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# DEVELOPMENT OF PUMPS WITH IMPROVED ANTI-CAVITATION CHARACTERISTICS

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***When considering the creation of pumps with improved anti-cavitation characteristics, the results of an in-depth analysis of the problem of pumping viscous liquids at high temperatures are presented. On the example of the technological process of evaporation of sugar syrup on a film evaporator of the latest type, the problem of the occurrence of cavitation when pumping viscous liquids at high temperatures was revealed.***

***After analyzing the existing machines used for the specified operating conditions, critical design and operating parameters were identified that affect the appearance of cavitation. Namely, the appearance of cavitation is influenced by the reduced diameter of the impeller inlet, the diameter of the impeller inlet, the number of blades, the width of the blades and the rotor speed.***

***To study the level of influence of these parameters, a method of physical modeling was chosen, an experimental stand was designed and manufactured. Studies have been carried out on the operation of the pump with and without a reducer. The work with a two- and three-blade inducer is analyzed, the work with an open and closed impeller, with one and two-level blade system is investigated.***

***As a result of the analysis of experimental data, the optimal design of the hydraulic part with a three-blade reducer and a semi-open impeller with a two-level blade system was chosen. In turn, this made it possible to reduce the compression of the flow at the inlet to the impeller without loss of energy efficiency; the angles of inclination of the inducer and impeller blades were synchronized.***

***The experience gained made it possible to design and manufacture an industrial sample of a cantilever pump with an inducer and a semi-open impeller. Thus, allowing to solve the problem of pumping thick syrup on a film evaporating unit of the Teofipol sugar plant (Khmelnytskyi region, Ukraine), with a cavitation reserve of 1.5 m***

***Keywords: cantilever pump, centrifugal impeller, reducer, cavitation reserve, film evaporator***

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## 1. Introduction

Significant competition in the world sugar market and constantly growing requirements for sugar quality necessitate constant modernization of all technological equipment. The sugar production technology provides for the constant pumping of sugar-containing liquids through the stages of the enterprise, from one technological process to another.

A modern sugar factory operates several dozen different types of pumps and kilometers of pipelines at different heights. There are many types of pumps for sugar factories: these are centrifugal pumps or rotary rotary pumps, and scoop pumps, screw pumps, and old gear pumps. In the sugar industry, a large number of high-tech equipment must operate on a continuous basis around the clock. One of the main stages of sugar production is an evaporation plant, in which excess moisture is evaporated from the sugar syrup and the sugar content in the syrup is concentrated. For the flow of this technological operation, it is necessary to pump a thick syrup with a high temperature and a dry impurity content of about 50 % without the formation of cavitation. Disruption of parameters or failure of the evaporator pump leads to disruption of the rhythm of the plant's operating cycles. This can cause crystallization of raw materials, shutdown of the production line and result in significant financial losses due to downtime.

That is why the task is to develop a new pump that will minimize production and operating costs. There will also be a unified design that will meet the requirements of efficiency as much as possible and have minimum prices, as well as provide a cavitation reserve at the level of 1.4–1.5 meters.

The market economy requires modern industries to continuously improve productivity and reduce the energy intensity of equipment. This is possible due to the constant modernization of production equipment and technological lines at enterprises. In the sugar industry, more complex, and in turn, efficient methods of evaporation of sugar syrup on a film apparatus require the use of pumps with increased anti-cavitation characteristics. Therefore, there is a need to develop and install modern pumping equipment that will be able to pump a viscous multiphase liquid with solid impurities at temperatures above 100 °C.

## 2. Literature review and problem statement

The article [1] presents the results of experimental studies of the possibility of increasing the suction capacity of an inducer centrifugal stage with a speed coefficient $n_s$=120 without changing the geometry of the inducer and impeller. The influence on the suction capacity of the investigated degree of such a factor as the type of the impeller system of the inducer has been established.

Experimental tests have shown that the execution of grooves (longitudinal or circular), or screw threading on the stator bushing, without changing the geometry of the inducer and the impeller, significantly changed the flow pattern.

In work [2], to improve the cavitation characteristics of a centrifugal pump with a diffuser, the study of the influence of the geometric parameters of the impeller on cavitation was carried out. The numerical experiment consisted in comparing the dependencies of various pump components: the diameter of the hydraulic part at the inlet to the impeller, the angles of inclination of the blades. Optimization results are obtained using a range analysis method to improve cavitation performance without clearly reducing the efficiency of the centrifugal pump.

The aim of research [3] is to control and contain the appearance of cavitation caused in a pump with a J-channel. «J-channel» are made up of shallow pump inlet grooves parallel to the flow. Experimental studies have shown that the cavitation performance is significantly improved and the reverse vortex flow is suppressed by the J-channel.

In work [4], studies of cavitation characteristics were carried out at the liquid inlet into the impeller, with and without an inducer centrifugal stage.

The main task is to determine the places of cavitation impact and the intensity of cavitation destruction. As an assessment of the intensity of cavitation impact in the practice of the Joint-Stock Company Research and Design Institute for Atomic and Power Pumpbuilding (Sumy, Ukraine), the main places of occurrence of cavitation caverns.

The study [5] shows experimental studies of the appearance of cavitation in water with different temperature ranges. The temperature varied in the range from 30 °C to 100 °C. The results showed that «aggressive» cavitation begins at a temperature of 60–65 °C. After analyzing the results, a numerical model was simulated to obtain a visual picture of the currents at various parameters of the output data.

The work [6] is devoted to the verification of the areas where cavitation originates by the method of modeling and visualization. Further experimental studies, in the form of virtual models, make it possible to predict the appearance of cavitation and ways to overcome cavitation phenomena by changing the design of the model.

The authors of [7] checked the dynamics of bubbles, which were formed by focusing giant pulses of a ruby laser into distilled water. The graphs of the dependences of the distance of the cavitation action on the time of its action were developed, which makes it possible to reliably calculate the velocity of the bubbles.

The purpose of the experimental study [8] is to offer information for testing computational models and shed light on non-stationary multiphase processes of cavitation. This helps to avoid the appearance of complications at the stage of numerical simulation of hydraulic parts and experiment.

The work [9] describes an experimental study of two similar impellers of a centrifugal pump with a low rotation speed. With the help of optical instruments, one can observe the appearance of cavitation cavities and the place of their frequent formation.

The work [10] is aimed at studying cavitation by the method of numerical simulation. Analysis of the data obtained gave a clear picture for comparing the destructive force of cavitation in different zones of the hydraulic part.

The problem posed is the need to pump a viscous liquid with solid inclusions and a high temperature, more than 105 °C. The authors of the cited sources investigated individual parameters of pumping liquids. These include fluids with high temperatures, fluids with solid inclusions, and studies of materials with cavitation-resistant characteristics. However, these studies were not carried out simultaneously with viscous and hot fluids.

However, taking into account the single experiments, according to the studies indicated above, a method was developed for calculating and subsequent manufacture of a pumping unit that allows to solve the problem of pumping viscous sugar syrup.

## 3. The aim and objectives of research

The aim of research is to determine the influence of design and operating parameters on the working process of a cantilever pump, which will operate in difficult conditions. Namely, when pumping viscous (up to 1220 kg/m$^3$) multiphase liquids (up to 50 % of dry impurities) at temperatures up to 105 °C and a low back pressure level at the pump inlet. This will allow the design of an upgraded Synerflow pump to solve the cavitation problem in the pumps in the sugar syrup evaporation line.

To achieve the aim, the following objectives were set:

– to determine the key design and operating parameters that improve the anti-cavitation characteristics of the pump;

– to experimentally investigate the influence of key parameters on the energy and anti-cavitation characteristics;

– to design and manufacture an industrial sample of a cantilever pump for the technological process of evaporation of sugar syrup.

## 4. Materials and methods of research

For the calculations of rotary pumps, the analysis of studies [11–15] was used, which in their topics are similar to the topics of developing pumps and overcoming the effect of cavitation. Cavitation damage during the operation of pumps, covered in [16, 17], can damage the unit due to the destruction of the impeller. These destructions take place in a short period of time, about 30–40 minutes in aggressive cavitation conditions. To solve problems associated with the destruction of impellers [18, 19], materials resistant to cavitation are used. Among such materials are stainless steels.

When designing rotary pumps [20], important and laborious tasks are the prevention of impeller blades. Taking this into account, in [21, 22] of the textbook, the procedure for profiling the impellers of centrifugal pumps by the method of conformal mapping on the cylinder is shown in detail. Some questions on overcoming the occurrence of cavitation on the flow parts of pumps were used [23].

First of all, to improve the anti-cavitation properties of the impeller, it is necessary to reduce the compression of the flow at the inlet to the impeller:

$$D_{1pr} = K_{in}\sqrt[3]{\frac{Q'}{n}}, \quad (1)$$

where $D_{1pr}$ – impeller diameter; $K_{in}$ – compression ratio of the flow at the inlet; $Q'$ – head.

In this case, this issue was resolved using two methods:

1. Increase in the reduced diameter of the impeller due to the choice of a larger coefficient of the inlet funnel, equal to 5.

2. A two-level blade system was used, which consists of 3 blades (Fig. 1), elongated to the suction nozzle – to dilute the flow, and 6 radial blades which create the necessary energy characteristics. The angles of inclination of 3 blades were coordinated with the angles of inclination of the inducer, according to the relevant recommendations [23, 24], which made it possible to fulfill the condition of a continuous flow of liquid.

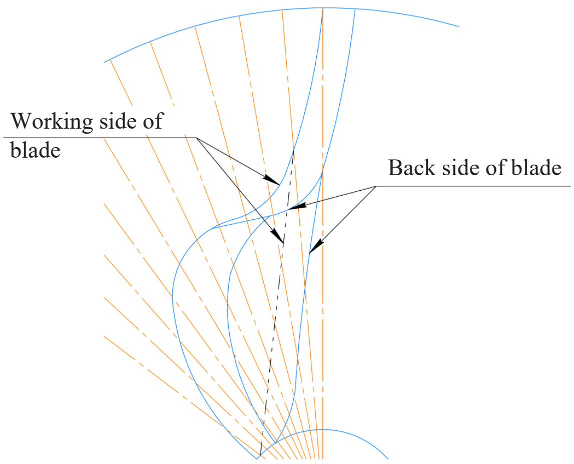



Fig. 1. Blade in plan

As a method for solving the problem, it was chosen to conduct a full-scale physical experiment and compare the data obtained with model inducer centrifugal stages, designed for various parameters and various designs.

In the practice of pumping, the method of constructing inducer centrifugal stages [24] for pure or industrial water is well known.

In this case, it is necessary to pump a viscous liquid, namely a syrup in which a sufficiently high operating temperature $T=105$ °C, the density of the liquid $\rho=1220$ kg/m$^3$, the dry matter content is about 52 %, as well as the juice level on the suction pipeline by 2 meters above the branch pipe.

For such conditions, it is necessary to achieve an accurate calculation of the value of the cavitation margin. For this, the formula for the cavitation reserve was used:

$$\Delta h = \frac{P_1}{\rho \cdot g} + \frac{v_1^2}{2 \cdot g} - \frac{P_{s.v.}}{\rho \cdot g}, \qquad (2)$$

where $P_1$ – saturated steam pressure for water at $t=105$ °C; $v_1^2$ – fluid velocity at the pump inlet; $P_{s.v.}$ – pressure of saturated vapor of the working fluid; $\rho$ – density of the liquid; $g$ – acceleration of gravity.

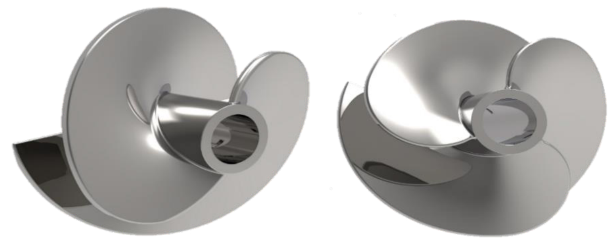
In this expression, the greatest attention should be paid to calculating the saturated vapor pressure of the working fluid, since the working fluid is a syrup for which there are no tabular and generally known values.

Therefore, a method was proposed for calculating the saturated vapor pressure for sugar syrup with a sugar solids content in the mixture $\omega=52$ %:

$$P_{s.v.} = P_0 - P_0 \frac{n}{N+n}. \qquad (3)$$

where $P_0$ – saturated steam pressure for water at $t=105$ °C; $n$ – the number of moles of sugar in the syrup; $N$ – the number of moles of water in the syrup.

This method of calculation allows to correctly calculate the required cavitation margin, and with the smallest error design an inducer centrifugal stage to suppress cavitation. Fig. 2 shows designed inducers for various operating parameters.



*a* *b*

Fig. 2. Designed inducers for various operating parameters: *a* — two-bladed $Q=200-400$ m$^3$/h; *b* — three-bladed $Q=400-600$ m$^3$/h

The inducer was designed with a closed and open impeller with an increased inlet diameter to reduce the compression of the flow at the inlet to the impeller. For the open impeller, a so-called two-level blade system was used. It consists of nine blades – three blades are elongated in the direction of the suction inlet, and six others create the necessary pressure and are located closer to the periphery of the impeller.

The choice of such a blade system is dictated by several factors.

Firstly, a feature of the design of the stage is the coordination of the angles of inclination of the inducer blade at the outlet and the angles of inclination of the impeller blade at the entrance.

Secondly, three elongated blades create less compression of the flow at the inlet to the impellers, which has a positive effect on preventing the formation of cavitation in the impeller.

Thus, after design and manufacture, three experimental tests were carried out with different options of hydraulic parts:

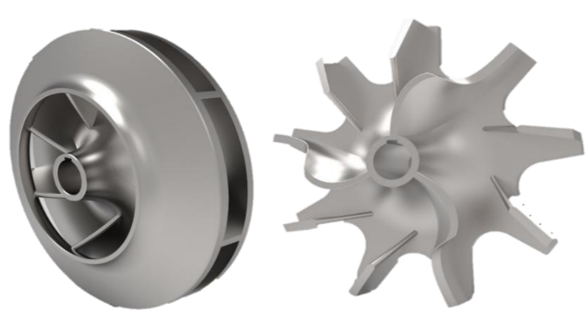
– Option No. 1 – open impeller and three-bladed inducer (Fig. 5).

– Option No. 2 – open impeller and two bladed inducer (Fig. 9, *b*).

– Option No. 3 – closed impeller and two bladed inducer (Fig. 12).

Each version of the experimental hydraulic part was tested on the experimental stand of the laboratory of the Department of Applied Hydroaeromechanics of Sumy State University (Ukraine). To check the pump, closed and open impellers were designed and manufactured, shown in Fig. 3.

To study the Synerflow pump, a test bench with a closed liquid circulation was developed (Fig. 4, 13). The instruments of the test bench are given in Table 1.



*a* *b*

Fig. 3. Designed impellers: *a* — closed; *b* — open

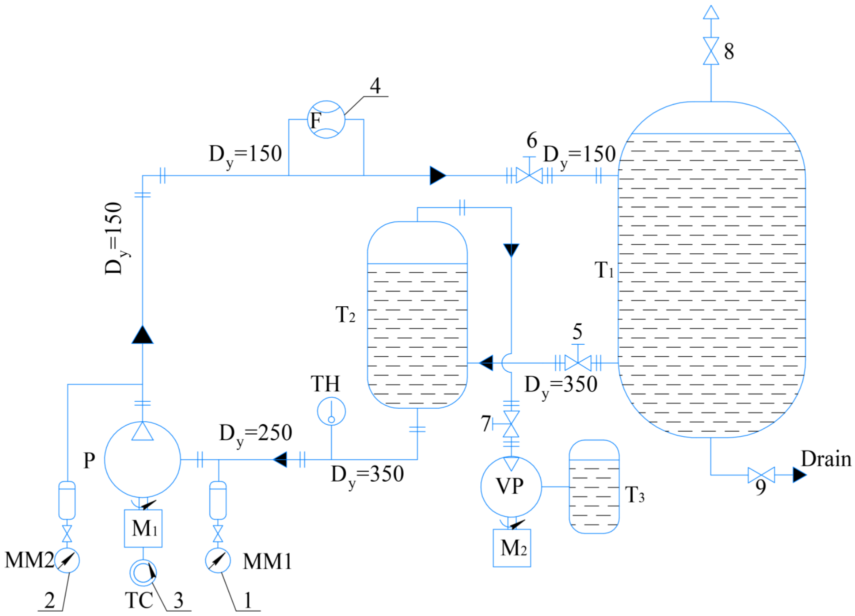



Fig. 4. Diagram of the test bench

Table 1

Test bench components

| Designation | Name | Number | Note |
|---|---|---|---|
| $T_1$ | Tank | 1 | $V$=10 m$^3$ |
| $T_2$ | Vacuum unit main tank | 1 | $V$=3 m$^3$ |
| $T_3$ | Vacuum unit auxiliary tank | 1 | $V$=0,5 m$^3$ |
| F | Ultrasonic flow meter | 1 | Взлёт-ПР |
| P | Pump | 1 | Synerflow |
| TC | Tachometer | 1 | TECA 3740 |
| TH | Thermometer | 1 | Mercury with a graduation of 0.1 °C |
| $M_1$ | Electric motor | 1 | АИР280S6, $N$=75 kW; $n$=1000 rpm |
| $M_2$ | Electric motor | 1 | АИР80А4 1, $N$=10 kW; $n$=1500 rpm |
| 5–7 | Gate valve | 3 | – |
| 8–9 | Valve | 2 | – |
| MM1 | Manovacuum meters | 1 | – |
| MM2 | Pressure gauge | 1 | – |
| VP | Vacuum pump | 1 | – |

Experimental tests were carried out according to DSTU GOST 6134:2009 «Dynamic pumps. Test methods».

An АИР280S6 electric motor with a power of 75 kW and a rotational speed of 1000 rpm was used as a drive. The regulation was carried out by a pressure valve 6. The pressure at the outlet to the pump was controlled by a pressure gauge 2, at the inlet of pressure gauges 1. The flow was measured with an ultrasonic flow meter 4. To obtain cavitation characteristics, the stand was equipped with a vacuum unit, which includes the main and auxiliary tanks (T2, T3), vacuum pump (VP).

The data obtained during the experiment were analyzed by the analytical method, on the basis of which the graphs of energy characteristics and graphs of shear cavitation characteristics were constructed.

## 5. Results of the study of experimental tests of the cantilever pump

### 5. 1. Key design and operating parameters that improve the anti-cavitation characteristics of the pump

The nature of cavitation in the general case has been widely studied, but in practice, each design has its own characteristics and criteria. As an example, cavitation on boat propellers and pump inducers is one and the same physical process, but the control methods are fundamentally different.

The occurrence of cavitation in the pump is influenced by a large number of parameters, design, operating and environment parameters.

Medium temperature, saturated vapor temperature and pump inlet pressure are key parameters that influence the occurrence of cavitation. Considering these parameters is important when designing a pump for a specific process line, where high temperature, viscous liquid and low head level are features of the process. In the experiment, these parameters were selected from the technical specifications and were considered as a constant.

Such a mode parameter as the speed, on the one hand, directly affects the pump performance, and on the other hand, it worsens the suction conditions and reduces the anti-cavitation parameters of the pump. After analyzing the operating modes of machines of analogues of leading world firms, it was determined that the speed of industrial machines, with increased requirements for the cavitation reserve, lie in the range of 750–1500 rpm. Given the complexity of the conditions, it was decided to calculate the hydraulic part at 1000 rpm.

The main design solution obtained is a combination of an inducer, which improves the supply of solids and creates additional pressure at the inlet to the impeller, and a two-level impeller blade system.

At the inlet to the impeller (Fig. 3, *b*), the blade cascade consists of 3 blades, which makes it possible to reduce the compression of the flow, and to the periphery, the number of blades increases to 9, which makes it possible to keep the efficiency at a sufficient level.

The number of blades and their width were selected from a hydraulic calculation and taking into account the technological features of production and strength calculations. For all experiments, 9 blades of the main blade array were selected.

These configurations may differ: the number of blades; pitch of the blades; angles of inclination of the blades.

To investigate the influence of the most difficult parameters in the assessment – the influence of the type of impeller and the number of blades of the inducer – it was decided to carry out an experiment.

**5. 2. Experimental study of the influence of key parameters on the energy, and anti-cavitation characteristics**

The results of parametric and cavitation tests were processed and presented in the form of graphs. Fig. 6, 8, 10 show graphs of energy characteristics for each of the three tests. Fig. 7, 9, 11 are graphs of shear cavitation characteristics.

The hydraulic parts of the pumps of experiments No. 1–3 are shown in Fig. 5, 9, *b*, 12, respectively.

Fig. 5. The hydraulic part of the impeller of tests of option No. 1

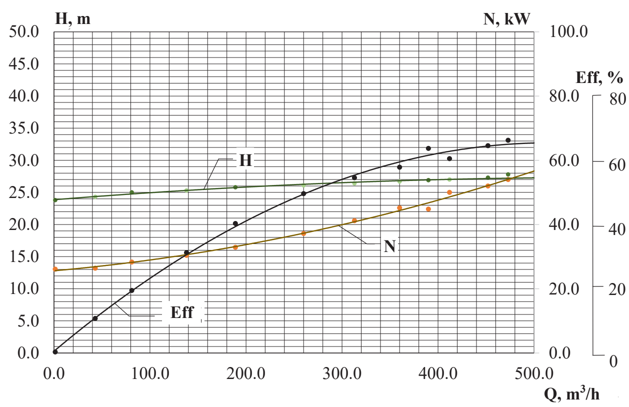



Fig. 6. Test results for option No. 1: energy performance

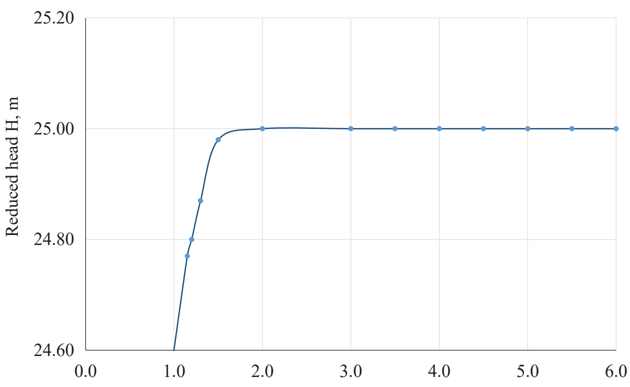



Fig. 7. Test results for option No. 1: graph of shear cavitation characteristics

The operation of the experimental variant No. 1 on the capacities of 0.4–0.8 $Q_{opt}$ was accompanied by an increase in noise and vibration, when the pump reached the optimal capacity values of 0.8–1.2 $Q_{opt}$, the pump operation became quiet and without significant vibration. This confirms the accuracy of the design of the inducer centrifugal stage in a specific operating point. The nature of the noise is hydrodynamic – at low capacities, the vacuum at the inlet to the pump is less, and therefore more air «collapses» on the blades of the inducer.

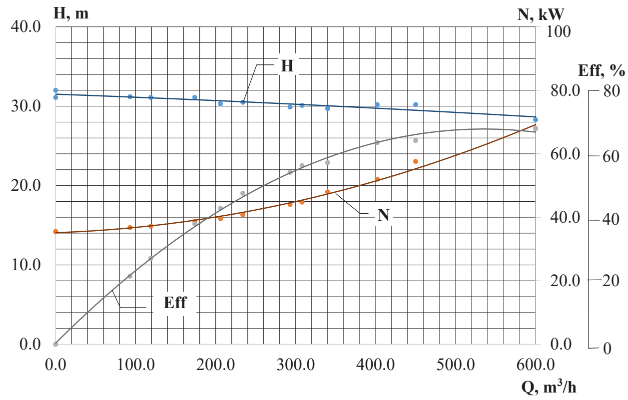
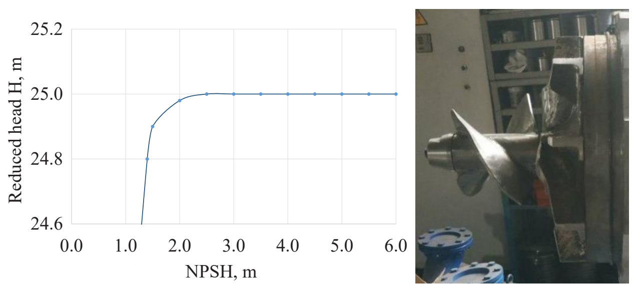



Fig. 8. Test results for option No. 2: energy performance




*a* *b*

Fig. 9. Test results of option No. 2:
*a* – shear cavitation characteristic; *b* – flow part of the tests of option No. 2

During the tests of the experimental sample No. 2, a similar increase in noise and vibration was observed as with the first sample, but in a slightly smaller order – because the pump is designed for lower capacities.

Tests of sample No. 3 showed the best results in terms of noise and vibration – they were absent at all over the entire range of capacities. Such indicators may indicate the fidelity of the design of the hydraulic part and the advisability of using a closed impeller together with an inducer for performing specific technological operations.

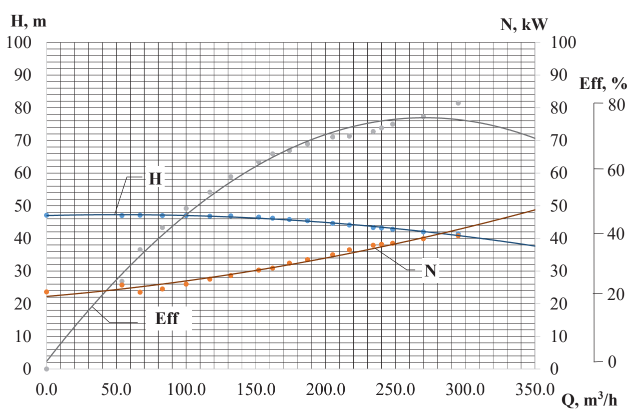



Fig. 10. Test results for option No. 3: energy performance

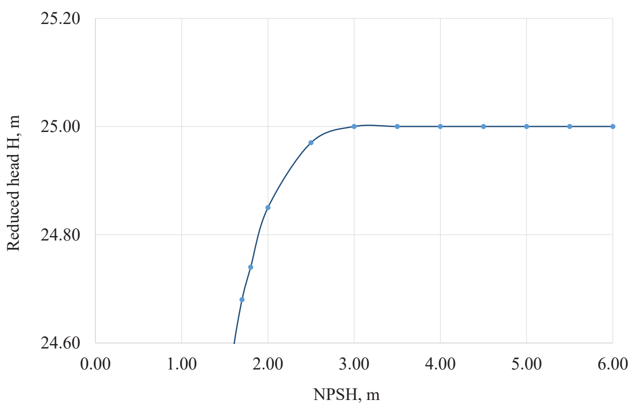



Fig. 11. Test results for option No. 3: graph of shear cavitation characteristics

Fig. 12. The hydraulic part of the impeller of tests of option No. 3

However, as practical observations show, the use of closed impellers leads to long-term repairs through crystallization of thick and hot liquids inside the closed impeller.

**5. 3. Design and manufacture of an industrial sample of a cantilever pump for the technological process of evaporation of sugar syrup**

The industrial design was developed in spite of the very complex technical problem of the plant. Namely, the capacity is $Q$=400 m$^3$, the head is $H$=25 m, the efficiency is not less than 60 %, the permissible operating temperature is 110 °C, the NPSH is not less than 2 m, the possibility of pumping solid impurities (up to 50 % by mass).

The task was implemented in full and was confirmed by parametric tests of an industrial design (Fig. 13) before shipment to the customer.

In the industrial sample, the pressure and flow met the conditions of the task, it was possible to achieve efficiency=67 %, which is 7 % more than in the task.

The modernized hydraulic part was installed in the unified Synerflow pump, Fig. 14, *a*.

After the pump was handed over to the customer, the pump was installed in the sugar syrup evaporation line to feed the raw material to the film evaporator. At the PJSC «Teofipol Sugar Plant» (Ukraine) (PRIVATE JOINT STOCK COMPANY TEOFIPOL SUGAR MILL), controlled operation was carried out, as a result of which the stable operation of the pump was confirmed at all stages, and the main task was solved – the pump operation without cavitation.

Fig. 13. Industrial design at the stage of parametric tests

*a*

*b*

Fig. 14. Industrial design of the Synerflow pump: *a* – unified Synerflow pump; *b* – Pump on the technological line of the plant

**6. Discussion of the results of the experimental study of the hydraulic part of the Synerflow pump**

In work [2], the problem of Investigation of the cavitation reserve was started by mathematical modeling, the authors managed to achieve a high agreement between the model and the physical experiment on pure water. But this method does not give convergence when calculating work on multiphase thick mixtures. Given the lack of a method for calculating the inducer centrifugal stage with a two-level blade system, in this work it was decided to start immediately with a physical experiment and use the results obtained as a basis for constructing an analytical model and further numerical modeling.

As a result of tests on the experimental stand of the Department of Applied Hydroaeromechanics of Sumy State University (Ukraine), a number of energy characteristics (Fig. 6, 8, 10) and cavitation characteristics (Fig. 7, 9, *a*, 11) were obtained. When testing the hydraulic part No. 1 at capacity rates of 0.4–0.8 $Q_{opt}$, increased noise and vibration were recorded, which disappeared at a capacity above 0.8 $Q_{opt}$. This confirms the correctness of the design of the inducer centrifugal stage at a specific operating point. The nature of the noise generation is hydrodynamic – at low rarefaction capacities, the flow at the pump inlet is less, which means more air «collapses» on the inducer blades. In contrast to experiment No. 1, the operation of the hydraulic part No. 3 was stable over the entire range of fcapacities, and this difference should be further investigated. Comparative analysis of the obtained characteristics (Fig. 6, 10) allows to quantify the change in the efficiency of the inducer centrifugal stage during the transition from a closed impeller to a half-open impeller with a two-level blade system, the change can reach 15 %. Analysis of the cavitation characteristics (Fig. 7, 11) makes it possible to determine that due to the use of a two-level blade system, it is possible to increase the cavitation margin.

In the future, it is advisable to conduct additional research at an industrial facility, where during the operation of the pump there is a simultaneous change in temperature, pressure at the pump inlet, the amount of solid phase in the liquid and other parameters. Such studies require special measuring devices that are resistant to crystallization of the working medium. But only a physical experiment on a natural environment will make it possible to refine the calculation method.

## 7. Conclusions

1. Analysis of the obtained energy and cavitation characteristics confirmed the correctness of the adopted design solution. And the very assumption that thanks to the combination of a three-blade inducer and a semi-open impeller with a two-level blade system, it is possible to create a pump with high anti-cavitation properties.

The correctness of the selected design and operating parameters, which have a key impact on the workflow, was confirmed. Namely, the installation of an inducer made it possible to increase the pressure at the inlet to the impeller, without a critical narrowing of the cross-section. The use of a two-level blade system, with 3 blades at the inlet to the impeller, made it possible to maximize the reduced diameter of the inlet to the impeller, confirmed the conclusions from work [2]. And the use of 9 blades at the outlet of the impeller made it possible to ensure high energy efficiency.

2. As a result of a physical experiment, energy and cavitation characteristics were obtained for a cantilever pump, which has a combination of a three-blade inducer and a half-open impeller with a two-level blade system. In experiment No. 1, noise and vibration arose at capacity rates 0.4–0.8 $Q_{opt}$, which disappeared in the range 0.8–1.2 $Q_{opt}$. The nature of the noise generation is hydrodynamic – at low rarefaction capacities, the flow at the pump inlet is less, which means more air «collapses» on the inducer blades.

The decrease in the energy efficiency of the pump during the transition from a closed to a half-open impeller was estimated; the decrease in efficiency can reach 15 %. But in difficult conditions, where it is possible to block the working channel with a solid fraction and crystallization of the working medium is possible, a half-open impeller significantly wins in reliability, and this is a decisive factor.

It has been proven that the use of a two-level blade system improves the cavitation performance and increases the NPSH by 1.2 m. This is due to an increase in the flow area at the pump inlet.

3. The projected hydraulic part was fabricated and installed on a unified Synerflow pump. After parametric tests, the pump was installed in the sugar production line at the Teofipol sugar plant. The pump is used to supply hot (105 °C) syrup to a film evaporating facility. The unit consistently delivers parameters throughout the entire evaporation cycle, despite the change in the percentage of solid phase, temperature, density and level of the working medium.

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