric equipment includes the following components which are characterized by significant energy losses: electric submersible pump (η_{ESP}), downhole motor (η_{DHM}), cable line (η_C), other elements (η_{other}), tubing (η_{tb}). The efficiency factors of cable lines can be estimated based on the known dependencies [3]. Considering the motor load, rotation speed, and relative pump capacity, the motor efficiency values can widely range from 82 to 98%. Surface ESP equipment (η_{se}) includes surface cable, high voltage junction box, step-up transformer, and surface operating unit. These elements are characterized by relatively low energy losses, with an efficiency of around 97%. The efficiency of an ESP with the components connected to the same circuit depends on the value of each element and can be recorded as:

$$\eta_{ESP} = \eta_{ESP} \cdot \eta_{DHM} \cdot \eta_C \cdot \eta_{other} \cdot \eta_{tb} \cdot \eta_{se} \quad (1)$$

According to the field data given in [4], the efficiency of ESPs of various manufacturers during well operation can be relatively low varying in the range of 23-57%. Thus, the choice of energy-efficient ESP + downhole motor assembly ensures energy-saving operation of the unit as a whole.

3 ESP efficiency calculation algorithm

The calculation algorithm for ESP energy efficiency is well known [5] and used in many software applications for ESP design and analysis. This study seeks to adjust the algorithm given the limited availability of field data based on the consolidation and analysis of over 2,500 modes of well operation and the integration of the obtained statistical data with the bench test results of ESP + downhole motor assembly.

The efficiency of the total submersible system can be represented as the ratio of the useful ESP- produced hydraulic capacity N_{hydr} and the electric power consumed by the system N_{el} :

$$\eta_{ESP} = \frac{N_{hydr}}{N_{el}} \quad (2)$$

The power consumption for the wells under study was determined based on the readings of the power meters installed in the surface operating unit. The readings of the electricity meters are collected in the database as values of the daily power consumption of the pumping system.

The useful hydraulic capacity of aESP was estimated as:

$$N_{hydr} = \alpha \cdot Q_{av} \cdot (P_{dis} - P_{int}), \quad (3)$$

where Q_{av} is the average flow rate, normalized to the respective pressure and temperature conditions, m^3/d ; P_{dis} is the pump discharge pressure, MPa; P_{int} is the pump intake pressure, MPa; α is the conversion factor from experimental metrics to the measurement system.

The biggest challenge for the efficiency of calculations is an accurate estimation of the pressure differential developed by the pump ($P_{dis} - P_{int}$). The inlet pressure was measured by telemetry gauges in the studied wells. The discharge pressure was estimated by hydraulic correlation based on the wellhead parameters. The change of PVT properties of the tubing fluid due to the intensive gas separation process was considered [6]. The research also contains the assumptions that the tubing is leak-proof, tubing parameters correspond to the ones specified in the database (tubing wells are free from depositions).

The pressure at the pump discharge point was determined based on pressure distribution in the tubing above the pump based on the buffer pressure values P_{buf} , well design, flow parameters Q_{av} , produced fluid water cut B, gas separation coefficient at the pump intake

K_{sep} , physical and chemical properties of formation fluids and their dependency on pressure and temperature [7]:

$$P_{dis} = f(P_{buf}, Q_{av}, B, P_{sep}, PVT) \quad (4)$$

4 Testing

4.1 Field tests

This research was primarily aimed at studying and comparing the results of evaluating the efficiency of ESPs from different manufacturers, based on bench tests and field tests conducted on the wells with working telemetry gauges. This study was aimed primarily at studying and comparing the results of evaluating the efficiency of ESPs from different manufacturers, based on bench tests and field tests performed on wells with working telemetry gauges.

To provide an accurate analysis of the efficiency of the pumping system and the possibility to compare the field data with the bench data, wells with a high water cut ($WC > 95\%$) were selected, with a BHP ranging from 3.8...to 5.5 MPa, an average gas factor of $33 \text{ m}^3/\text{m}^3$ and saturation pressure of 7 MPa; that is in conditions of gas consumption at the pump intake not exceeding 2% [6]. The study considered the manufacturers of ESPs, widely represented in the Khanty-Mansiysk Autonomous Okrug, with a nominal shaft speed of 3000 and 10000 rpm. Based on the data of 2500 process modes (actual production rate, average dynamic head, and energy consumption), the pump efficiency was calculated for various values of pump performance on an extended time scale (Figure 3).

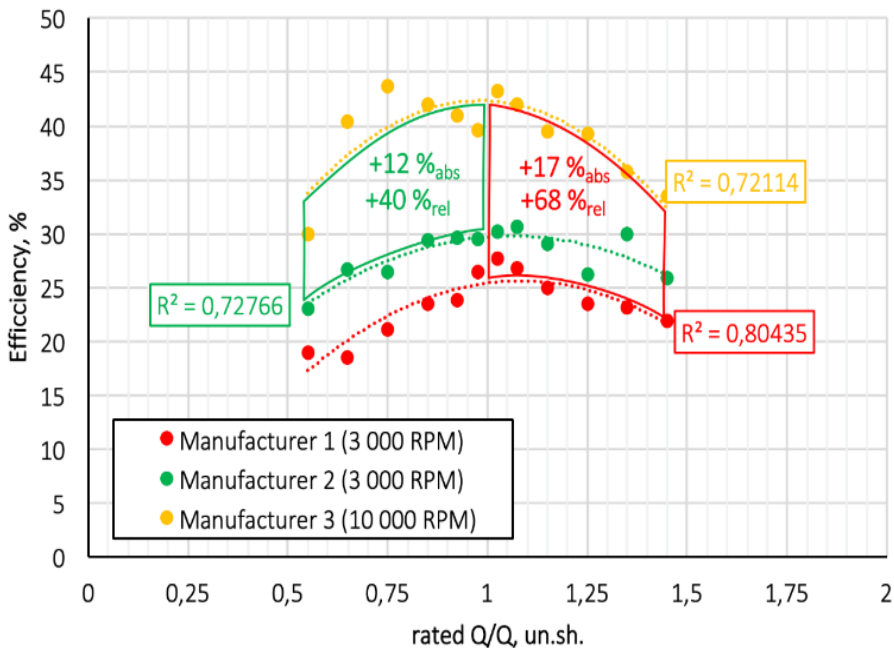


Fig.3. Efficiency of ESPs of various manufacturers with the nominal capacity below $100 \text{ m}^3/\text{d}$.

The average efficiency value for high-speed ESPs is 12-17% higher in absolute value and 40-68% higher in relative value than that of pumps with a nominal speed of 3000 rpm.

High-speed electric submersible pumps are capable of operating at a speed from 1,000 to 12,000 rpm with a permanent magnet motor having three pairs of poles. The nominal rotation speed of 10 000 rpm is achieved at 500 Hz. The motor performance is shown in Figure 4. TI Impellers are made of materials with increased wear resistance. The total length of the ESP is significantly lower (by 50-70%) compared to ESPs of other manufacturers; that makes possible full-scale pump assembling and testing at the factory. As a result, the system requires minimum time and effort for installation, and the compact design allows the pump to be run-in in intervals with high rates of wellbore buildup [8].

In accordance with GOST 56624-2015 to determine the energy efficiency of submersible pumps during oil production, pumps from three different manufacturers were ranked by energy efficiency. Pumps with less than 100 m³/d capacity produced by manufacturer No 1 correspond to energy efficiency classes

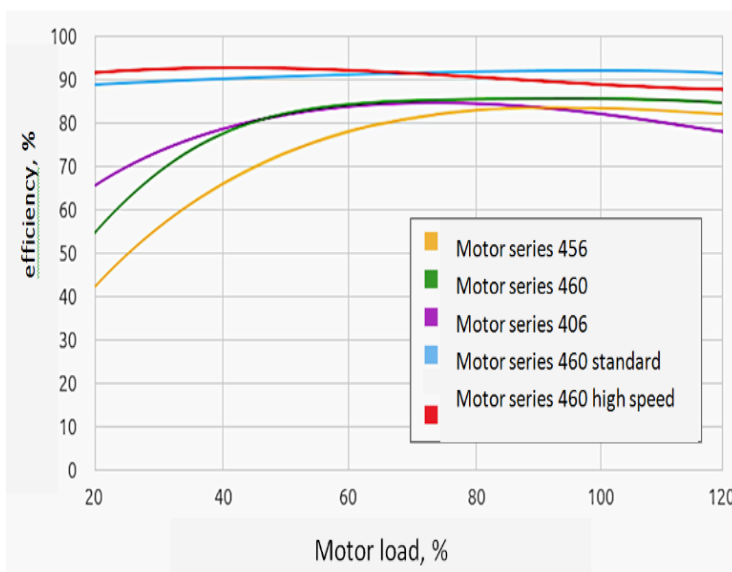


Fig. 4. Characteristics of induction submersible and permanent magnet motors.

E1 and E2, pumps of manufacturer No 2 - to E2 and E3 classes, pumps of manufacturer No 3- to E3 class.

4.2 Bench tests

Pump performance analysis and its comparison in bench and field conditions were conducted by bench test with water medium for one section (56 stages) of a high-speed pump of manufacturer No. 3. The test was supported by specialists of Gubkin Russian State University of Oil and Gas.

The test resulted in obtaining pressure and power consumption parameters of the pump at 2000-10000 rpm (Fig. 5). Figure 5 shows a significant increase in pump assembly efficiency when the rotation speed changes from 2000 rpm to 5000 rpm (Zone I), and a gradual efficiency decrease after 5000 rpm (Zone II). The obtained result also relates to the pump efficiency. The assembly efficiency at 10,000 rpm during the bench test differs from the field test by 12% in absolute value and by 17% in relative value (40% and 68% respectively). Such a significant deviation is explained by the fact that the bench test does

not consider tubing friction losses, surface electrical equipment losses, wellhead losses, and cable line losses.

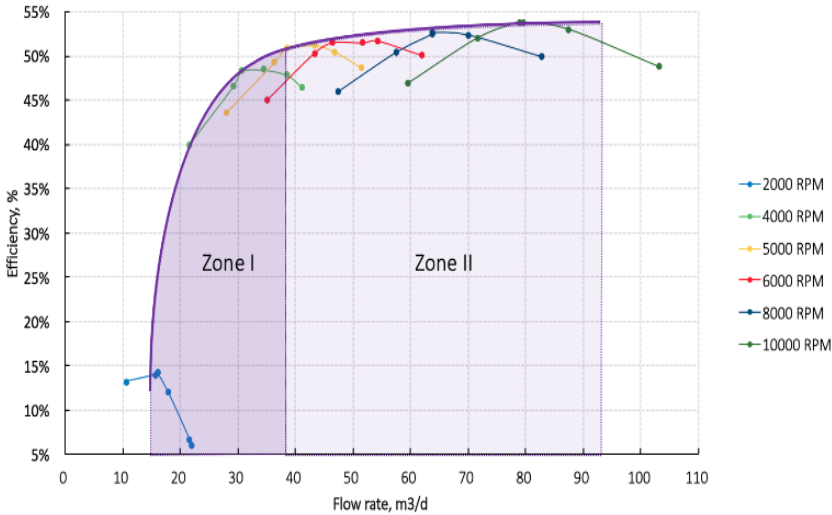


Fig. 5. Pump efficiency at 2000-10000 rpm.

The following conclusions were made based on the bench tests for high-speed pump systems:

1. The affinity law is observed for the head-capacity curve, but not for power consumption.
2. The pump efficiency is functionally dependent on the shaft rotation speed.
3. It has been found that higher rotation speed leads to increased pump stage efficiencies. High-speed pump units with a nominal rotation speed of 10000 rpm should be operated with the shaft speed of at least 5000 rpm to ensure energy efficiency in production.

When selecting high-speed pumps or optimizing well performance, the pump head should be determined based on the affinity law. Efficiency and capacity estimation should be based on adjusting correlations. It is known that for the pumps with standard rotation speed (3000 rpm) according to GOST 6134-2007 the following dependence for efficiency adjustment is applied:

$$\eta_{op} = \frac{\eta_t}{\eta_t + (1 - \eta_t) \left(\frac{n_t}{n_{op}}\right)^{0.17}}, \quad (5)$$

where η_{op} is the efficiency under the operating RPM; η_t is the efficiency during the test. Similar corrections are made to adjust the efficiency in case of temperature change:

$$\eta_{op} = \frac{\eta_t}{\eta_t + (1 - \eta_t) \left(\frac{\nu_t}{\nu_{op}}\right)^{0.07}}, \quad (6)$$

where η_{op} is the water kinematic viscosity under the test temperature; η_t is the water kinematic viscosity under the operating temperature.

When consolidating the bench test results of high-speed pumps, correlation (4) does not ensure precision and should be adjusted. To enable the experiments as part of the present research, the factor α was specified for the index of $(n_t/n_{op})^\alpha$. The general correlation

dependence for the pump of manufacturer No 3, characterizing pump efficiency dependence on the RPM, can be recorded as:

$$\eta_{op} = \frac{\eta_t}{\eta_t + (1 - \eta_t) \left(\frac{n_t}{n_{op}}\right)^\alpha} \tag{7}$$

The empirical coefficient can be recalculated individually for each stage, depending on the manufacturer, based on statistical data resulting from tests using regression analysis.

The foreign literature uses the Akeret correlation for efficiency adjustment [9]:

$$\eta_{op} = 1 - (1 - \eta_r) \left(\frac{n_t}{n_{op}}\right)^\alpha \tag{8}$$

Using dependence (7), η_{op} can be estimated with high accuracy.

Figure 6 shows the dependence of efficiency on RPM for standard and high-speed pumps of manufacturer No 1 and No 3 based on GOST 6134-2007 and the Akeret correlations. The pump efficiency values based on the bench tests and the calculations demonstrate identical dynamics with a permanent deviation of 10-11% in absolute numbers.

It is known that ESP bench test performance significantly differs from the nominal one. The bench test performance obtained in the course of a serial pump operation with water medium considers geometry deviations of the flow channels as well as the quality of impellers and diffusers.

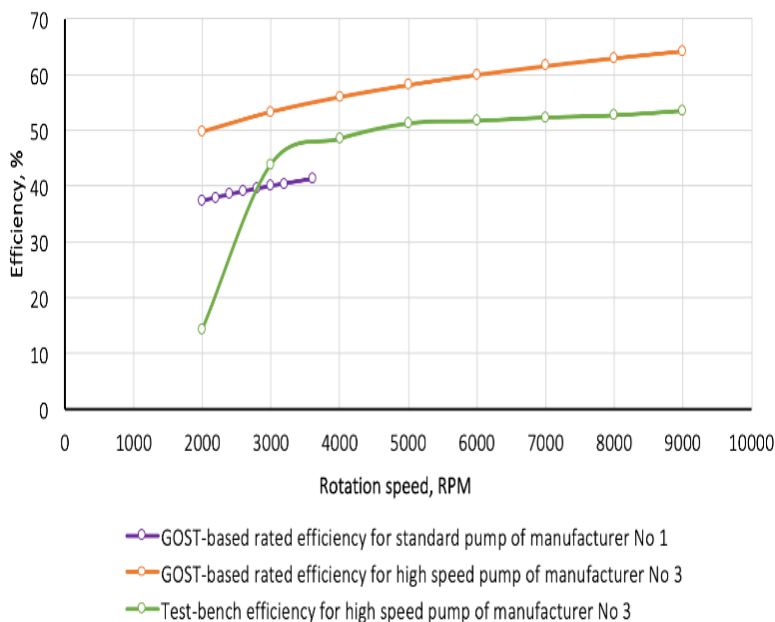


Fig.6. Nominal (datasheet) and bench efficiency for pumps of manufactures No. 1 and No. 3.

During the analysis of the nominal (datasheet) and the test-bench performance of high-speed pumps in the range of 5000-10000 rpm demonstrating the highest energy efficiency, the authors of the study suggested an approach to assessing the efficiency of pumps of various manufacturers. Table 1 gives an example of generalized correlations for bench efficiency for the pump of manufacturer No 3.

Table 1. Generalized bench test correlations for high-speed pumps of manufacturer No. 3.

Base correlation name	Type of correlation	Type of correlation adjusted to bench tests results	Adjusting coefficients, un.fr.	Rel. deviation, %
GOST 6134-2007	$\eta_{op} = \frac{\eta_t}{\eta_t + (1 - \eta_t) \left(\frac{n_t}{n_{op}}\right)^{0.7}}$	$\eta_{op} = \frac{\eta_t}{\eta_t + (1 - \eta_t) \left(\frac{n_t}{n_{op}}\right)^{\alpha - A}}$	$\alpha = 0,061; A = 10$	0,22
Akeret correlation	$\eta_{op} = 1 - (1 - \eta_r) \left(\frac{n_t}{n_{op}}\right)^{\alpha}$	$\eta_{op} = 1 - (1 - \eta_r) \left(\frac{n_t}{n_{op}}\right)^{\alpha - A}$	$\alpha = 0,1; A = 0,1$	0,22

5 Conclusions

The availability of power consumption measurements and data on well operation modes allows estimating ESP efficiency values. This algorithm of efficiency estimation is a convenient tool for monitoring the energy efficiency of the producing well stock.

The above experimental studies demonstrate that the nominal pump efficiency can be recalculated to bench-test characteristics with high accuracy, and with the availability of substantial field data, to the operational characteristics even without data on individual components' efficiency. The efficiency estimate can be applied to estimate the energy efficiency of the pumps from different manufacturers using correlations (6) and (7). The suggested approach can be expanded as a methodology for wells with more complicated operating conditions and more complex pump units.

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