

Досліджено вплив установки надроторних елементів у вигляді статорної втулки з повздовжніми прямими пазами над передвключеним колесом на характеристики модельного шнекововідцентрового ступеня. Проведено фізичний експеримент з використанням планування для вирішення проблеми оптимізації геометричних параметрів статорної втулки з повздовжніми прямими пазами в багатофакторній задачі покращення кавітаційно-ерозійних характеристик шнекововідцентрового ступеня за допомогою надроторних елементів. Було визначено спектр збуджуючих частот коливань досліджуваного шнекововідцентрового ступеня від кавітаційних процесів для можливості використання параметра стійкості до кавітаційної ерозії у якості параметра оптимізації. Експериментальним шляхом визначено оптимальні розміри надроторної втулки досліджуваного шнекововідцентрового ступеня:  $Z=32$ ,  $b=14$ ,  $l_1=20$ ,  $l_2=20$ . Це дозволило покращити кавітаційно-ерозійні якості шнекововідцентрового ступеня без зміни габаритних розмірів та не погіршити напірні та енергетичні характеристики. Проведено додатковий фізичний експеримент за допомогою альтернативного методу визначення кавітаційно-ерозійних якостей для підтвердження отриманих у дослідженні результатів завдяки застосуванню надроторних елементів у шнекововідцентровому ступені. Використання надроторних елементів у складі шнекововідцентрових ступенів зазвичай обмежувалося лише потребами підвищення кавітаційних якостей ступеня. В рамках дослідження, що описано в даній статті, запропоновано використання цього елемента для боротьби з негативними наслідками кавітаційної ерозії. Була підтверджена можливість такого використання та розроблені науково-методичні рекомендації щодо проектування надроторних елементів у складі шнекововідцентрового ступеня. Впровадження удосконалених перших шнекововідцентрових ступенів з надроторними елементами в існуючі конструкції відцентрових насосів дозволить збільшити наробітку до відмови, що актуально для всіх галузей промисловості, де використовуються відцентрові насоси

**Ключові слова:** відцентровий насос, шнекововідцентровий ступінь, надроторні елементи, кавітаційно-ерозійні характеристики

## 1. Introduction

Today one of the main problems is a lack of energy resources. Therefore, one of the main tasks of Ukraine and the world is to reduce inefficient energy consumption significantly. It is

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# IMPROVEMENT OF CAVITATION EROSION CHARACTERISTICS OF THE CENTRIFUGAL INDUCER STAGE WITH THE INDUCER BUSH

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well known that pumps are used almost in all industries, and according to various estimates consume from 20 % to 25 % of all electricity produced in the world, and in some industries, this value can range to 50 % [1]. One indicator of the pump energy efficiency is the cost of its life cycle, the analysis of

which shows that one of the significant components is the final cost of the pump [2]. The final pump cost depends directly on its mass and overall characteristics. The reduction of mass and overall characteristics will not only reduce the final pump cost and pump life cycle cost, but also improve its energy efficiency. This fact prompts new research in the field of pump engineering.

One of the most energy-consuming pump systems is the systems with main feed water pumps used in nuclear and thermal power plants, which are characterized by high mass and dimensional characteristics. One of the effective ways to reduce mass and dimensional characteristics is to use main pumps with centrifugal inducer stage (first stage) instead of booster pumps. This helps not only completely remove booster pump from the pump system but also operate with higher speed [3]. The first centrifugal inducer stage (Fig. 1) came to industrial pump engineering from the rocket industry in which the reduction of mass and dimensional characteristics has always been a primary target, and today it has been widely used in many designs of centrifugal pumps.

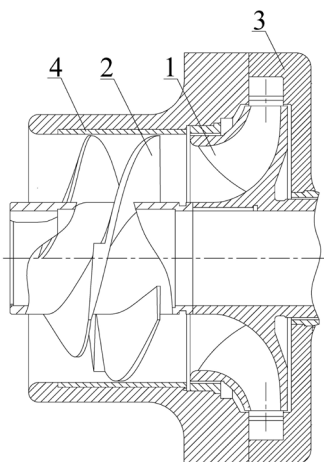


Fig. 1. Centrifugal inducer stage: 1 – centrifugal pump impeller; 2 – inducer; 3 – diffuser; 4 – casing inducer bush over inducer

The significant advantage of an inducer over a centrifugal stage without inducer is its improved cavitation characteristics. The value of suction specific speed  $Nss_{cr}$  of the centrifugal inducer stage reaches the value of 3,000, in contrast to the centrifugal stage with  $Nss_{cr}=1,000-1,110$  [4].

But at the same time, the centrifugal inducer stage has a negative feature characterizing the pump operation – the existence of a complex three-dimensional flow at the inlet. This feature is evident as severe reverse flows which can be characterized by strong unsteady behavior and lead to low-frequency self-vibrations leading to the inducer damage. If the pump is designed with centrifugal inducer stage, it is the inducer that is mostly subjected to cavitation erosion. Despite this, more than half a century, the specialists of VNIIAEN (Research and Design Institute for Atomic and Power Pump-building, Sumy, Ukraine) have been designing industrial pumps with centrifugal inducer stages (first stage). We have designed and implemented a variety of design solutions that allowed us to successfully use the centrifugal inducer stages as the first stages in feed water pumps, condensate pumps, crude oil pumps and other centrifugal pumps. Among these developments, we may point out the most effective one in terms of its

resistance to cavitation erosion which is the inducer that has a ledge on the suction surface of the blade.

Adequate cavitation erosion resistance of the hydraulic part has always been an urgent problem for designers of centrifugal pumps intended for nuclear and thermal energy industries and today's world demands raise the bar of these requirements higher and higher. Thus, now there is a requirement to provide the centrifugal pump impeller life of at least 40,000 hours without the critical cavitation damage. Moreover, recently, more severe requirements for NPP feed water pumps began to appear which require reliable long-term operation within a wide range of capacities – from 20 to 130 % of the rated flow rate, as well as operation without time limits with feed water temperature of +110°C and over.

## 2. Literature review and problem statement

The study aimed to improve the cavitation erosion resistance of the centrifugal inducer stage is a multi-faceted problem. To solve this problem, it is necessary to find a compromise solution to improve the cavitation erosion resistance of the centrifugal inducer stage as well as maintain adequate head and sufficiently high efficiency without increasing the mass and dimensional characteristics of the pump. An obvious solution to this problem is to use double-suction impeller in the first stage with inducers being installed upstream of each impeller eye. This design ensures a significant reduction of centrifugal inducer stage wear rate occurred due to cavitation erosion but at the same time it leads to a more complex design of the pump and increases its mass and dimensional characteristics.

The analysis of the study [3] suggests that the resources for improving the cavitation erosion resistance of industrial pump centrifugal inducer stages due to the geometry of the inducer blade system are exhausted. The results presented in [4] indicate that improvement of the cavitation erosion resistance of centrifugal inducer stages is possible only due to a significant decrease in the value of  $Nss_{cr}$  and cost-effectiveness or increase in size which is considered inappropriate. The results of long experience in designing of inducers installed in the first centrifugal inducer stages of industrial pumps, which can be used to assess the modern achievements in this field, are presented in [5]. The study [6] analyzes the effect of the clearance between the inlet casing and the inducer, and also states that cavitation erosion most often occurs in the peripheral areas of the inducer. Hence, the emphasis should be on this area of the centrifugal inducer stage which in the classic design (Fig. 1, Ref. No. 4) is a smooth surface. There are a number of publications regarding the impact of inducer bushes, with a variety of shaped grooves, installed instead of inducer bushes with a smooth surface on the energy and cavitation characteristics of the centrifugal inducer stage.

In [7], the effect of a nonstandard plate being installed in the inlet casing above the inducer was studied. Thanks to this design, they were able to change the flow parameters at the inlet of the centrifugal inducer stage. The study [8] shows the possibility to improve the cavitation characteristics of the turbomachine within the whole range of the capacities through the use of the device “J-groove”, but with a certain drop in efficiency. The study [9] provides an analysis of designing a high-speed turbine driven pump under which the possibility to overcome the cavitation in the blade system

of the inducer using the J-groove was analyzed. An analysis of the influence of the groove location in the inducer bush installed above the inducer in the axial direction in terms of impact on cavitation instability is given in [10]. The paper [11] describes the improvement of cavitation and, at the same time, power performance of the multistage industrial pump. This was because of the implementation of five helical grooves made in the direction opposite to the rotor rotation on the inner surface of the inducer bush. The authors of the papers [8–11] are united in the opinion that the positive effect of the inducer bushes with grooves can be explained by suppression of the vortex and cavitating flows. These concerned in particular the reverse flow that occurs at the inlet of the centrifugal inducer stage and which is known to be one of the main sources of cavitation damage.

Requirements for cavitation resistance of impellers of centrifugal pumps are constantly increasing. In view of this, it becomes clear that now it is not enough to achieve the cavitation erosion resistance that first inducers had in order to ensure the reliable operation of a new generation of NPP feed water pumps operated without booster pumps. Therefore, the solution to the above problem may be the use of inducer bushes.

### 3. The aim and objectives of research

The aim of this study is the improvement of the cavitation erosion characteristics of the centrifugal inducer stage by means of inducer bushes and development of design recommendations for them. This will help to refine the existing centrifugal inducer bush design without changing their overall dimensions.

To achieve this aim, several objectives shall be accomplished:

- to perform a physical experiment to define the spectrum of frequencies excited by cavitation in order to compare the cavitation erosion characteristics of centrifugal inducer stages with/without inducer bushes, using vibration data;
- to find an optimal combination of inducer bush geometrical parameters which have a considerable impact on the cavitation erosion resistance of the centrifugal inducer stage and at the same time do not deteriorate other inducer stage characteristics;
- to develop design recommendations for inducer bushes in order to increase cavitation erosion resistance of the centrifugal inducer stage;
- to check the obtained results by means of an alternative method for the determination of cavitation erosion characteristics using soft paint coatings.

### 4. Impact of inducer bush geometric parameters on centrifugal inducer stage performance

#### 4.1. Methods of study

The most useful method to find the optimal combination of the inducer bush geometric parameters, which provides the improvement of cavitation erosion resistance of the centrifugal inducer stage, is a physical experiment.

To reduce the number of experiments required to find the optimum area and determine the best variant, it is useful to design an experiment; it is possible only with the availability of certain initial information. The analysis of the previous experiment results [12] not only confirmed the prospect of the use of inducer bushes, but also allowed us, in combination with the literature analysis, to identify the significant factors whose impact should be considered and establish the appropriate levels of variation. The following factors were determined as the main factors being studied (Fig. 2):

- number of grooves ( $Z$ ) in the casing bush;
- width of grooves ( $b$ ) in the casing bush;
- length of grooves ( $l_1$ ) upstream the leading edge of the inducer blades (on the periphery);
- length of grooves ( $l_2$ ) downstream the leading edge of the inducer blades (on the periphery).

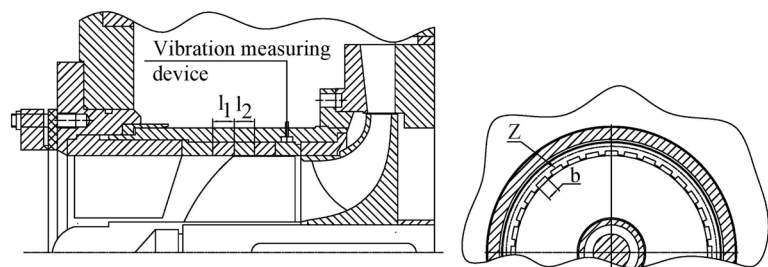


Fig. 2. Constructive diagram of the experimental device

As the main purpose of the study is to obtain improved cavitation erosion characteristics of the centrifugal inducer stage, therefore, the threshold value of the cavitation erosion resistance  $K_{ec}$  was used as an optimization parameter:

$$K_{ec} = K_{ec(b)} \cdot \sqrt[3]{\frac{w_{c(b)}}{w_{c(s)}}}, \quad (1)$$

where  $w_{c(s)}$  and  $w_{c(b)}$  are the values of vibration acceleration due to cavitation for the centrifugal inducer stage being studied and for the baseline (reference) centrifugal inducer stage with smooth inducer bush respectively, which are tested under identical conditions;  $K_{ec(b)}$  is the threshold value of the cavitation erosion parameter for the baseline inducer.

The experimental values of  $K_{ec(b)}$  obtained in VNIAN depend on the inducer design and the type of pumped medium are given in [13].

A full factorial experiment  $2^4$  considering the interaction effects was conducted, since the analysis [12] showed that the interaction effects are significant. The levels of factors and variation intervals that are going to be used during a physical experiment are given in Table 1.

To exclude systematic errors, the experiments were performed according to a random numbers table. To compensate the effect of random errors, the experiment results were twice duplicated.

The adequacy validation was performed using the F-criterion (Fisher criterion). The evaluation of result significance was performed using the Student t-test. At the same time, the 5 % level of significance was used, which is typical for engineering calculations.

**Table 1**  
Levels and intervals of factor variation during the physical experiment

Factor	Designation	Mea- surement interval	Factor level		
			Basic 0	Upper +	Lower -
Number of grooves, (Z)	X <sub>1</sub>	8	24	32	16
Width of grooves (b), mm	X <sub>2</sub>	4	10	14	6
Length of grooves (l <sub>1</sub> ), mm	X <sub>3</sub>	20	40	60	20
Length of grooves (l <sub>2</sub> ), mm	X <sub>4</sub>	10	30	40	20

**4. 2. Means of study**

The physical experiment regarding the subject of this study was performed on a model test rig of VNIIAN. The test rig operates on technical water with characteristics according to GOST 6134-2007. This test rig has a closed loop configuration which ensures energy and cavitation tests of the studied centrifugal inducer stage. The hydraulic diagram of the test rig is shown in Fig. 3.

The main components of the test rig are: experimental pump 1; experimental pump driver 2; vacuum pump 3; pressure tank 4; stabilizer tank 5; measuring device for flow rate and head. The pipelines with shut-off and control valves allow us to change the flow rate and pressure at the inlet of the experimental pump.

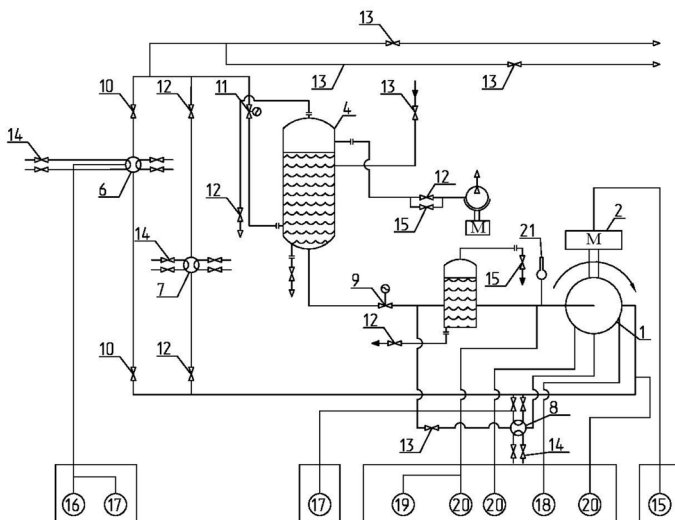


Fig. 3. Hydraulic diagram of the test rig: 1 – experimental pump; 2 – experimental pump driver; 3 – vacuum pump; 4 – pressure tank; 5 – stabilizer tank; 6 – flow meter Dy150; 7 – flow meter Dy100; 8 – flow meter Dy50; 9 – electrically driven gate valve Dy300; 10 – gate valve Dy150; 11 – electrically driven gate valve Dy150; 12 – gate valve Dy100; 13 – valve Dy50; 14 – shut-off valve (steel); 15 – valve Dy15; 16 – differential pressure gauge; 17 – differential pressure gauge; 18 – rotation frequency measuring device; 19 – vacuum gage; 20 – pressure gage; 21 – temperature gage

The experimental pump is driven by the balanced motor MBP 423/30 which allows us to perform testing at speeds within the range of 1,000–3,000 rpm.

The physical experiment was controlled at the test rig from the control panel.

The main element of the test rig is an experimental device which is a single-stage radially split pump with a transfer shaft. Such design provides a quick replacement of pump parts without complete disassembling of the pump (Fig. 2). The experimental device allows us to test the first centrifugal and centrifugal inducer model stages for a single stage configuration.

The inlet casing of the pump, in which the inducer centrifugal stage is installed, is of axial type and there is an axial lattice made of four straight radial plates which is aimed to stabilize the flow. The centrifugal impeller has seven blades with the specific speed  $n_s=120$ , the leading edge is radial, the inlet coefficient is  $K_{inlet}=5$ . The diffuser is designed as the last stage diffuser with nine passages.

The inducer has three blades with the blade cascade thickness on the periphery  $l/t=1$ , the profile of the blade is made as an arc of a circle with a ledge on the suction surface. Such design of the inducer provides the best cavitation erosion characteristics for today with cavitation erosion resistance  $K_{ec}=20$  [13]. Therefore, it was decided to perform the physical experiment regarding the study of the inducer bush impact using this inducer, since improving the cavitation erosion resistance with this inducer is the most expedient.

The study of all variants of inducer bushes according to the matrix of variants was performed by means of a physical experiment during which hydraulic performance and cavitation tests were performed within 5 modes with capacities of  $0.3Q_{rated}$ ,  $0.5Q_{rated}$ ,  $0.75Q_{rated}$ ,  $1.0Q_{rated}$  and  $1.2Q_{rated}$ . During cavitation tests, the vibration characteristics were measured by a vibration analyzer VD-1854. To determine the spectrum of oscillations excited by cavitation, spectrographs of vibration acceleration were analyzed (Fig. 4).

The mean-square value of the vibration acceleration at NPSH of 15 m was  $13.8 \text{ m/s}^2$ , and with NPSH of 1.15 m was  $41.8 \text{ m/s}^2$ .

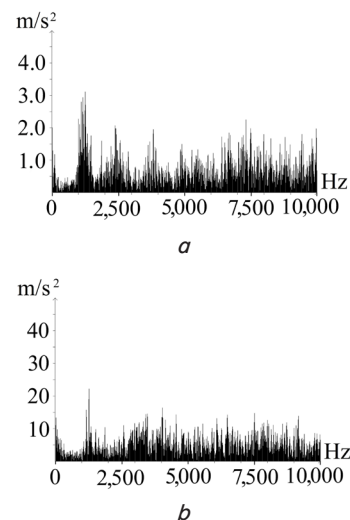


Fig. 4. Spectrograph or relationship of vibration acceleration spectral density and frequency at NPSH a – 15 m and b – 1.15 m



The analysis of the spectrographs given in Fig. 4 showed that recording of the impact of cavitation in the centrifugal inducer stage is worth to perform with the mean square value of vibration acceleration. The main component of the vibration is within the range of 10 Hz to 10 kHz, therefore, the measurement of the vibration characteristics was performed to determine the vibration acceleration  $w_c$  within this range.

**5. Study results of the impact of inducer bush geometric parameters on the centrifugal inducer stage performance**

Since, as it was found [13], the most dangerous in terms of cavitation resistance is the operation with the capacity of 0.75  $Q_{rated}$ , and then it will be obvious that the analysis should be performed precisely in this mode.

Vibration behavior obtained in the study of the inducer bush without grooves allows us to obtain the value of the vibration acceleration  $w_{c(b)}=37 \text{ m/s}^2$ , which is used as the base value.

The study results obtained by the equation (1) as the arithmetic mean value of the optimization parameter  $K_{ec}=f(w_c)$  are given in Table 2.

Table 2

Results of studies performed according to the planning matrix

Experiment No.	$w_c$	$Y=K_{ec}$
1	34.5	20.47
2	36.0	20.18
3	35.6	20.26
4	34.7	20.43
5	30.6	21.31
6	35.8	20.22
7	30.7	21.28
8	34.1	20.55
9	28.4	21.84
10	32.9	20.80
11	32.9	20.80
12	31.0	21.21
13	22.9	23.46
14	32.5	20.88
15	31.0	21.21
16	26.7	22.30

Calculations produced the variance of optimization parameters  $G_p=0.35$  which does not exceed the table value [14]  $G_T(2-1, 16)=0.4709$  (adopted 5 % level of significance), and hence the variances are uniform.

The variance of the experiment is  $s_y^2=0.711$ , the variance of regression coefficients is  $s^2\{b_i\}=0.022$ , the value error of the  $i$ -th regression coefficient is  $s\{b_i\}=0.149$ , the confidence interval of the regression coefficient is  $Db_i=\pm 0.316$ .

As a result of the performed factor experiment, after the elimination of coefficients less than the confidence interval, the regression equation is obtained:

$$Y=21.08-0.33X_3-0.49X_4+0.37X_1 \cdot X_2. \tag{2}$$

The adequacy of the obtained model was verified using the  $F$ -criterion. The value calculated by the  $F$ -criterion is  $F_p=0.92$ , the table value of the  $F$ -criterion at 5 % of significance level and the numbers of degrees of freedom for the numerator 11 and for the denominator 16 is  $F_T=2.4$ . Because  $F_p < F_T$ , the model is adequate.

Using the transfer equation from the code values of factors to the natural values, the equation (2) can be transformed into:

$$K_{ec}=25.975-0.116 \cdot Z-0.278 \cdot b-0.016 \cdot l_1-0.046 \cdot l_2+0.012 \cdot Z \cdot b \tag{3}$$

To find the best value of the response function optimization parameter (3), the steepest ascent method was used. The steepest ascent starts with a zero ( $Z^*=24, b^*=10, l_1^*=40$ , and  $l_2^*=30$ ). After completing the linearization  $Z \cdot b$  near the zero point, the equation (3) will be:

$$K_{ec}=23.095+0.004 \cdot Z+0.010 \cdot b-0.016 \cdot l_1-0.049 \cdot l_2. \tag{4}$$

According to the obtained model (4), the cavitation erosion of the stage  $K_{ec}$  increases with decreasing the lengths of the grooves  $l_1$  and  $l_2$  and increasing the number  $Z$  and the width of the grooves  $b$ . Calculation of gradient motion is given in Table 3.

Table 3

Calculation of steepest ascent

Description	$Z$	$b$	$l_1$	$l_2$	$K_{ec}$
Base level	24	10	40	30	-
Coefficient $b_i$	0.004	0.010	-0.016	-0.049	-
Variation interval $\epsilon_i$	8	4	20	10	-
$b_i \times \epsilon_i$	0.032	0.040	-0.320	-0.490	-
Step $D_i$	3	2.5	-10	-5.31	-
Rounded step	3	2	-10	-5	-
Thought experiment No.17	27	12	30	25	21.55
Thought experiment No.18	30	14	20	20	22.17
Physical experiment No.19	32	16	20	20	21.95

In the experiment No.19, we obtained the decreasing of the cavitation erosion value of the stage of  $K_{ec}=21.95$ , which is lower than the result of the thought experiment No. 18 and lower than the result of the best experiment No. 13 ( $Z=32, b=14, l_1=20, l_2=20, K_{ec}=23.46$ ) in the experiment plan by 10 %. Therefore, we end calculation of the extreme point which was made by means of the steepest ascent method.

Fig. 5 shows the comparative characteristics of the centrifugal inducer stage with a smooth inducer bush and inducer bush with grooves No.13.

Analysis of the experiment results according to the experiment design and the obtained regression equation allows us to develop the following design recommendations for the inducer bush to improve the cavitation erosion resistance of the centrifugal inducer stage:

- width of the groove: about  $b=0.007$  of the impeller outer diameter of the stage  $D_2$ ;
- depth of the groove: about  $h=0.33$  of its width  $b$ ;
- number of grooves in the inducer bush:  $Z=32$ ;
- location of the inducer bush starting from the leading edge on the periphery of the inducer – about to  $l_1=l_2=0.21$  of the total length of the blade system of the inducer.

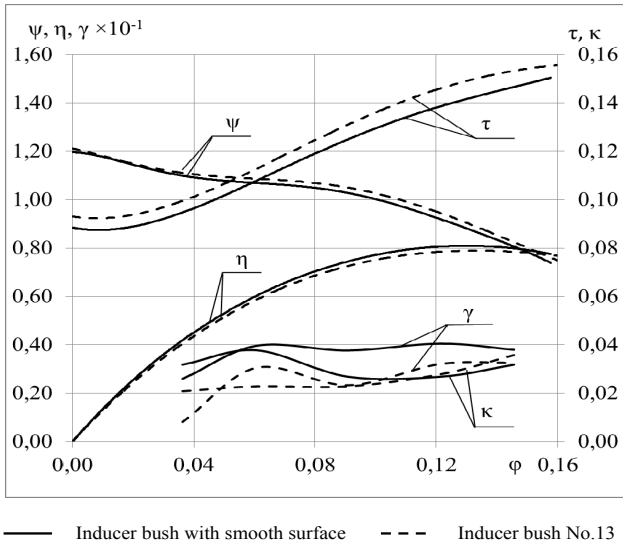


Fig. 5. Centrifugal inducer stage characteristic curves:

$$\phi = \frac{Q}{\pi \cdot D_2 \cdot b_2 \cdot U_2} \text{ - capacity coefficient, } \Psi = \frac{2 \cdot g \cdot H}{U_2^2} \text{ - head coefficient,}$$

$$\tau = \frac{2 \cdot P}{\pi \cdot \rho \cdot U_2^3 \cdot D_2 \cdot b_2} \text{ - power coefficient, } \kappa = \frac{2 \cdot g \cdot NPSH3}{U_2^2} \text{ - NPSH coefficient, } \gamma = \frac{\omega_{\kappa}}{g} \text{ - vibration acceleration coefficient}$$

The recommendations were developed considering the change of groove parameters within the limits defined in the experiment design and are suitable for pumps with the inducer installed in the first stage with the value of specific speed of which is about to  $n_s=120$ .

The adequacy of the obtained results was verified by an alternative method using soft paint coatings. For this purpose, a special soft paint was applied to the surface of the inducer which was then tested as a part of the centrifugal inducer stage with and without the inducer bush. The inducer bush selected with geometric parameters according to preliminary calculations ( $Z=32, b=14, l_1=20, l_2=20, K_{ec}=23.46$ ) should improve the cavitation erosion resistance of the centrifugal inducer stage according to predicted values. It was installed above the inducer and the centrifugal inducer stage was tested with and without it under similar conditions with  $0.75Q$  of rated capacity during 4 hours in cavitation mode. After the tests of the inducer performed with and without the inducer bush, the soft paint coating on the inducer was examined, and no cavitation damage was detected on the inducer installed with the inducer bush. The inducer after testing is given in Fig. 6.

So, Fig. 6, *a, c* show a clear “trace”, of cavitation erosion indicated the damaging of soft paint caused by the collapse of the cavitation bubbles on the blade surface of the inducer, which is observed on the trailing edge of the blade suction side. Also, the small damage is observed in the middle part of the pressure side of the blade. The picture of the damage qualitatively coincides with the results previously obtained with the inducer of the

similar design [4]. Fig. 6, *b, d* show only slight damage of soft paint on the peripheral parts of the inducer blade as well as on its leading edge caused by interaction of liquid flow. The pattern of this damage indicates that they are caused not by cavitation. The performed additional experiments using the soft paint have clearly demonstrated the effectiveness of the proposed method of improving the cavitation and erosion resistance of the centrifugal inducer stage by means of inducer bushes.



*a*



*b*



*c*



*d*

Fig. 6. Inducer after testing performed with a soft paint technique during 4 hours in cavitation mode: *a* – the suction side of the inducer blade after testing without the inducer bush; *b* – the suction side of the inducer blade after testing with the inducer bush; *c* – the pressure side of the inducer blade after testing without the inducer bush; *d* – the working side of the inducer blade after testing with the inducer bush

## 6. Discussion of the study results regarding the impact of inducer bush geometric parameters on the centrifugal inducer stage performance

Improvement of the cavitation erosion resistance of the pump centrifugal inducer stage was achieved by the positive impact of the inducer bush geometric parameters on the flow behavior at the inlet of the centrifugal inducer stage. Also, the inducer bush ensured the reduction of the destructive effect of cavitation cavities occurred on the periphery of the inducer.

The obtained results are mainly associated with the impact of the inducer bush on the flow behavior at the inlet of the centrifugal inducer stage and its blade system. The operation of the inducer is accompanied by the reverse flows which have a negative impact on the centrifugal inducer stage. In a case of inducer bushes installed over the inducer, the reverse flows get into the grooves and lose their energy which leads to the decreasing of their negative impact on the main flow. In turn, the main flow due to the weakening of the reverse flows becomes steadier in the area of the blade system of the inducer. This contributes to the reduction of pressure fluctuations of the flow and the improvement of the vibrational characteristics of the stage. In addition, in the case of the interaction of reverse flows with grooves of the inducer bush, vortices occur in them. These vortices break down the cavitation cavities that occur on the inducer blades which leads to an improvement of the cavitation characteristics of the stage.

The study, described in this paper, presents the optimal dimensions of the inducer bush of the studied centrifugal inducer stage, which provides the achievements of the maximum value of the cavitation erosion resistance parameter. At the same time, the cavitation characteristics were improved without significant deterioration of the pressure and energy characteristics of the centrifugal inducer stage. From a practical point of view, this allowed us to develop the design recommendations for the inducer bush installed in the first centrifugal inducer stage in order to improve the cavitation and erosion characteristics. An applied aspect of using the obtained scientific result is the possibility of improving the existing first centrifugal inducer stages of pumps.

However, it should be noted that the results of the improvement of cavitation and erosion characteristics are obtained for a small range of the centrifugal inducer stages with values of speed coefficients about  $n_s=120$ . This imposes certain limitations on the use of the developed design recommendations for inducer bushes. Also, it should be noted that due to such a complex interaction of inducer bushes with fluid flows at the inlet of the centrifugal inducer stage, there is a probability that grooves will be damaged.

But the methods proposed in this study do not allow us to test this assumption. The inability to refute this

assumption within this study generates a potentially interesting direction for further research. Particularly, they can be focused on detecting the starting point of damaging the grooves and what causes it. Determination of these data will help to investigate their nature and methods of overcoming, which will allow to increase the mean time between failures of the centrifugal inducer stage with the inducer bush.

## 7. Conclusions

1. The physical experiment was performed. The results of this experiment allowed us to obtain parametric characteristics and to determine the frequency spectrum of excited oscillation of the studied centrifugal inducer stage with the inducer bush. It was found that excitation caused by cavitation is within a wide frequency spectrum ranged from 10 Hz to 10 kHz.

2. The regression equation was obtained for the cavitation erosion resistance parameter  $K_{ec}$ , which allowed us to determine the significance of the inducer bush geometric parameters considering their impact on the cavitation erosion resistance of the centrifugal inducer stage. These parameters are: the number of grooves ( $Z$ ), the width of the grooves ( $b$ ), the lengths of grooves ( $l_1$ ) upstream the leading edge of the inducer blades and the length of the grooves ( $l_2$ ) downstream the leading edge of the inducer blades. The obtained regression equation indicates that the most significant parameters influencing the cavitation erosion resistance of the centrifugal inducer stage are the number of grooves and their width. An increase of these parameters improves the resistance to cavitation erosion of the centrifugal inducer stage with the inducer bush. Due to the application of the steepest ascent method to the obtained regression equation, the optimal dimensions of the inducer bush of the studied centrifugal inducer stage by means of which the maximum value of the cavitation erosion resistance  $K_{ec}$  is achieved, are the following:  $Z=32$ ,  $b=14$ ,  $l_1=20$ ,  $l_2=20$ ,  $K_{ec}=23.46$ . At the same time, the cavitation characteristics were improved without significant deterioration of the pressure and energy characteristics of the centrifugal inducer stage.

3. The study results allowed us to develop design recommendations for the inducer bushes used in the first stages of centrifugal pumps with specific speed about  $n_s=120$  in order to improve their cavitation erosion resistance.

4. The physical experiment with the use soft paint coatings has clearly confirmed the adequacy of the results obtained in the study and showed the utilization efficiency of inducer bushes as a mean against cavitation erosion in centrifugal inducer stages.

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