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Pump Efficiency Dependence on Variable Rotational Speed

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Abstract. To improve the efficiency of the main petroleum pipeline operation and planning of operating modes when using the method of changing the rotor speed, it is necessary to carefully evaluate and predict the efficiency of pumps depending on the rotor speed. Therefore, experimental research of the dependence of efficiency on the rotor speed is needed. Various modes were considered: from the current frequency of 50 Hz to 25 Hz. The results of the study show us that with a decrease of the rotor speed, there is also a decrease in efficiency, which is opposed to the theory of similarity. The obtained results indicate that during the operation and planning of work, it is necessary to take into account the efficiency of the pumps for the correct forecasting of energy costs.

1. Introduction

Ensurance of the energy efficiency of main pipeline systems for the transport of oil and petroleum products is one of the key tasks in the process of their operation, at the same time energy spent for electricity to drive pumping units is the highest of energy costs [1, 2].

In order to ensure the technological process of pumping in such a way as to rich optimal mode with the lowest resource consumption it is necessary both to carefully plan the operating modes of the pumping units and to control and monitor their technical condition [3].

Currently, the most promising and progressive method of control the operating mode of the petroleum pipeline to ensure the required capacity is a variable frequency drive (VFD) of pumping units [4]. The development of this method makes it possible to reduce the consumption of electricity, eliminate water hammer in the technological (process) piping and increase the overall level of automation of control over the pumping process [4].

Obviously, along with a decrease of the rotor speed, there are also changes in the energy characteristics of the pumping unit. In particular, with a decrease of the rotor speed, the power consumed by the electric motor also decreases, which in turn affects the efficiency of the electric motor: with a decrease of the degree of load of the electric motor, a decrease of the efficiency also occurs [6,7]. At the same time, based on the similarity theory, despite the changing of the rotor speed (operating in similar modes) the efficiency of the pumps themselves is considered to be unchanged [8].

However, in real operation conditions, it is impossible to keep a complete (absolute) similarity. Applying the similarity theory in practice, a number of assumptions are made, including the invariability of the efficiency for similar modes. In practice, a decrease of the pump rotor speed leads

to a decrease of the Reynolds number and an increase of the relative value of mechanical losses in the bearings and, as a consequence, to a decrease in the pump efficiency [9].

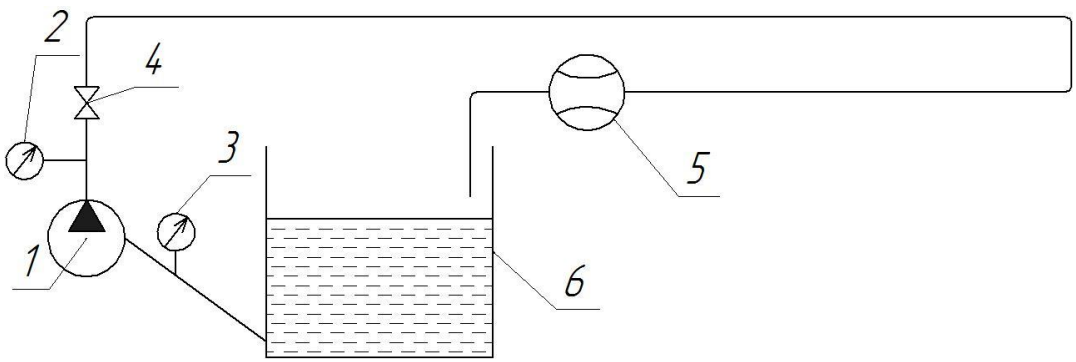
Consequently, in order to ensure effective planning of the operating modes of pumping units, it is also necessary to take into account the change in the pump efficiency depending on the shaft rotation frequency, despite the fact that, based on the theory of similarity, the pump characteristics are recalculated based on the equality of the efficiency in similar modes. [10, 11, 12].

Acceptance of the invariability of the efficiency when recalculating the pump characteristics for different rotor speeds can lead to errors in planning of the operating modes of the pumping units, as well as lead to incorrect conclusions about the technical condition of the unit during parametric diagnostics.

In order to confirm the above, the authors determined the actual efficiency of a centrifugal pump with an asynchronous electric motor, equipped with a frequency converter, depending on the speed of the pump rotor.

2. Research description

The analysis of the dependence of the efficiency of a centrifugal pump on the shaft rotation frequency is carried out according to the results of testing a laboratory pumping unit. This laboratory facility includes: a monoblock pump unit KM-40-25-160/2-5-2M-UZ, equipped with an AIR80V2 asynchronous electric motor, measuring instruments (pressure and vacuum gauge, electromagnetic flowmeter VSE-I), a control valve on the discharge pipeline, a water tank. A schematic diagram of the laboratory facility is shown in Figure 1.



1 – pump unit KM-40-25-160/2-5-2M-UZ; 2 – pressure gauge; 3 – compound pressure gauge; 4 – control valve; 5 – electromagnetic flow meter; 6 –water tank.

Figure 1. Schematic diagram of the laboratory facility.

The pump unit is equipped with a Hyundai N700E frequency converter, which allows to change the frequency of the electric current in the range from 0 to 50 Hz, which corresponds to the range of the pump rotor speed of 0–2900 rpm.

The pump was tested in accordance with GOST 6134-2007 (ISO 9906: 1999). «Rotodynamic pumps. Test methods». The tests are supposed to be carried out without adjusting the developed head, taking into account the friction energy losses from the pump nozzles to the pressure gauges. The liquid pumped over by the pump during the test was water which temperature was 20–22 °C.

The definition of the pressure created by the pump was carried out due to the GOST 6134-2007 (ISO 9906: 1999) according to the following relationship, which determines the pump pressure as the difference in specific energies in the discharge and suction nozzles [13]:

$$H = Z_2 - Z_1 + \frac{P_2 - P_1}{\rho g} + \frac{v_2^2 - v_1^2}{2g}, \quad (1)$$

where Z_2, Z_1 are the heights of the centers of the section above the reference plane, where the pressure is measured, at the discharge and suction, respectively; P_2, P_1 are the measured overpressures at the discharge and suction of the pump, respectively; v_2, v_1 are the average velocities of fluid movement in the discharge and suction pipelines at the points of connection of the pressure measuring instruments, respectively.

The difference in elevation between the points at which the pressure and vacuum gauge are installed is 35 cm, the inner diameter of the suction line is 40 mm, and the discharge line is 32 mm.

The installed frequency converter allows you to display on its screen information about the output power, which is the power consumed by the pump drive. The following power characteristics were calculated: useful power of the pump, efficiency of the pump unit (η_{pu}), efficiency of the electric motor (η_e) and efficiency of the pump (η_p). Because of the laboratory pump is a monoblock, the output power of the electric motor (N_e) is the power consumed by the pump.

The tests were carried out in the following sequence: for current frequencies from 50 Hz to 25 Hz with a step of 5 Hz, the H-Q curve for pump was taken, the power consumed by the electric drive was recorded according to the readings of the frequency converter.

In order to assess the efficiency of the centrifugal pump there is a need to know the amount of energy lost in the electric motor, i.e. the efficiency of the electric motor. At the same time, the powerful characteristics of the electric motor will also depend on the frequency of the electric current and the loading of the electric motor. In particular, for asynchronous electric motors which has an underload, the part of reactive power increases in comparison with active power, i.e. reduced power factor $cos\varphi$ and efficiency [14, 15].

At the same time, in the specialized literature, functional dependencies are quite rare, which make it possible to assess the dependence of the efficiency of electric motors on the load factor. One of the equations that allows to evaluate the efficiency of asynchronous machines on the degree of loading of the electric motor, presented in [7]:

$$\eta_e = \frac{1}{1 + \left(\frac{1}{\eta_{e\,rat}} - 1\right)\beta}, \tag{2}$$

where $\eta_{e\,rat}$ is rated efficiency of the electric motor, for AIR80V2 $\eta_{e\,rat}$ = 81 %.

To determine β, use the equation:

$$\beta = \frac{\frac{\alpha}{K_{load}} + K_{load}}{1 + \alpha}, \tag{3}$$

where K_{load} is the ratio of the actual power to the rated, for AIR80V2 the nominal power is 2.2 kW;

The pump efficiency was determined from the following equation [16, 17]:

$$\eta_p = \frac{\rho g H Q}{N_e \eta_e}, \tag{4}$$

where ρ is a density of water circulating in the laboratory facility, ρ = 1000, kg/m^3; Q the volume rate of the pump, m^3/h.

The efficiency of the pumping unit was determined from Equation 6:

$$\eta_{pu} = \frac{\rho g H Q}{N_e}. \tag{5}$$

3. Analysis of test results

As it was mentioned before, the pump was tested at a current frequency of 50 to 25 Hz in 5 Hz steps. At the same moment, the rotational speeds of the pump shaft were approximately equal to 2900, 2600, 2300, 1700 and 1500 rpm. The recorded parameters were used to calculate the total head and power characteristics. First of all, the actual efficiency of the pumping unit was determined at different speeds of rotation of the electric motor according to the Equation 6. The results of calculating the efficiency of the pumping unit depending on the frequency of the current are shown in Figure 2.

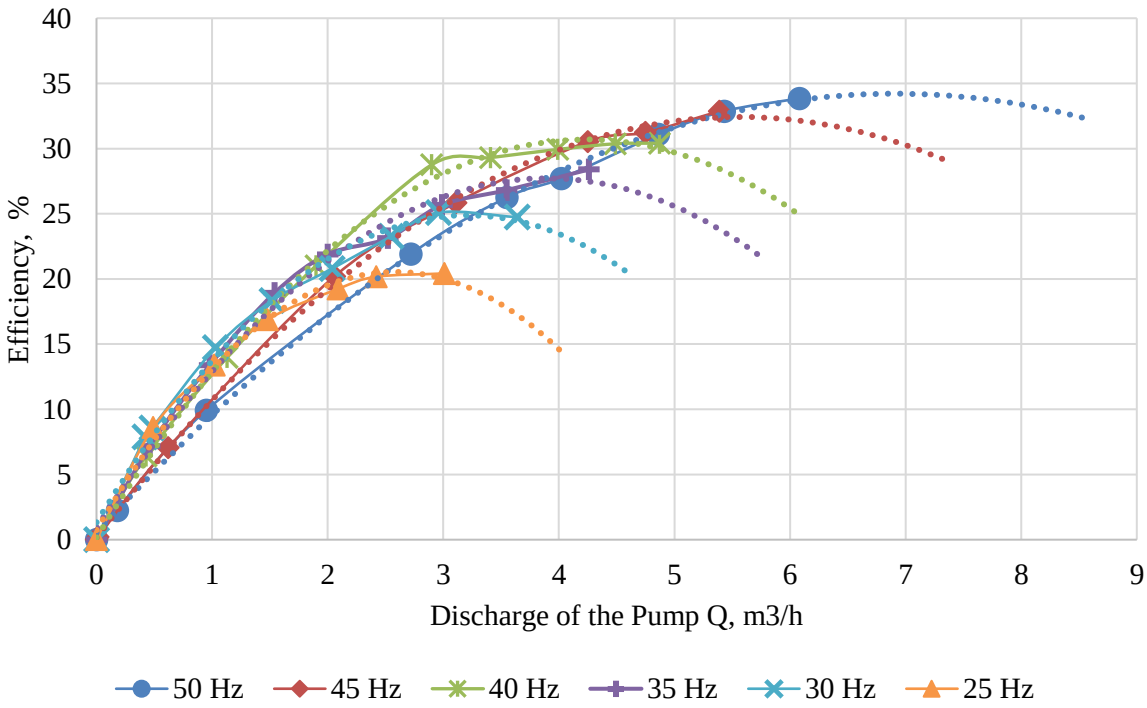


Figure 2. Efficiency of the pump unit.

Figure 2 shows the following: when controlling the frequency of rotation of the shaft, the maximum value of the efficiency of the pumping unit decreases. So, if at a current frequency of 50 Hz (unit shaft rotation frequency of 2900 rpm) the maximum efficiency value is about 34-35%, then by changing the current frequency by half, to 25 Hz, the efficiency value decreases to 20%. At the same time, it should be noted that the power consumption was determined by the output parameters of the frequency converter, i.e. it should be borne in mind that the power consumed from the electricity network will have a higher value, because there are also energy losses in the frequency converter [18].

In other words, the total values of the efficiency of the laboratory facility will be less than those shown in Figure 2. The decrease in the maximum values of the efficiency is caused by increasing energy losses both in the electric motor and in the pump. It is obvious that the decrease in the efficiency of the unit is greatly influenced by the degree of loading and the rotational speed of the electric motor. However, in the pump energy losses also increase and for a correct assessment of the efficiency of the entire unit, it is necessary to know the degree and nature of the dependence of the pump efficiency on the rotor speed. For this, the values of the efficiency of the pump itself were calculated separately according to Equations 3, 4 and 5 according to the actual parameters taken from the measuring instruments.

The actual measured pressure characteristics were compared with the characteristics obtained using particular similarity equations [19, 20]:

$$\frac{Q}{Q_0} = \left(\frac{n}{n_0}\right); \tag{6}$$

$$\frac{H}{H_0} = \left(\frac{n}{n_0}\right)^2; \tag{7}$$

where n_0, n are the rated and actual value of the pump rotor speed, respectively; Q_0,H_0 are the rated discharge and head values, respectively; Q, H are the rated values of discharge and head when changing the rotor speed, respectively.

The results are shown in Figure 3. Figure 3 shows that the actual H-Q curves almost completely coincide with those calculated by the particular formulas of similarity based on the pump characteristic taken at a nominal current frequency of 50 Hz, which indicates that the calculations were performed correctly.

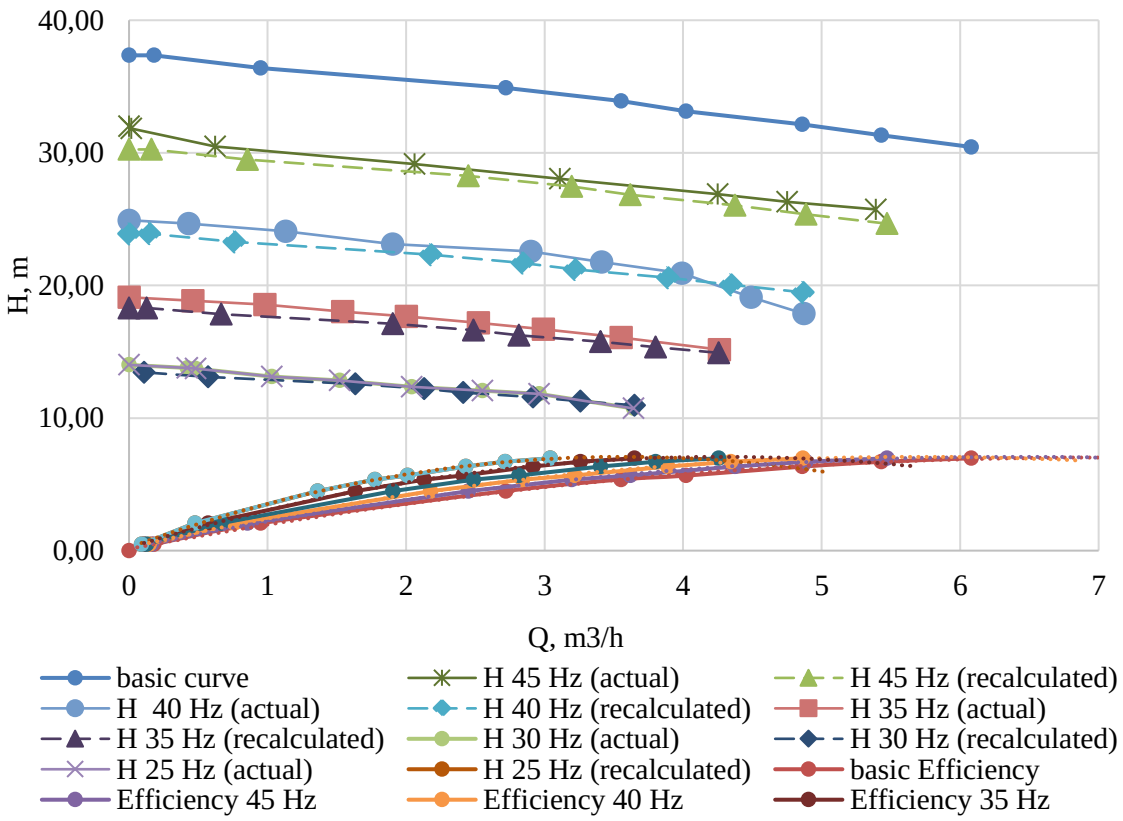


Figure 3. Actual and calculated H-Q and Efficiency curves for different current frequencies.

Obviously, when using the particular similarity equations for recalculating the pump efficiency, the maximum values and a behavior of the efficiency curves will not change with a decrease in the rotor speed, but will only shift the curves to the region of lower discharges, since it is the principle of equality of efficiency for similar modes that underlies the recalculation of pump characteristics.

However, when processing the actual measurements and calculating the actual efficiency in different modes, the efficiency curves were obtained (Figure4), which differ from those shown in Figure 3. Considering that when registering parameters during pump testing, errors of various kinds

arise, the actual efficiency was analyzed not by the calculated efficiency values, but by constructing approximating functions in the MS Excel spreadsheet editor.

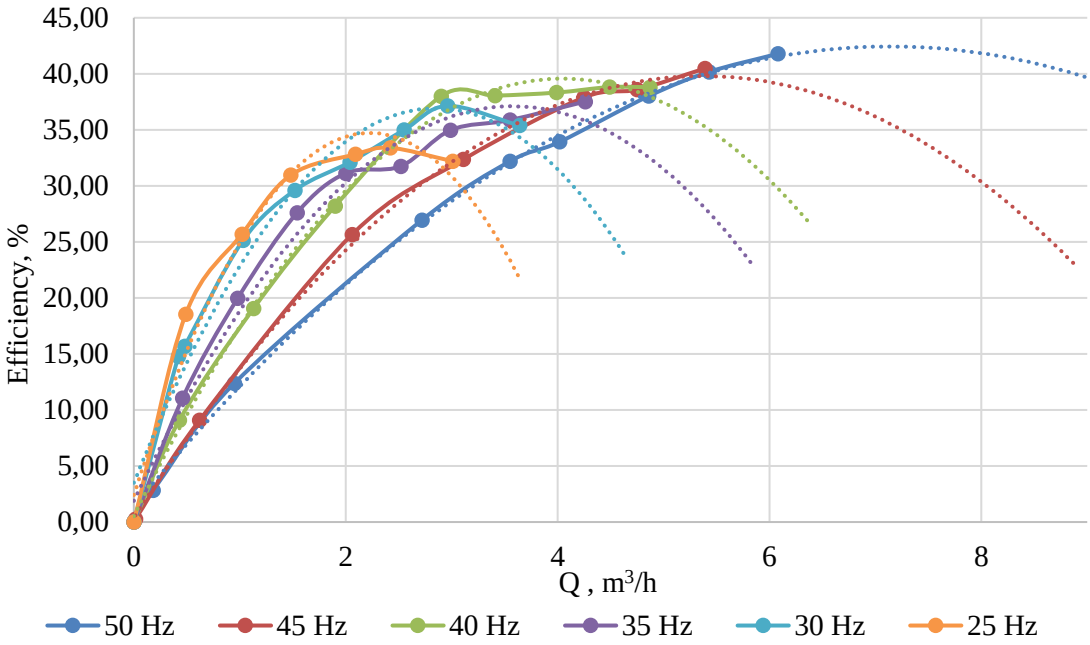


Figure 4. Results of calculated the actual efficiency of the pump.

As a result of plotting the graphs of the approximating functions, a decrease in the maximum values of the pump efficiency can be seen. So, if at a rated current frequency of 50 Hz, the maximum value of the pump efficiency is about 42%, when the frequency is halved (up to 25 Hz), the maximum value is about 35%. In turn, the efficiency of the pump unit decreased from 34-35% to 20%.

Hence, it can be concluded that when controlling the operating modes of pumps equipped with asynchronous electric motors as drives, a significant decrease in the efficiency of the unit occurs, mainly due to a decrease in the efficiency of the electric motor, which depends on the degree of loading. But at the same time, the results of pump tests showed that there is also a decrease in the efficiency of the pump.

Further, the change in efficiency for similar modes was analyzed in terms of actual parameters. The results are shown in Figure 5.

With the help of an arbitrarily constructed similarity parabola, the selected modes were found. The efficiency values in Figure 5 are given for mains frequencies of 50 Hz (basic curve), 35 Hz and 25 Hz. It can be seen from the Figure 5 that for the modes that are considered similar, the efficiency is currently being performed: at lower rotor speeds, the efficiency decreases: from 39% at frequencies to 35% at a current frequency of 25 Hz. When calculating the efficiency, there are errors: measuring instruments, errors in calculations and work with graphs, as well as other random errors, and indeed the efficiency value may be greater or less than the obtained values, but the general pattern is consistent.

For low-power pumps, neglecting the change in efficiency with a decrease in the speed of the pump rotor is not critical and this cannot be said for large industrial units: if, when choosing the most efficient pump operating modes when planning the pumping process, neglect the change in pump efficiency, then there is a chance to select modes that are not rational.

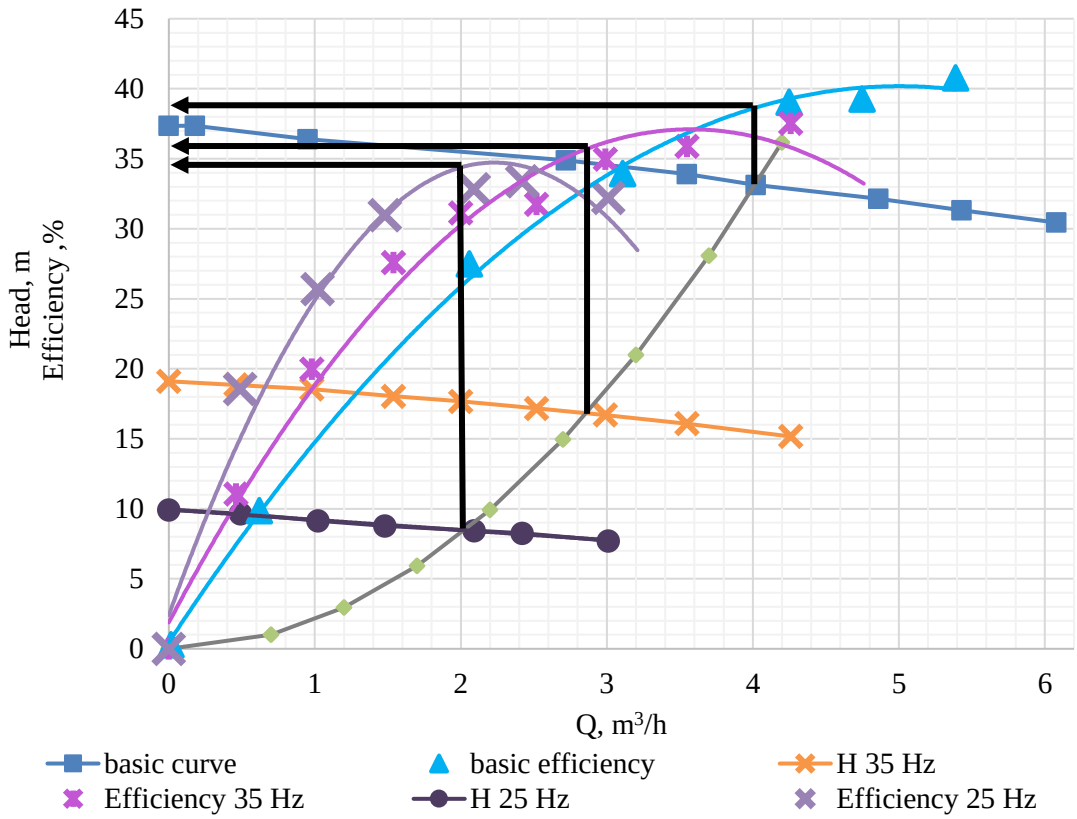


Figure 5. Determination of the actual efficiency of the pump for similar operating modes.

Thus, the task of assessing the efficiency of pumping units equipped with a VFD before putting it into operation is formed. Thus, the task of assessing the efficiency of pumping units equipped with a VFD before putting it into operation is formed. It should also be noted that the passport characteristics of pumps obtained during tests with water must be recalculated taking into account the viscosity of the pumped liquid, i.e. it is necessary to take into account the change in the efficiency of the pump both from the change in the speed of rotation of the shaft, and from the viscosity of the pumped liquid.

4. Conclusions

In this research, the authors tested a centrifugal pump at different speeds of rotation of the shaft in order to depend on the efficiency of the pump. The results shown that when controlling operating modes by frequency controlling, the efficiency values of centrifugal pumps decrease, despite the fact that it is generally accepted that for similar modes the efficiency values remain constant, and for the effective operation of modern pumping units, this must be taken into account, and the question itself needs further research.

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