

Investigation of the installation for the preparation of mixtures in the vane pump mode

*Pavel Solonshickov**, Irina Tolstoukhova, and Artem Shevchenko

Vyatka State Agrotechnological University, Kirov, Russia

Abstract. The article covers a review and analysis of centrifugal (vane) pumps produced and manufactured in our country and abroad. Among the variety of requirements for the design of pumps, the fundamental ones were identified, which directly affect the course of the technological process as a whole. Based on the analysis and review, a method for determining the design parameters of the pump has been developed and described. In this case, the described technique can be used when developing mixers using a centrifugal (blade) wheel. Using the described methodology, an impeller was developed and the technological process of its operation was described. In the course of theoretical calculations, a regression equation was obtained to determine the pressure at different speeds of the impeller shaft, taking into account the corresponding resistances, depending on the feed. Experimental and theoretical studies have confirmed the design of the developed wheel for a mixing plant based on a vane pump. At the same time, the nominal values of indicators such as flow, pressure, efficiency and useful power were obtained for various operating options of the installation. Thus, the installation showed its operating efficiency as for a conventional pump, which can move liquid and mixtures.

1 Introduction

The design of a modern pump will inevitably depend on the physical and chemical properties of the pumped or processed medium. The standard for food pumps GOST 52743-2007 [1] 6 common pumped media is defined. Therefore, pumps can operate with clean and slightly contaminated liquids, gas-liquid mixtures and aggressive liquids [2].

Vane-type pumps are most widely used in the food industry. They are mainly used when receiving milk from automobile, railway tanks and other containers, when pumping it on the territory of a factory or workshop, as well as in continuous technological schemes for the processing and production of various products. Pumps are also designed to supply liquid or product through other devices, for example, plate and tubular pasteurizers, coolers, filters, sealed separators, spray nozzles and other devices [3,4].

The following requirements apply to pumps for milk and dairy products:

* Corresponding author: solon-pavel@yandex.ru

- during operation, the pump must have the least possible mechanical impact on the product without changing its natural properties, for example, not reducing the consistency of the product below the permissible level;
- working parts of pumps that are in direct contact with the product must be made of steel and other materials;
- the design of the pumps should provide easy access to its working parts, allowing for cleaning (rinsing);
- pumps when operating in a production line must provide the necessary flow and pressure when injecting the product [2]. The market for pumping equipment for the dairy and food industries offers a wide selection of pumps, both domestic and imported. The use of pumps of different operating principles and designs is due to the variety of pumped media with different parameters of viscosity, density, temperature, the presence of various types of inclusions, as well as, in some cases, the requirement of careful handling of the product.

Currently, the market offers a wide range of centrifugal pumps of both domestic and foreign production. Of the domestic pumps, the most widely used are pumps with a volumetric flow from 12 to 50 m³/h.

Due to the high price range of imported pumps, domestically produced pumps are in greatest demand.

OJSC Nekrasovsky Machine-Building Plant, whose supplier on the market is Pishmashservice LLC, produces centrifugal pumps of the ONTs1 brand and self-priming ONTs1-S. The company ENA LLC (Shchelkovo Machine-Building Plant) produces centrifugal pumps of the ONTs, ONTs and SNTs brands.

New domestic manufacturers have appeared on the market, such as Slavutich LLC (Cheboksary), which produces pumps of the VGNTs brands, as well as Voronezhprod mash LLC (Voronezh), which produces pumps of the OPA, OPB, OPL, OPN and OPBE brands.

One of the pump manufacturers in the Volga region is the OJSC Selmash Plant, which produces pumps of the NLC series (developed by ZAO OKB Russian Dairy Machines, Kirov).

For producers and processors of milk and dairy products, pumps of the NMU-6 brand are produced in 2 versions: a stainless-steel body and a plastic body. The manufacturer is OJSC Kurganselmash. Ufa Aggregate Production Association (Ufa) produces electric pumps of the NCU series, designed for pumping milk, washing and disinfecting liquids. In design and purpose, they are similar to the NMU-6 pump. The most advanced, but at the same time expensive, milk pumps are from Alfa Laval (Sweden), which produces pumps of the following brands: LKH, LKHex, LKHI.

The LKH pump is a highly efficient and economical centrifugal pump that meets the strictest sanitary requirements, ensures gentle product processing and is resistant to aggressive substances. This series comes in twelve standard sizes.

The LKHex pump is a highly efficient and economical centrifugal pump, meeting the requirements of ATEX Directive 94/9 IEC, Group II, Category 2 and 3, Temperature Class T3 and T4. This series comes in nine standard sizes.

The LKHI pump is a highly efficient and economical centrifugal pump, specially designed to handle inlet pressures up to 1600 kPa. The LKHI pump meets strict sanitary requirements, ensures gentle product processing and is resistant to aggressive substances. This series comes in nine standard sizes.

The Packo company (Fullwood Packo Group, Belgium) produces pumps of the following brands: ICP, IFF and FP. ICP model pumps have proven their reliability and performance in major process industries.

The main performance capabilities of this series are determined by the use of electropolished stainless steel parts in combination with standard electric motors and seals.

These features, as well as their robust, wide-discharge design, make these pumps exceptionally efficient when pumping aggressive media, contaminated liquids and volatile chemical liquids. Branches of the ICP series are pumps of the IFF (vortex impeller) models.

FP series centrifugal pumps are designed to meet the strictest hygienic requirements. The FP pump was the first centrifugal pump to receive EHEDG certification.

There are also small companies on the market for pumping products that copy previously listed pumps, but their products often do not meet reliability requirements, and the performance characteristics do not correspond to the declared ones.

The main indicators characterizing the operation of the pump are determined by the pressure-flow characteristic. For domestically produced pumps, three groups can be distinguished:

- small pumps (flow up to 15 m³/h, head 16-20 m), used mainly in milking lines and primary milk processing;
- medium pumps (flow up to 21 m³/h, head 20-29 m), used for pumping during milk processing and as part of technological installations;
- large pumps (flow up to 36 m³/h, head 29-40 m), most often used for sanitary processing of technological equipment of a milk processing plant and in high-capacity technological lines [5].

Foreign-made pumps are characterized by a wide range of pressure and flow control. This is all explained by the fact that in the manufacturing process of foreign pumps only the best, most expensive and high-quality materials are used, as well as the latest advanced technologies. It is precisely because of this that the cost of foreign-made pumps is significantly higher. However, even despite this, more and more buyers are giving their preference to this particular equipment. Due to the use of good materials and new technologies, foreign pumps are characterized by higher quality, reliability, and a fairly long service life.

2 Materials and methods

One of the main indicators today that characterizes an object, in particular a pump, is the energy consumption for the pumping process. An indicator characterizing this process will be the efficiency of the pump. Since cavitation is an indicator that affects pressure drop or efficiency, it is also necessary to take this indicator into account when developing a new pump design.

To calculate impellers, methods based on the jet theory and the use of similarity theory have become widespread. Both methods widely use characteristic parameters and coefficients [5].

Due to historical circumstances, the speed coefficient n_s has become prevalent, which primarily characterizes the efficiency, as well as the shape of the flow part and the ratio of geometric dimensions [5,6]:

$$n_s = 3.65 \cdot \frac{n \cdot \sqrt{Q}}{\sqrt[4]{H^3}}, \quad (1)$$

where Q – pump flow, m³/s;

N – pump head, m.

The speed factor shows that a vane pump wheel, designed to operate at a given head and flow, will have greater speed if the impeller speed is higher. In turn, the increase in rotation speed is determined by the small size and weight of the pump with a high efficiency. Therefore, the use of wheels with a high-speed coefficient is economically feasible due to the large energy reserve.

The numerical value of the speed coefficient is also necessary when choosing factors influencing the recalculation of the characteristic lines of the pump when supplying viscous or solid-containing liquids [3].

Depending on the speed n_s , the design designs of impellers are classified as follows: centrifugal (low-speed, normal, high-speed), diagonal, axial (Figure 1) [2].

Blades of different speeds have different operating conditions. An example is the low-speed wheel in Figure 1.a. The resulting streams of fluid flow move under almost identical conditions, and the inlet edge of the blade lies on a cylindrical surface, while the blade is cylindrical. This distinctive feature is typical for radial centrifugal wheels. Impellers of normal and high-speed type, having blades, the inlet edges of which are placed in the area of rotation of the fluid flow, that is, in the area where the direction of the fluid flow changes from axial to radial [4].

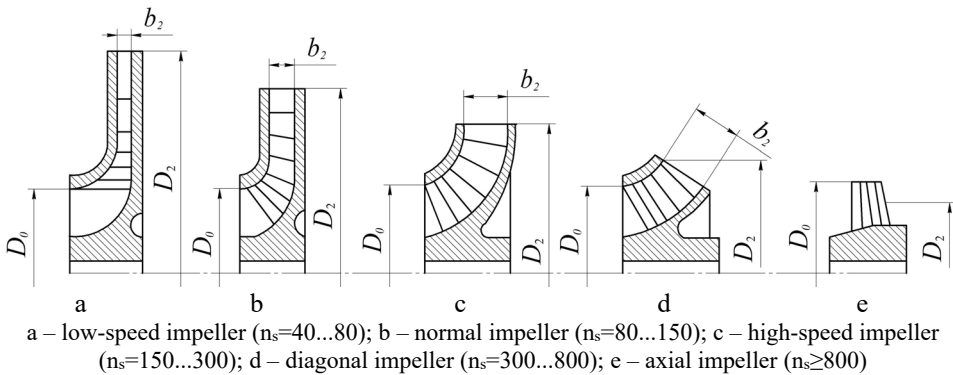


Fig. 1. Design types of impellers.

The least mechanical impact on milk and food liquids of various viscosities is exerted by a low-speed centrifugal wheel. Therefore, we can consider the classification of bladed impellers by type of design and present it in the form of a diagram (Figure 2).

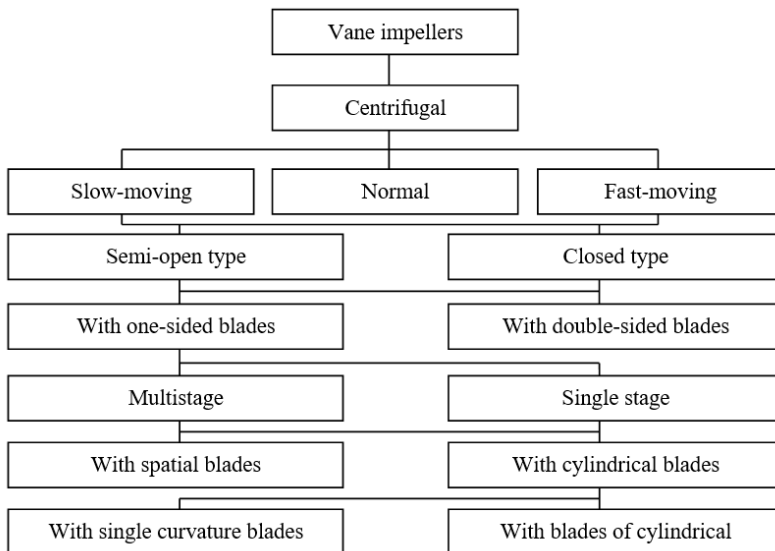


Fig 2. Classification of vane impellers.

From the presented diagram it can be seen that the designs of the centrifugal impeller can be different. The best performance indicators are closed type wheels. But, as practice shows, some pump manufacturers are trying to make an impeller in a simpler way, and at the same time provide it with performance characteristics that are reliable and stable in operation.

In order to decide on the choice of impeller design, you can be guided by two indicators: efficiency and cavitation reserve. Therefore, to assess the efficiency and cavitation qualities of centrifugal pumps intended for pumping food products, you can use the methodology proposed at VNIIGidromash [1,2,3,5,6].

When obtaining dependencies, the principle of constructing envelopes drawn through reference points with the values of the highest achieved indicators is used. For vane pumps with a closed impeller and design inlet diameter D_0 into the impeller [2,3,4]:

$$D_o = k_0 \cdot \sqrt[3]{\frac{Q}{n}}, \tag{2}$$

where k_0 – calculated coefficient of the input funnel of the wheel;
 n – impeller rotation speed, min^{-1} .

The outer diameter of the impeller is determined approximately, which allows us to operate with the concept of “the minimum achievable relative thickness of the casting wall”. This thickness is related to the technological capabilities of casting and is important for the production of pumps. Therefore, we have the following relationships of geometric parameters:

$$\frac{D_2}{D_0} = 2,5, \tag{3}$$

where D_2 – diameter of the impeller, mm.

The cavitation qualities of the pump are determined using the cavitation coefficient:

$$\sigma = \frac{216 \cdot n_s^{\frac{4}{3}}}{10^6}, \tag{4}$$

In addition to the cavitation coefficient, the cavitation speed coefficient is used, calculated for the optimal operating mode of the centrifugal pump, i.e. at supply and pressure that correspond to the maximum efficiency of the pump [10]:

$$C = \frac{5,62 \cdot n \cdot \sqrt{Q_{omn}}}{\sqrt[4]{\Delta h(NPSH3)^3}}, \tag{5}$$

where $\Delta h(NPSH3)$ – cavitation reserve corresponding to a 3% pressure drop, m.

Thus, the expressions described above allow us to be guided by a method for assessing the level of efficiency and cavitation qualities of centrifugal pumps, which can be used as a tool for selecting the optimal pump, as well as a method for determining various sizing ratios of impellers and outlets when designing new pumps. Thanks to this technique, it is possible to set geometric parameters in advance when designing new pumps and strive to improve the pressure-flow characteristics.

From the analysis of the design diagrams of vane pumps, it is clear that in each design there is the installation of various devices to improve the quality of injection and mixing. At the moment, there is a trend towards the development of mixing pumps that combine the functions of a pumping device and a mixer.

Thus, centrifugal pumps, which are widely used in various lines (milking, primary processing, processing, etc.), can be upgraded into a mixer while maintaining the function of the pump.

But at the same time, when considering the problem of increasing the efficiency of livestock farming, it should be borne in mind that the intensification of production at the

current stage of development of the agricultural sector in a market economy implies not only an increase in additional investments per unit of area and head of animals. First of all, the means of intensification must be improved based on the introduction of scientific and technological progress and improving the quality of animals. It is also necessary to develop and introduce new progressive technologies, to ensure improvement in accordance with the changed technology and technology of organizing labor production [11,18,19].

When developing the installation for preparing mixtures, these ratios were taken into account when designing the impeller.

Figure 3 shows a diagram of the operation of the installation's impeller, where it can be seen that the liquid enters the center of the impeller and then into the inter-blade channels. And bulk or powdery material enters through windows 1 into another part of the inter-blade channels [12].

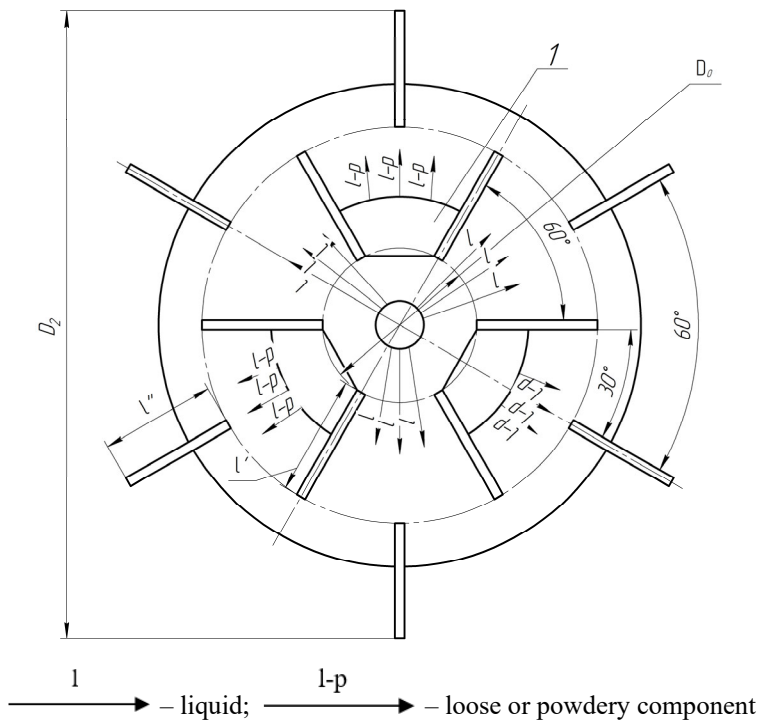


Fig. 3. Diagram of the impeller of an installation for preparing mixtures.

3 Results and discussion

The installation for preparing liquid feed mixtures (Figure 4) combines the functions of a pump and mixer [17,20].

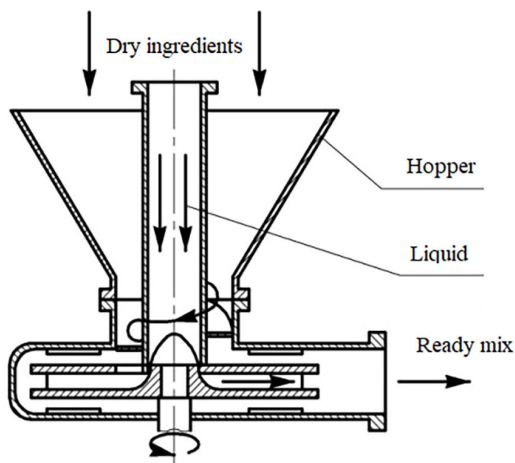


Fig. 4. Installation diagram.

Figure 5 shows the dependence of the maximum value of liquid supply on the speed of rotation of the impeller [13].

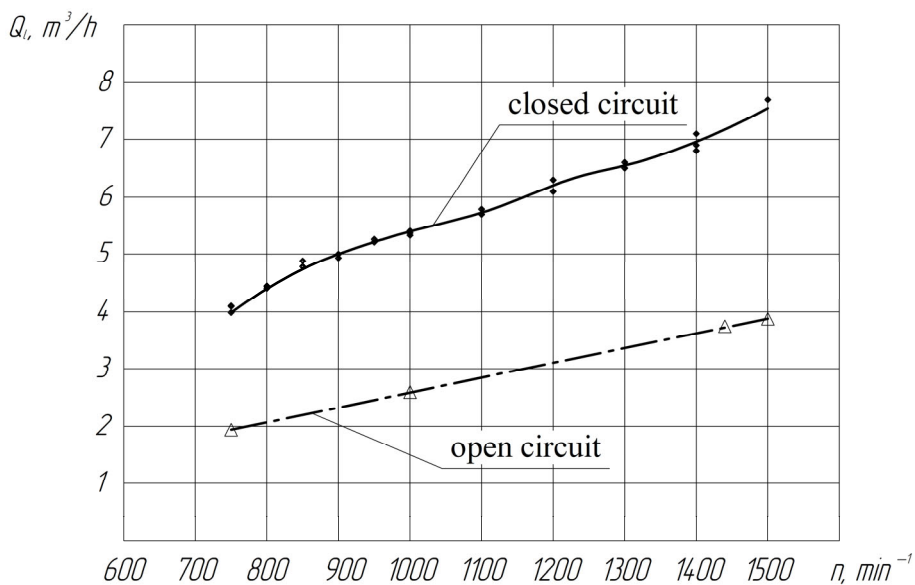


Fig. 5. Dependence of the maximum liquid supply Q_l on the impeller rotation speed.

The pressure and energy characteristics of the installation are presented in Figure 6. The options differ in the presence of a closed (with a sealed lid) and an open circuit, at a rotation speed of $n=1500 \text{ min}^{-1}$ [14].

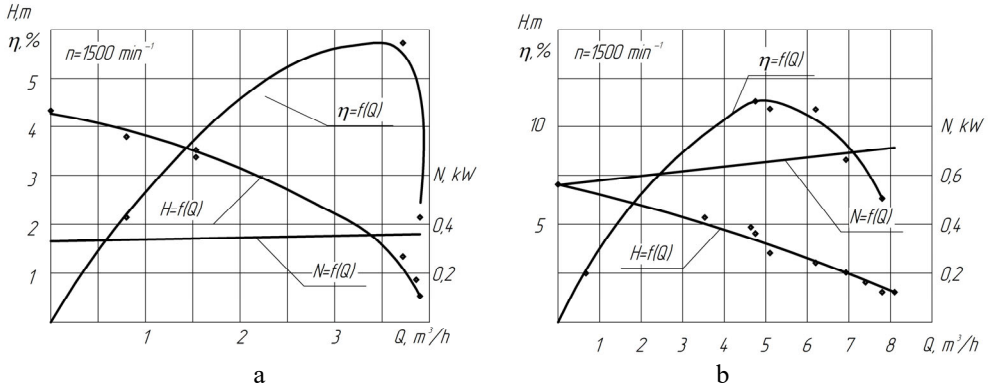


Fig. 6. Pressure and energy characteristics of the installation (a) open and closed circuit (b).

Analysis of the obtained pressure and energy characteristics showed that with an increase in rotation speed there is an increase in pressure, flow and efficiency and, as a consequence, an increase in power consumption.

When the circuit operates with a closed loop, the indicator values are higher. During operation of the installation in the production line with a continuous supply of dry component into the loading chamber, the latter will prevent the entry of air. Therefore, it is possible to predict the compliance of indicators when working according to a closed-loop scheme.

To take into account the resistance in the inter-blade channels, we take the dependence on flow rate in a form similar to that for a pipeline [15]:

$$h_c = h_0 + k_1 Q + k_2 Q^2. \quad (6)$$

Then the dependence $H=f(Q)$, taking into account the resistance, will be written as

$$H = (A - h_0) - k_1 Q - k_2 Q^2, \quad (7)$$

where h_0 – specific losses in channels, m;

k_1 and k_2 – are experimental coefficients obtained as a result of studying the characteristics of the installation.

We determine the coefficients A , k_1 and k_2 in equations (7) using Microsoft Office Excel 2007 spreadsheets and the least squares method, and we obtain:

$$H_{1500}^{close} = 6,97 - 0,292 \cdot Q_{close} - 0,044 \cdot Q_{close}^2. \quad (8)$$

$$H_{1500}^{open} = 4,31 - 0,382 \cdot Q_{open} - 0,148 \cdot Q_{open}^2. \quad (9)$$

Using the components of equations (8) and (9), it is possible to predict the pressure characteristics of the installation at different speeds of the impeller shaft, taking into account the corresponding resistances and operation scheme [14].

When studying the nominal indicators, the pressure-flow characteristic was determined. We investigated the mutual influence of the rotation speed of the electric motor shaft n , the number of stationary blades Z and the pressure in the loading chamber p_3 (during the research it changed randomly and was fixed according to the standard method [16]) on the target functions: nominal flow Q_n , m³/h; nominal pressure H_n , m; rated useful power P_n , W and efficiency factor η , %. Pressure p_3 in this case will simulate the presence of material in the loading chamber.

When taking the pressure-energy characteristics of the device, a full factorial experiment of type 2^3 was carried out.

During testing, the pressure in the loading chamber varied and was not constant, so the factor was uncontrollable.

Normalization of pressure in the chamber during an active-passive experiment was carried out as follows [16]:

$$x_i = \frac{\tilde{x}_i - \tilde{x}_i^o}{\varepsilon_i}, \tag{10}$$

where x_i – normalized factor value;
 \tilde{x}_i – named factor value at the i level;
 \tilde{x}_i^o – named factor value at zero level;
 ε_i – variation interval.

$$\varepsilon_i = \frac{\tilde{x}_i' - \tilde{x}_i^l}{2}, \tag{11}$$

where \tilde{x}_i' – named factor value at the top level, it is recommended to use it as \tilde{x}_i' maximum factor value $x_i^{\max} = \tilde{x}_i'$;
 \tilde{x}_i^l – a named factor value at the lower level. Recommended for use as \tilde{x}_i^l minimum factor value $x_i^{\min} = \tilde{x}_i^l$.

Named factor value at zero level

$$\tilde{x}_i^o = \frac{\tilde{x}_i' + \tilde{x}_i^l}{2}. \tag{12}$$

Table 1. Plan matrix 2³ and results of experimental studies when studying the influence of factors on the nominal performance of the installation.

Levels of factor variation	Factors			Optimization criteria			
	Shaft rotation speed n , min^{-1}	Number of fixed blades Z , pcs	Pressure in the loading chamber p_3 , kPa	Feed Q_n , m^3/h	Head H_n , m	Useful power N_n , W	Efficiency, η , %
	x_1	x_2	x_3	y_1	y_2	y_3	y_4
Upper level (+)	1500	18	98.1	-	-		-
Lower level (-)	750	0	95	-	-		-
Experiments							
1	-1	-1	-1	2.79	0.2	1.52	6.8
2	+1	-1	-1	3.5	1.57	14.97	6.74
3	-1	+1	-1	2.75	0.24	1.79	5.65
4	+1	+1	-1	3.85	1.72	18.04	5.73
5	-1	-1	+1	1.75	1.5	7.15	10.02
6	+1	-1	+1	4.23	3.13	36.07	15.13
7	-1	+1	+1	3	1.18	9.64	5.5
8	+1	+1	+1	5	4.02	54.77	11.32

After excluding insignificant regression coefficients, the recalculated mathematical models of the workflow have the form:

$$\hat{Q} = 3.35 + 0.79 \cdot x_1 + 0.32 \cdot x_2 - 0.14 \cdot x_3 - 0.31 \cdot x_1 \cdot x_3 - 0.24 \cdot x_2 \cdot x_3, \tag{13}$$

$$\hat{H} = 1.65 + 0.81 \cdot x_1 + 0.07 \cdot x_2 - 0.69 \cdot x_3 + 0.14 \cdot x_1 \cdot x_2 - 0.09 \cdot x_1 \cdot x_3, \tag{14}$$

$$\hat{N} = 17.27 + 11.17 \cdot x_1 + 2.84 \cdot x_2 - 7.85 \cdot x_3 + 1.88 \cdot x_1 \cdot x_2 - 4.18 \cdot x_1 \cdot x_3 - 1.08 \cdot x_2 \cdot x_3, \tag{15}$$

$$\hat{\eta} = 8.68 + 1.45 \cdot x_1 - 0.48 \cdot x_2 - 2.21 \cdot x_3 + 0.82 \cdot x_1 \cdot x_2 - 1.48 \cdot x_1 \cdot x_3. \quad (16)$$

Analysis of response surfaces (Figure 7) in coordinates: rotation speed n and pressure in the loading chamber p_3 shows that, with an increase in n from 1350 to 1500 min^{-1} and p_3 up to 94.1 kPa (simulates the presence of material in the loading chamber), the nominal flow increases to 5.2 m^3/h , nominal head - 3.5 m, useful power - 45 W, efficiency - 13.2%.

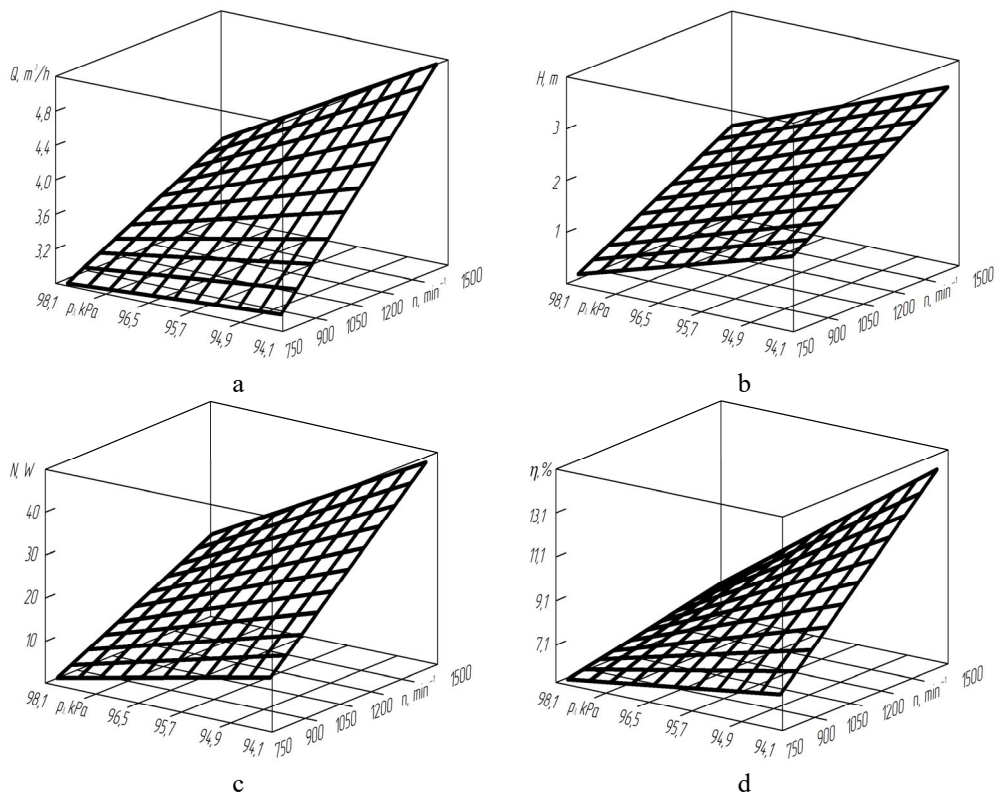


Fig. 7. Two-dimensional sections of response surfaces for nominal: flow Q_n , m^3/h (a), pressure H_n , m (b), power N_n , W (c) and efficiency η , % (d).

4 Conclusion

Thus, if loose or powdery material is continuously loaded into the loading chamber of the installation, we will have the highest values of the pressure-flow characteristics at the corresponding rotation speed, and vice versa, if there is no material in the chamber, the hydraulic performance will be lower due to air entering the system. Consequently, during operation of the installation, it is possible to predict the amount of flow and pressure, that is, use it as a pump.

References

1. S.Yu. Bulatov, The Perm agrarian journal **1(17)**, 55-64 (2017)
2. A. Marczuk, W. Misztal, S. Bulatov, V. Nechayev, P. Savinykh, Sustainability **12(3)** 1050 (2020)

3. P. Solonshchikov, P. Savinykh, S. Ivanovs, Ural sustainability research **45(340)**, 13-20 (2021)
4. P. Solonshchikov, Vestnik NHIEEI. Technical Sciences **2(57)** (Knyaginino, NHIEEI, 2016), p 81-88
5. V. Sysuev, F. Mukhamadyarov, *Methods to increase the agro-bio-energetic efficiency of crop production* (Kirov, NIISKh Severo-Vostok, 2001), p. 216
6. P. Savinyh, A. Aleshkin, V. Nechaev, S. Ivanovs, Engineering for Rural Development: Proceedings, 309-316 (2017). <https://www.doi.org/10.22616/ERDev2017.16.N061>
7. A. Marczuk, J. Caban, A.V. Aleshkin et al., Sustainability **11(18)**, 4873 (2019). <https://doi.org/10.3390/su11184873>