TESTES LABORATORIAIS DE APARATO DE JATO COM O OBJETIVO DE AUMENTAR A CARGA LÍQUIDA POSITIVA DE SUCÇÃO DE BOMBAS CENTRÍFUGAS E AXIAIS

LABORATORY TESTS OF A JET DEVICE TO INCREASE THE CENTRIFUGAL AND AXIAL PUMP SUCTION HEAD

ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ СТРУЙНОГО АППАРАТА С ЦЕЛЬЮ ПОВЫШЕНИЯ КАВИТАЦИОННОГО ЗАПАСА ЦЕНТРОБЕЖНЫХ И ОСЕВЫХ НАСОСОВ

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RESUMO

O trabalho é dedicado a estudos experimentais em laboratório para determinar o valor da carga líquida positiva de sucção de bombas centrífugas através da instalação de aparatos de jato na linha de sucção de unidades de bombeamento alimentadas por uma linha de recirculação. O diagrama de instalação com a localização dos equipamentos e instrumentos é apresentado. Na determinação dos dados experimentais sobre o valor da carga líquida positiva de sucção, fontes literárias foram utilizadas para determinar os parâmetros ótimos do aparato de jato de acordo com o coeficiente de eficiência. As dimensões dos parâmetros estudados do aparato de jato e a magnitude das pressões antes e depois do aparato são tomadas como fatores nos estudos. Como critério, o valor da carga líquida positiva de sucção Δh foi considerado. De acordo com os resultados dos estudos usando a teoria de planejamento de experimentos, foram obtidas dependências empíricas para determinar os critérios nos intervalos com a ajuda dos quais, com os tamanhos relativos ótimos do aparado de jato, é possível determinar para as estações de bombeamento operacionais o grau de aumento da carga líquida positiva de sucção com parâmetros de energia ótimos.

Palavras-chave: *estação de bombeamento, pressão de aparato de jato, linha de recirculação, coeficiente de ejeção, eficiência de unidade de jato.*

ABSTRACT

The article is devoted to experimental laboratory studies to determine the value of the cavitational reserve of centrifugal pumps by installing jet devices in the suction line of pumping units powered by a recirculation line. The installation diagram with the location of equipment and instruments is shown. Literary sources were used to determine the optimal parameters of the jet apparatus according to the efficiency coefficient in determining the experimental data on the value of the cavitation reserve. The dimensions of the studied parameters of the jet apparatus and the magnitude of the pressures before and after the apparatus are taken as factors in the studies. The value of the cavitation stock Δh was taken as a criterion. According to the results of the studies using the experiment planning theory, empirical dependencies were obtained to determine the criteria in the intervals by which, at the optimum relative sizes of the jet apparatus, it is possible to determine the degree of increase in the cavitation stock at the optimal energy parameters for operating pumping stations.

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Keywords: *pumping station, jet device pressure, recirculating line, coefficient of ejection, jet knot efficiency.*

АННОТАЦИЯ

Работа посвящена экспериментальным лабораторным исследованиям для определения величины кавитационного запаса центробежных насосов методом установки струйных аппаратов на всасывающей линии насосных агрегатов с питанием от линии рециркуляции. Показана схема установки с расположением оборудования и приборов. При определении опытных данных по величине кавитационного запаса использовались литературные источники для определения оптимальных параметров струйных аппаратов по величине КПД. В качестве факторов при исследованиях, приняты размеры исследуемых параметров струйного аппарата и величины давлений перед аппаратом и после него. В качестве критерия принята величина кавитационного запаса Δh. По результатам проведенных исследований с использованием теории планирования эксперимента, получены эмпирические зависимости для определения критерия в интервалах, с помощью которых при оптимальных относительных размерах струйного аппарата, имеется возможность определять для эксплуатационных насосных станций, степень увеличения кавитационного запаса при оптимальных энергетических параметрах.

Ключевые слова: *насосная станция, напор струйного аппарата, линия рециркуляции, коэффициент эжекции, кпд струйного узла.*

INTRODUCTION

With the beginning of using the methods of computational hydrodynamics in engineering practice, it became possible to calculate the fluid flow in the flow part of the pump and to obtain the calculated characteristics of the pump in a short time compared with the time for obtaining the experimental characteristics. This made it possible to modify the flow part according to the results of numerical simulation in the design process and thereby obtain more advanced designs without long experimental studies of the influence of the geometric parameters of the flow parts on the pump characteristics (Brennen, 2011; Syzrantsev *et al.*, 2018).

However, the process of finding the optimal design solution based on such calculations is usually based on intuitive methods, which means that the efficiency of optimization both in terms of time spent and in terms of the quality of the result obtained strongly depends on the skills and experience of the calculator (Danilin *et al.*, 2016; Formalev *et al.*, 2017).

The development of formal mathematical methods for finding the optimal design solution is an actual modern problem. Due to the complex nature of the dependence of optimization criteria (energy efficiency, reliability, resource, etc.) on the set of geometrical parameters of the pump flow section and the duration of the calculation of pump characteristics using computational fluid dynamics (Ferziger and Peric, 2002), universal optimization methods are poorly suited to solve the problem (Ojha *et al.*, 2010; Kumar, 2014). The method of calculating the flow-through part of the pump based on optimization algorithms must take into account the type of flow-through part, the formulation and number of optimization criteria must be easily tunable when introducing additional conditions into consideration and must lead to the desired result in the shortest possible time.

The need to develop such methods of calculation is also dictated by the current state of the pump engineering industry (Han *et al.*, 2018; Zhang, 2018; Dhaimat and Al-Helou, 2004; Sokolov, 2002). All new requirements and standards for the efficiency and reliability of pumping equipment are introduced, and methods for designing blade machines developed 20-30 years ago do not allow to achieve the required results.

The tasks of the research included:

- determination of the optimal relative parameters of the jet device that increases the suction height of the pumps (cavitation margin);

- determination of the optimal installation location of the apparatus in the suction inlet of the volute pump;

- derivation of the dependence of the value of cavitation margin Δh as a function of the parameters of the annular jet device.

MATERIALS AND METHODS

To determine the actual magnitude of the increase in cavitation margin of volute pumps at the Laboratory of the Novocherkassk Engineering and Melioration Institute after A.K. Kortunov of the Don State Agrarian University laboratory studies at the facility (Figures 1, 2) were conducted in order to determine the optimal geometric and hydraulic relative parameters of the inkjet node of the recycling line (Krivchenko, 1986; Arora, 1989) to increase the cavitation margin of the volute pumps (Binamaa *et al.*, 2016).

When determining the installation criterion – the cavitation margin values were measured:

Q_0 and $\frac{P_3}{g\rho_0}$ – the flow and pressure of the working stream in the recirculation line in the section "e-e" with a pressure gauge 13, a flow meter 8;

h_1 – excess of the gauge axis above the water level in the working tank;

$h_{wвх}$ – pressure loss at the entrance to the jet device (the difference between the readings of the piezometer 21 and the man-vacuum meter 7).

The measured values were determined:

– the volumetric coefficient of ejection (Equation 1);

– average flow rate in the nozzle jet device (Equation 2, where ω_0 – jet device nozzle cross-sectional area);

– a reduced pressure discharge jet node in the mixing chamber (section d-d) (Equation 3);

– a reduced head blower jet node in the recirculation line (Equation 4);

– jet knot efficiency (Equation 5).

For further studies of the Jet device as a device that increases the cavitation margin, we used the experimental data of literary sources (Taras'yants et al., 2006; Taras'yants, 1993; Taras'yants, 1976) for determining the characteristics of jet pumps. The characteristics revealed the possibility of optimal use of the investigated annular Jet device, as the most efficient in energy efficiency (Taras'yants and Charkin, 1991).

RESULTS AND DISCUSSION:

Studies were carried out using the experiment planning theory (Voznesensky, 1981) in the following sequence: an ink ring apparatus was installed in the suction piping (Lima Neto, 2011) of the volute pump 6, allowing the output of the working jet from the nozzle flowing around the hub of the Volute pump impeller; margin Δh, determined by the experimental relationship: $\Delta h = f(x_1, x_2, \ldots x_n)$, where $x_1, x_2, \ldots x_n$ are the relative geometrical dimensions and hydraulic parameters of the jet unit installed in front of the slave denote wheel volute pump (Pei *et al.*, 2017). For the experiments, the value of Δh was determined by the readings of the instruments. (Figure 1).

The following factors were assumed: in natural and relative values (the ratio of the size of the factor to the diameter of the mixer) (x_1) is the diameter of the outer nozzle; b(x_2) – the width of the slit in the nozzle; Lc (x_3) – the length of the cylindrical part of the mixing chamber of the Jet device; Z(x_4) is the distance from the nozzle edge to the beginning of the impeller hub; P_3(x5) – pressure in the recirculation line (pressure in cross-section e-e); P_1(x_6) is the flow head before entering the pump impeller. The diameter of the mixer D_c is assumed to be 1.1 of the diameter of the outer nozzle, 55 mm (Table 1).

The preliminary intervals of variation are shown in Table 2, the planning matrix and the results of the 1st group are in Table 3.

According to the results of the experiment, the regression equations were obtained (Equations 6, 7).

Analysis of Equations 6, 7 allowed the factors $\bar{L}_c$ (X_3) and $\bar{b}$ (X_2) to be stabilized as having a small effect on the relative values of 2.22 and 0.96, and the factor P_3 on the value of 25 m (maximum pressure in the recirculation line).

For the final determination of the calculated values of the remaining three factors by the value, the second group of experiments was carried out by analogy with the first and using the three-factorial plan with varying intervals of variation $x_1(d_0')$, x_4(Z) and $x_5(P_1)$. The encoding conditions are shown in table 4.

Processing and analysis of data for the 2nd group of experiments allowed us to stabilize the factor Z(x_4) at a relative value of 0.52 and to obtain empirical two-factor models in general form and in canonical form (Equations 8-13). In addition, the efficiency value for each device was calculated according to the dependence (Table 5) and graphic images of the response surface d_0' (x_1) и P_1 (x_5) for the values of η and Δh were constructed. (Figure 3).

Analysis of Figure 4 shows that as the pressure P_3 increases (from 15 to 25 m), the cavitation margin increases from 0.3 to 0.7 m. This factor is also influenced by the Coefficient of ejection α_0. With an increase in the coefficient α_0, the value of Δh increases (from 0.30 with α_0 = 1.0 to 0.70 with α_0 = 2.0).

The parameters obtained from laboratory results were verified under field conditions at a circulation pumping station with axial pumps OPV 2-110 of Novocherkassk State District Power Station (Figures 5, 6).

During the test, the head in the recirculation line was changed by the valve 5, the head was used to determine the flow rate in the nozzle V_0 and the flow rate in the recirculation line Q_0. The calculation of the experimental data during the testing of the Jet device is given in Table 6.

Analysis of table 6 showed the maximum possible value of increasing the cavitation margin of axial pumps (up to 0.87 m) with pressures in the recirculation line up to 15 m.

CONCLUSIONS:

According to the results of the research, the following conclusions were made:

- The greatest influence on the cavitation margin Δh and the efficiency value is exerted by the pressure in the recirculation line and the suction pipe of the pump P_3 (x_5) and P_1 (x_6), the inner diameter of the outer nozzle d_0' (x_1), the length of the mixer L_c (x_3).
- Conducted studies allow calculating the efficiency values and the cavitation margin Δh for existing pumping stations using the relative values of the above factors based on empirical dependencies (6 ÷ 12) to determine the relative geometric dimensions of the Jet device in the studied intervals, the diameter of the outer nozzle $\bar{d}_0^{/}$ = 0,87, the width of the slit in the nozzle $\bar{b}$ = 0,10, the length of the mixing chamber $\bar{L}_c$ = 1,63 and the distance from the nozzle edge to the beginning of the mixing chamber $\bar{Z}$ = 0,27, and for the outer diameter of the nozzle $\bar{d}_0^{/}$ and head in the suction pipe P_1 images of the surface and responses.

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$$\alpha_0 = \frac{Q_2}{Q_0} - 1 \quad (1)$$

$$V_0 = \frac{Q_0}{\omega_0} \quad (2)$$

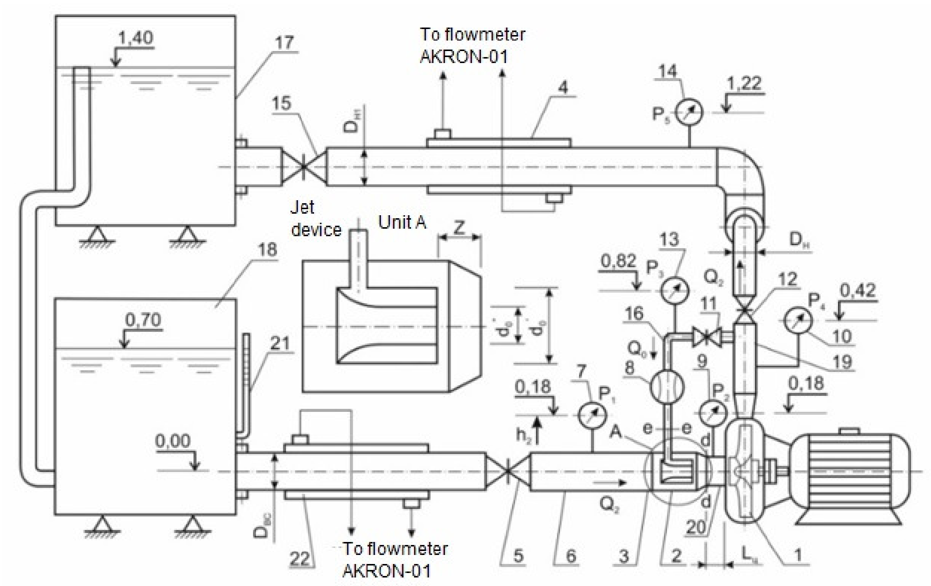
$$P_{d.r.} = \frac{P_d}{g\rho_0} + \frac{V_d^2}{2g} - h_{WBX} \quad (3)$$

$$P_{s.h.} = \frac{P_e}{g\rho_0} + \frac{V_e^2}{2g} + h_{WBX} \quad (4)$$

$$\eta = \alpha_0 \frac{H_{d.r.}}{H_{s.r.}} \quad (5)$$

$$\eta = 21{,}6 + 28x_1 - 0{,}4x_2 + 23{,}06x_3 + 13{,}2x_4 - 6{,}6x_5 - 10{,}6x_6 \quad (6)$$

$$\Delta h = 0{,}3 + 0{,}15x_1 - 0{,}20x_2 + 6{,}3x_3 + 0{,}2x_4 - 6{,}21x_5 - 6{,}28x_6 \quad (7)$$



(a)

(b)

Figure 1. *Diagram and general view of the laboratory setup for determining the value of cavitation margin of the volute pumps: 1 – volute pump impeller; 2 – jet device; 3 – inkjet unit; 4 – sensor ultrasonic flow meter; 5, 11, 12, 15 – gate valves; 6 – suction pipe; 7.9 – vacuum gauges; 8 – flow meter; 10, 13, 14 – pressure gauges; 16 – recirculating line, 17 – pressure tank, 18 – water intake tank; 19 – pressure pipe; 20 – jet device mixer; 21 – piezometer; 22 – sensors ultrasonic flow meter*

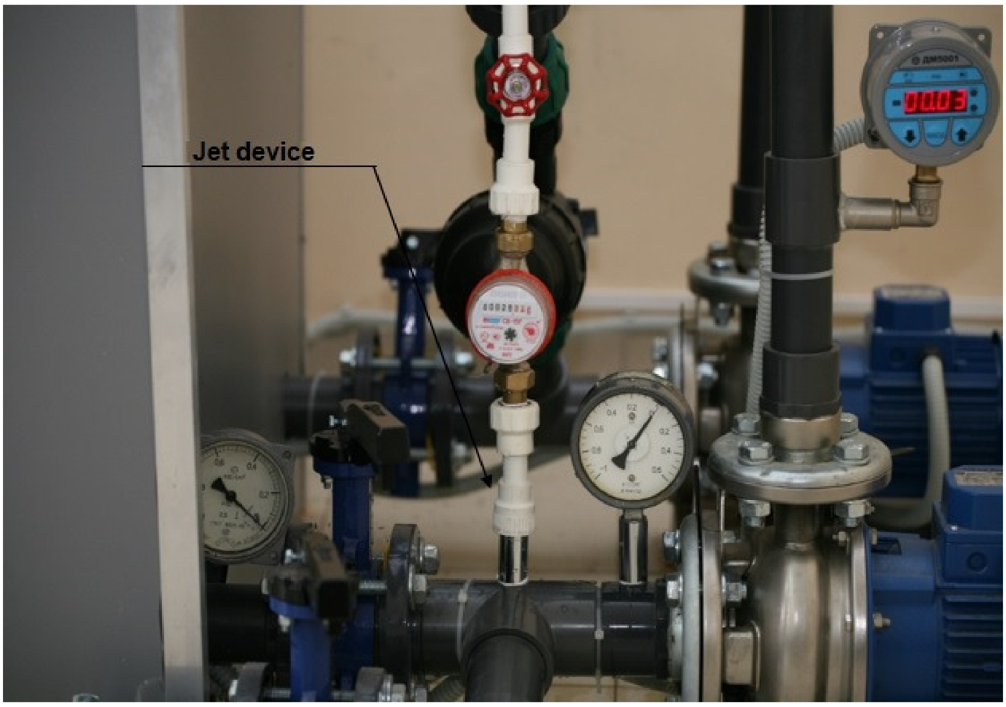


Figure 2. *A jet device installed in the volute pump suction piping*

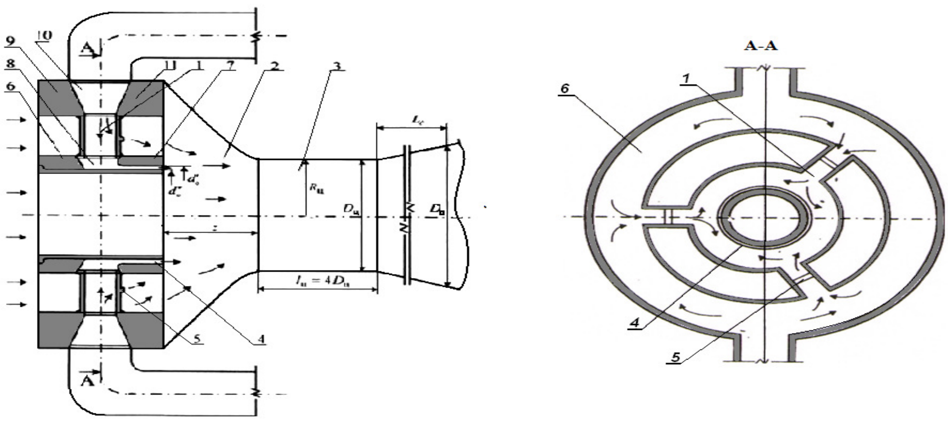


Figure 3. *Diagram of the jet ring two-surface pump: 1 –pipe connecting; 2 – inner chamber; 3 – mixing chamber; 4 – active nozzle; 5 – gap between the nozzles; 6 – inner rear flange; 7 – inner front flange; 8 – ring internal collector; 9 – rear outer flange; 10 – outer annular collector; 11 – front outer flange*

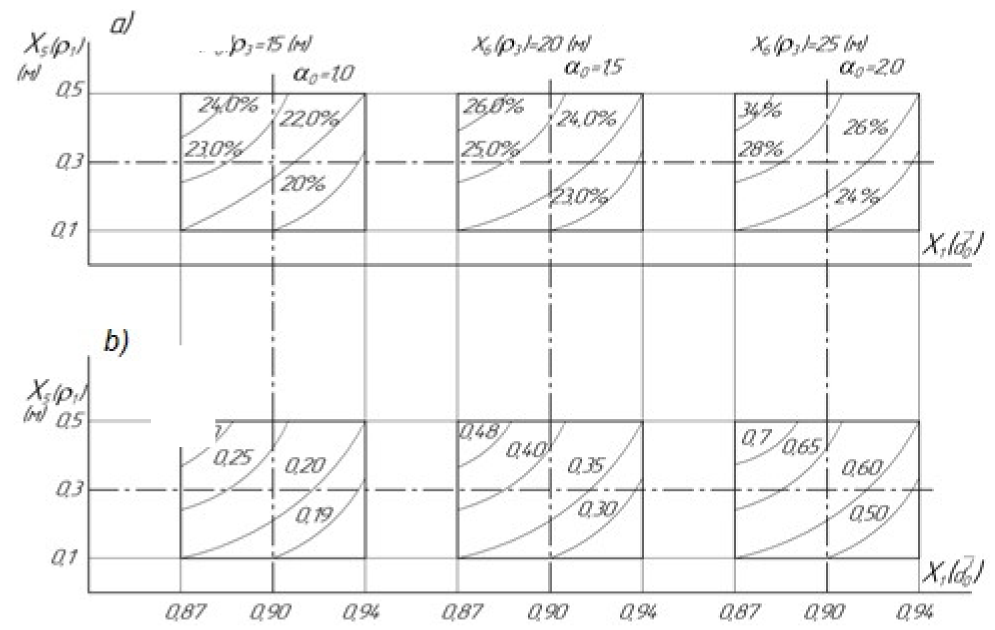


Figure 4. *Graphic images of the response surface $X_1(d_0^{/})$ and $X_5(P_1)$ depending on the values: a) η, (%) and b) Δh, (m)*

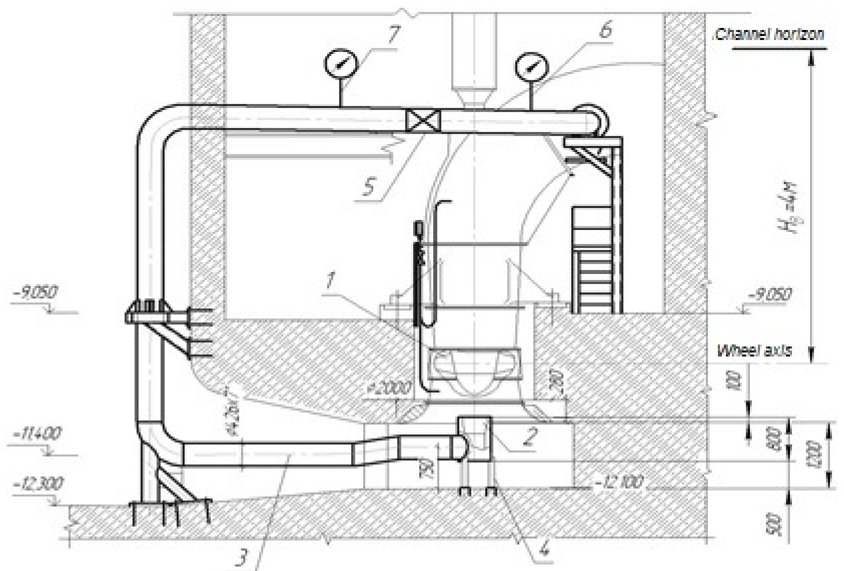


Figure 5. *Jet device installation diagram in front of the impeller pump impeller: 1 – pump impeller; 2 – annular two-surface jet device; 3 – pipeline recirculation line; 4 – jet pump support; 5 – gate valve; 6, 7 – manometers*

Figure 6. *Installation of the annular jet device on the recycling line of the axial pump OPV 2-110 of the Novocherkassk State District Power Station*

__Table 1.__ Sizes of jet device elements and volute pump impeller

Diameter of mixing chamber, mm	Outer diameter of the pump impeller, mm	The diameter of the impeller hub, mm	Annular nozzle	
			Inner diameter of the outer nozzle, mm	Outer diameter of the inner nozzle, mm
54	140	45	52	46

__Table 2.__ Coding and variation variables for the 1st group of experiments

Factors	Code	Main level	Variation interval	Lower level	Upper level
d_0', mm	x_1	48 / 0,87 (0)	2 / 0,036	46 (-)	50 (+)
b, mm	x_2	6 / 0,10 (0)	2 / 0,036	4 (-)	8 (+)
$L_{ц}$, mm	x_3	90 / 1,63 (0)	30 / 0,54	60 (-)	120 (+)
Z, mm	x_4	15 / 0,27 (0)	5 / 0,09	10 (-)	20 (+)
P_1, m	x_5	0,5 (0)	0,2	0,3 (-)	0,7 (+)
P_3, m	x_6	20 (0)	5	15 (-)	25 (+)

__Table 3.__ The results of the I group of experiments

No. of experiments	d_0' x_1	b x_2	L_c x_3	Z x_4	P_1 x_5	P_3 x_6	Δh, m
1	-	-	-	-	-	-	0,15
2	+	+	+	-	+	-	0,4
3	+	+	-	+	-	+	0,6
4	-	-	+	+	+	-	0,35
5	+	-	-	-	+	+	0,38
6	-	+	+	-	-	+	0,40
7	-	+	-	+	+	-	0,28
8	+	-	+	+	-	-	0,32

__Table 4.__ Coding and variation variables for the 2nd group of experiments

Factors	Code	Main level, mm	Variation interval, mm	Lower level, mm	Upper level, mm
d_0', mm	$x_1(d_0')$	50 / 0,9	2 / 0,031	48 / 0,87	52 / 0,94
Z, mm	$x_4(Z)$	20 / 0,36	5 / 0,09	15 / 0,27	25 / 0,45
P_1, mm	$x_5(P_1)$	0,3	0,2	0,1	0,5

Table 5. *Empirical two-factor models for Δh*

Coefficient of ejection, α_0	In general	In canonical form	
1,0	$\Delta h = 0,63 - 0,35x_5^2 + 0,3x_1x_5$	$\Delta h - 0,44 = 0,40{x'_1}^2 + 0,22{x'_5}^2$	(8)
1,3	$\Delta h = 0,44 + 0,3x_1 + 0,4x_5 + 0,3x_5^2$	$\Delta h - 0,31 = -0,21{x'_1}^2 + 0,40{x'_5}^2$	(9)
1,6	$\Delta h = 0,64 - 0,3x_5 - 0,3x_1^2 - 0,3x_5^2 - 0,3\,x_1x_5$	$\Delta h - 0,64 = -0,3{x'_1}^2 + 0,25{x'_5}^2$	(10)
1,8	$\Delta h = 0,38 - 0,4x_1 + 0,3x_1^2 - 0,3x_1x_5$	$\Delta h - 0,41 = -0,38{x'_1}^2 + 0,24{x'_5}^2$	(11)
2,0	$\Delta h = 0,54 - 0,38x_1 - 0,26x_5 + 0,3x_1^2$	$\Delta h - 0,54 = 0,33{x'_1}^2 + 0,20{x'_5}^2$	(12)
2,2	$\Delta h = 0,49 + 0,4x_5 - 0,6x_1^2 - 0,6x_5^2 - 0,41x_1x_5$	$\Delta h - 0,42 = 0,6{x'_1}^2 - 0,2{x'_5}^2$	(13)

Table 6. *The dependence of the magnitude of the cavitation margin on the pressure in the recirculation line of the axial pump, the coefficient of ejection of the jet device and pump feed*

Axial pump feed, thousand m³/h	Axial pump feed, m³/s	Kinetic energy flow $\frac{V_к^2}{2g}$, m	Pump head in the recirculation line, m	Nozzle speed V_0, m/s	Potential energy before entering the pump $2,38 - \frac{V_к^2}{2g}$ m	Coefficient of ejection α_0	Nozzle flow rate $Q_0 = V_0 \cdot \omega_0$, m³/h	Speed before the blades suction flow V_f, m/s	Magnitude increase of cavitation margin in Δh, m
10	2,77	0,43	15,0	13,7	1,95	1,5	1,096	4,13	0,87
11	3,05	0,52	14,0	13,4	1,86	1,3	1,072	3,76	0,72
12	3,33	0,62	13,0	12,77	1,76	1,2	1,021	3,43	0,59
13	3,60	0,72	11,5	12,01	1,66	<0	1,016	-	-
14	3,88	0,85	10,8	11,7	1,53	<0	0,936	-	-
15	4,16	0,97	9,6	11,0	1,41	<0	0,880	-	-