Influence of Geometric Parameters of Inducer Bush Design on Cavitation Erosion Characteristics of Centrifugal Inducer Stage of Pump

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Abstract. The article represents the research results of a centrifugal inducer stage with inducer bush. We determined the optimal inducer bush design that would improve the cavitation erosion characteristics without deteriorating the energy levels and preserving overall dimensions of the centrifugal inducer stage at the same time.

1. Introduction
Currently, one of the topic issue in the field of pumpbuilding is the assurance of centrifugal pump service life of at least 40,000 hours without the critical consequences of cavitation wear in accordance with modern requirements for feed water pumps operated in nuclear and thermal power plants [1]. A guaranteed solution of this problem is the use of double suction fist stage and two inducers. However, this method will lead to a significant complication of the design, as well as an increase in overall dimensions and mass, respectively. The analysis of the literature sources [2-5], as well as experience of the centrifugal inducer stage design suggests that cavitation erosion resistance increase due to only the geometry of the inducer vane system has already been exhausted, therefore, it seems reasonable to find a solution of the problem through others elements of the centrifugal inducer stage. It is known that inducer peripheral areas are subjected to the greatest damage caused by cavitation erosion, therefore attention was paid to this place.

Proceeding from the abovementioned, the idea to solve the problem of the cavitation erosion wear using the centrifugal inducer stage with the inducer bush was proposed. This will permit to improve the cavitation erosion characteristics and will not impair the energy properties at the same time. Figure 1 shows a schematic diagram of traditional design of centrifugal inducer stage, where a smooth bush (Figure 2 (a)) is placed over the inducer (Figure 1, item 2) and idea is to replace this smooth bush with a bush with axial grooves – ( Figure 2 (b)).
Figure 1. Principal scheme of traditional centrifugal inducer stage design: 1 - impeller; 2 – inducer; 3 – diffuser; 4 – smooth inducer bush.

The advantage of this technical solution is that the improvement of the cavitation erosion characteristics of the centrifugal inducer stage can be obtained with the current hydraulic passage while maintaining the overall dimensions of the stage. Presumably, the positive effect of the implementation of the inducer bush with grooves is achieved due to the occurrence of vortexes in bush grooves which positively influence on reverse flows at the inducer inlet and also eliminate cavitation cavities located on periphery thus protecting inducer from damage.

Figure 2. Design of bush being under research: (a) – smooth bush; (b) - bush with grooves.

2. Research Task
It is known that first traces of cavitation erosion in pumps appear only after the incubation period which can last dozens of hours [6, 7]. Such a long duration of incubation period greatly complicates the possibility of systematic tests for pump cavitation wear and determine its cavitation erosion characteristics. Therefore, in order to confirm the expediency of inducer bush a method for assessing
the cavitation erosion characteristics of the centrifugal inducer stage was developed [8]. This method will allow to estimate the cavitation wear as well as save time for research as much as possible. According to this method, a threshold value of the resistance to cavitation erosion $K_{cr}$ is chosen as a value of the cavitation erosion characteristics of the centrifugal inducer stage with grooved bush being under research [2].

$$K_{cr\,(ex)} = K_{cr\,(b)} \left( \frac{w_{k\,(b)}}{w_{k\,(ex)}} \right)^{1/3}$$

where $w_{k\,(ex)}$ and $w_{k\,(b)}$ – cavitation vibration acceleration value for the centrifugal inducer stage with the grooved inducer bush being under research and the centrifugal inducer stage with the smooth inducer bush (reference value) that are tested under identical conditions, respectively;

$K_{cr\,(b)}$ – threshold value of cavitation erosion parameter for centrifugal inducer stage with smooth inducer bush (reference value).

The research first step is to carry out tests on the model test stand using the test procedures where the following geometric parameters of the inducer bush are used as the main influence factors: $z$ - number of grooves, $b$ - width of grooves, $l_1$ - length upstream and $l_2$ – length downstream the leading edge of inducer vanes. The 16 variants of the inducer bush with different geometric parameters have been designed, where combinations of the geometric parameters for inducer bush are combined within the variability interval of the factor level.

Figure 3. Constructive diagram of the experimental device.

Figure 3 shows a schematic diagram of the experimental device in which the centrifugal inducer stage is placed. It consists of inducer, impeller, diffuser and axial grid at the inlet.

3. Description of Physical Experiment

The tests were conducted on the model test stand, the basic diagram of which is shown in Figure 4. The test stand operates as a closed loop and uses service water.

The main element of the test stand is the experimental device (Figure 3) - a single-stage axially split pump with a transfer shaft, which permits the operative replacement of the working parts without complete disassembly of the pump. The experimental device is driven by a balanced motor which provides the possibility of testing at speed range of 1000-3000 rpm.
Figure 4. Principal scheme of the experimental stand.

The tests were conducted on the experimental model test stand at the rotor speed of $n=2000$ rpm. The method of recording and plotting energy and cavitation characteristics curves during the tests meets the requirements of the Standard [9]. Cavitation tests were carried out at 5 flow rates: $0.3 \, Q_n$, $0.5 \, Q_n$, $0.75 \, Q_n$, $1.0 \, Q_n$ and $1.2 \, Q_n$. During these tests the vibration characteristics were measured. In determining the vibration characteristics the vibration acceleration was measured by waterproof sensor located on the inducer bush which made it possible to determine the vibration characteristics more precisely and to refuse of vibration acceleration measurements on other surfaces of the examine centrifugal inducer stage.

4. Analysis of Research Results

The results of the tests are shown in Table 1. The table represents such parameters as: index of cavitation erosion characteristics $K_{cr(ex)}$, ratio of critical suction specific speed $C_{cr}/C_{cr\, sm}$, ratio of efficiency $\eta/\eta_{sm}$ and ratio of head $H/H_{sm}$, where the index $sm$ denotes characteristics of the centrifugal inducer stage with a smooth inducer bush, and without an index - characteristics of the centrifugal inducer stage with a inducer bush with grooves and corresponding number of assembly variant from first column of the table.

| Assembly variant No. | Parameter | 0.3 $Q_n$ | 0.5 $Q_n$ | 0.75 $Q_n$ | 1.0 $Q_n$ | 1.2 $Q_n$ |
|----------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1                    | $K_{cr\, (ex)}$ | 18.42     | 20.83     | 20.37     | 19.93     | 21.05     |
|                      | $C_{cr}/C_{cr\, sm}$ | 1.46      | 1.20      | 1.08      | 0.97      | 0.84      |
|                      | $\eta/\eta_{sm}$ | 0.91      | 0.92      | 0.93      | 0.95      | 0.95      |
|                      | $H/H_{sm}$ | 1.00      | 1.00      | 1.00      | 0.99      | 0.97      |
| 2                    | $K_{cr\, (ex)}$ | 20.26     | 21.66     | 20.09     | 20.21     | 19.7      |
|                      | $C_{cr}/C_{cr\, sm}$ | 1.16      | 1.20      | 1.17      | 1.00      | 0.91      |
|                      | $\eta/\eta_{sm}$ | 0.96      | 0.96      | 0.97      | 0.97      | 0.97      |
|                      | $H/H_{sm}$ | 1.02      | 1.01      | 1.02      | 1.00      | 0.98      |
| Assembly variant № | Parameter     | 0.3 Q_n | 0.5 Q_n | 0.75 Q_n | 1.0 Q_n | 1.2 Q_n |
|---------------------|---------------|---------|---------|----------|---------|---------|
| 3                   | $K_{er}^{(ex)}$ | 18.96   | 21.08   | 20.26    | 20.57   | 22.37   |
|                     | $C_{cr/cr^s_m}$ | 1.10    | 1.10    | 1.24     | 1.06    | 0.93    |
|                     | $\eta / \eta_{sm}$ | 0.97    | 0.98    | 0.96     | 0.97    | 0.97    |
|                     | $H / H_{sm}$   | 1.02    | 1.01    | 1.01     | 0.99    | 0.98    |
| 4                   | $K_{er}^{(ex)}$ | 20.03   | 21.28   | 20.43    | 20.81   | 23.16   |
|                     | $C_{cr/cr^s_m}$ | 1.07    | 1.20    | 1.20     | 1.09    | 0.91    |
|                     | $\eta / \eta_{sm}$ | 0.98    | 0.98    | 0.99     | 0.98    | 0.98    |
|                     | $H / H_{sm}$   | 1.02    | 1.01    | 1.01     | 0.98    | 0.96    |
| 5                   | $K_{er}^{(ex)}$ | 18.78   | 21.04   | 21.31    | 21.88   | 23.23   |
|                     | $C_{cr/cr^s_m}$ | 1.46    | 1.31    | 1.11     | 0.97    | 0.80    |
|                     | $\eta / \eta_{sm}$ | 0.92    | 0.92    | 0.93     | 0.93    | 0.93    |
|                     | $H / H_{sm}$   | 1.01    | 1.01    | 1.01     | 0.99    | 0.97    |
| 6                   | $K_{er}^{(ex)}$ | 34.65   | 20.73   | 20.71    | 19.90   | 19.63   |
|                     | $C_{cr/cr^s_m}$ | 1.13    | 1.40    | 1.05     | 1.00    | 0.72    |
|                     | $\eta / \eta_{sm}$ | 0.96    | 0.96    | 0.97     | 0.96    | 0.96    |
|                     | $H / H_{sm}$   | 1.01    | 1.01    | 1.01     | 0.99    | 0.97    |
| 7                   | $K_{er}^{(ex)}$ | 18.72   | 21.39   | 21.28    | 22.53   | 24.91   |
|                     | $C_{cr/cr^s_m}$ | 1.10    | 1.23    | 1.32     | 1.12    | 0.88    |
|                     | $\eta / \eta_{sm}$ | 0.96    | 0.96    | 0.97     | 0.97    | 0.96    |
|                     | $H / H_{sm}$   | 1.01    | 1.01    | 1.00     | 0.98    | 0.96    |
| 8                   | $K_{er}^{(ex)}$ | 19.75   | 21.57   | 20.55    | 20.48   | 19.7    |
|                     | $C_{cr/cr^s_m}$ | 1.10    | 1.13    | 1.20     | 1.12    | 0.89    |
|                     | $\eta / \eta_{sm}$ | 0.97    | 0.97    | 0.98     | 0.97    | 0.97    |
|                     | $H / H_{sm}$   | 1.01    | 1.01    | 1.00     | 0.98    | 0.96    |
| 9                   | $K_{er}^{(ex)}$ | 23.71   | 23.32   | 22.11    | 21.74   | 20.90   |
|                     | $C_{cr/cr^s_m}$ | 1.07    | 1.36    | 1.32     | 1.12    | 0.91    |
|                     | $\eta / \eta_{sm}$ | 0.94    | 0.93    | 0.94     | 0.95    | 0.96    |
|                     | $H / H_{sm}$   | 1.02    | 1.02    | 1.02     | 1.00    | 0.97    |
| 10                  | $K_{er}^{(ex)}$ | 21.31   | 21.73   | 20.80    | 20.44   | 19.58   |
|                     | $C_{cr/cr^s_m}$ | 1.40    | 1.51    | 1.20     | 1.12    | 0.95    |
|                     | $\eta / \eta_{sm}$ | 0.99    | 0.99    | 0.99     | 0.97    | 0.97    |
|                     | $H / H_{sm}$   | 1.04    | 1.02    | 1.01     | 1.00    | 0.98    |
| 11                  | $K_{er}^{(ex)}$ | 24.64   | 21.73   | 21.97    | 21.60   | 20.81   |
|                     | $C_{cr/cr^s_m}$ | 1.23    | 1.51    | 1.24     | 1.09    | 0.89    |
|                     | $\eta / \eta_{sm}$ | 0.98    | 0.99    | 0.99     | 1.00    | 1.02    |
|                     | $H / H_{sm}$   | 1.02    | 1.01    | 0.99     | 1.00    | 1.00    |
| 12                  | $K_{er}^{(ex)}$ | 18.29   | 21.15   | 21.22    | 21.65   | 19.06   |
|                     | $C_{cr/cr^s_m}$ | 1.20    | 1.27    | 1.28     | 1.06    | 0.92    |
|                     | $\eta / \eta_{sm}$ | 1.00    | 1.00    | 1.00     | 1.01    | 1.04    |
|                     | $H / H_{sm}$   | 1.01    | 1.01    | 1.01     | 1.01    | 1.01    |
| 13                  | $K_{er}^{(ex)}$ | 34.65   | 33.23   | 21.97    | 21.53   | 19.48   |
|                     | $C_{cr/cr^s_m}$ | 1.40    | 1.31    | 1.32     | 1.03    | 0.88    |
|                     | $\eta / \eta_{sm}$ | 0.95    | 0.96    | 0.97     | 0.98    | 1.01    |
|                     | $H / H_{sm}$   | 1.02    | 1.01    | 1.03     | 1.03    | 1.02    |
Table 1c. Research results.

| Assembly variant № | Parameter | 0.3 $Q_n$ | 0.5 $Q_n$ | 0.75 $Q_n$ | 1.0 $Q_n$ | 1.2 $Q_n$ |
|-------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 14                | $K_{er\ (ex)}$ | 32.61    | 23.35    | 30.63    | 21.91    | 19.61    |
|                   | $C_{cr}/C_{cr\ sm}$ | 1.07    | 0.98   | 1.24    | 1.06    | 0.81    |
|                   | $\eta/\eta\ sm$ | 0.98    | 0.98   | 0.99   | 1.00    | 1.02    |
|                   | $H/H_{sm}$ | 1.01    | 1.01   | 1.02   | 1.02    | 1.02    |
| 15                | $K_{er\ (ex)}$ | 26.25    | 22.92    | 21.45   | 21.40    | 23.92    |
|                   | $C_{cr}/C_{cr\ sm}$ | 0.98    | 1.10   | 1.17   | 1.09    | 0.88    |
|                   | $\eta/\eta\ sm$ | 0.99    | 0.98   | 0.99   | 1.01    | 1.03    |
|                   | $H/H_{sm}$ | 1.01    | 1.00   | 1.01   | 1.01    | 1.01    |
| 16                | $K_{er\ (ex)}$ | 41.08    | 21.41    | 22.30   | 20.30    | 19.8    |
|                   | $C_{cr}/C_{cr\ sm}$ | 1.20    | 1.13   | 1.11   | 1.06    | 0.89    |
|                   | $\eta/\eta\ sm$ | 0.99    | 0.98   | 1.00   | 1.00    | 1.02    |
|                   | $H/H_{sm}$ | 1.01    | 1.00   | 1.01   | 1.01    | 1.01    |

Since this article is devoted to research the influence of the inducer bush on the cavitation erosion characteristics of the centrifugal inducer stage, it is necessary to pay attention to threshold value of the cavitation erosion parameter $K_{er\ (ex)}$ and ratio of the critical suction specific speed $C_{cr}/C_{cr\ sm}$. According to the method described in [8] and experimental value of $K_{er(b)}$, depending on the inducer design and type of handled medium [2], the confirmation of improvement of the cavitation erosion characteristics of examine inducer centrifugal stage will be the accomplishment of the inequation $K_{er\ (ex)}>20$. As can be seen from Table 1, the value of $K_{er\ (ex)}$ exceeded the required threshold value for most assembly variants, but not stable within full flow rate range, only some assemblies gave a significant increase of the cavitation erosion parameter within full flow rate range.

According to Table 1 the ratio of the critical suction specific speed $C_{cr}/C_{cr\ sm}$ which characterizes the cavitation characteristics of the centrifugal inducer stage indicates that the use of the inducer bush improves the cavitation characteristics of the centrifugal inducer stage during operation at partload flow rates for all assembly variants and nominal flow rates for most assembly variants. During operation at overload flow rate all assembly variants with the inducer grooved bush had a negative effect on the cavitation characteristics.

As for the energy curve of the centrifugal inducer stage, the use of the inducer bush leads to efficiency decreasing in the most assembly variants. It can be said that only in some variants with a smooth inducer bush the efficiency remains at the same level and only the one variant (assembly No.12) showed a positive result – the efficiency was slightly increased and improvement of the cavitation performance has been achieved.

The head curve of the centrifugal inducer stage with inducer bush is practically unchanged throughout the full flow rate range.

Analyzing the physical experiment research results, we found that the best values for both energy and cavitation erosion characteristics were shown by inducer bushes which grooves have a square cross section. This fact confirms the theory that vortices occurred in the bush grooves reduce the influence of reverse flows at the inducer inlet and also eliminate the cavitation cavities located on its periphery thus protecting inducer from damage, since exactly this form of grooves provide more stable vortices in comparison with grooves that has rectangle cross section.

Also, there was observed an ambiguous influence of the position of inducer bush relatively to the inducer vane leading edge on the characteristics of the centrifugal inducer stage as the assemblies that have a similar shape and number of grooves but differ only in configuration have differences in energy and cavitation erosion characteristics. The general recommendation for obtaining better values is that the length of inducer bushes should be not more than half length of the inducer vane system starting...
from the leading edge and lengthen outside the inducer vane system by 0.4-0.7 of the length of the inducer vane system.

5. Conclusions
1. We experimentally proved the general possibility of using the inducer bush for improving cavitation erosion characteristics of the centrifugal inducer stage as well as maintaining the economic qualities and overall dimensions of the stage.
2. The influence analysis of the geometric parameters of the inducer bush on cavitation erosion and energy characteristics of the centrifugal inducer stage and the selection guideline of the inducer bush optimal design are given.
3. In order to confirm obtained results of erosion wear reduction by means of evaluating the cavitation erosion characteristics of the stages based on the cavitation vibration acceleration it will be necessary to perform their selective qualitative inspection using the method of evaluation of cavitation resistance by applying fragile lacquer coatings for stages with the best variants of inducer bush design and their further comparison with similar results of a smooth inducer bush. After that it is possible to develop a design procedure of inducer bushes of centrifugal inducer stages.

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