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Application of rapid prototyping technology in pump engineering

Abstract. *The article presents the results of the use of rapid prototyping technology when modifying the impeller of a centrifugal pump in order to increase efficiency. As a result of the implementation of the technology, the influence of parameters such as the printing speed of the main layers, the printing speed of the current layers, the thickness of the layers on the geometric accuracy of printed products was studied. According to the results of experiments, it was revealed the effect of the feed rate on the OZ axis, an increase in speed will lead to lower surface quality, higher roughness. The distance between the layers is 0,15 mm/s, getting a roughness of Ra 6,3 microns, and in the right case we used a distance of 0,05 mm/s between the layers, getting a roughness of Ra1,6 microns. The article presents the results of the analysis of the effect of exposure time and exposure time in the UV chamber on the hardness of printed products. The article presents a method for determining and compensating the geometry of prototypes based on reverse engineering technology based on the use of an optical scanner. The tests of a centrifugal pump with a prototype of a modified wheel confirm the need for such innovations as rapid prototyping to shorten the design cycle of new products, as well as reduce the cost of their development.*

Keywords: *rapid prototyping, digital twins, 3D printers, printing parameters, efficiency, centrifugal pump and reverse engineering.*

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1. Introduction

There are discussions in the scientific community on the degree of identity of the concepts of ‘innovation’ and ‘novelty’. In science, there are two approaches to the interpretation of the term ‘innovation’:

– process, positioning innovation as the process of implementing an idea and turning it into a finished result (or individual stages of this process);

– an object representing innovation as the final result, an embedded object [1-5].

Innovations are trends introduced into enterprises: smart factory, digital factory, rapid prototyping, reverse engineering, new materials. At the stage of the digital factory, the design and production of a prototype product is concentrated. According to Deloitte, investments in digital factories have led to an increase in production by an average of 10%.

The key technology at this stage is digital twins. These are virtual models of processes or material objects. It can be a model of a production chain, an airplane, sneakers, or a self-piloted rocket. Designing a future product, you can accurately describe its characteristics and calculate production costs. It can be tested in the same system, while the results of virtual tests will be as accurate as real ones [5-8].

One of the directions in the modernization of existing technological equipment in order to increase energy efficiency is the application of the concept of a digital twin of a system sample in order to improve its geometry.

Many reviews and scientific articles have already been devoted to the latest technologies of the digital factory, such as rapid prototyping, reverse engineering. Thus, the authors of the article [9] systematized the prototyping process in the form of a hierarchical sequence of the implementation of the process of machine design technology, where level I represents the pre-design stage, level II is the process of implementing the machine design procedure, taking into account the possibility of ornamental design of the projected product, if this is provided for by the requirements of the terms of reference; level III reflects the phase of creating a solid–state model of the product.

The author [10] presented the results of manufacturing model tooling with the required accuracy by laser-computer prototyping technology using sheet material.

In the article [11], the author gave an overview of rapid prototyping technologies used more and more at modern machine-building enterprises to increase the efficiency of design processes.

The main purpose of the research paper. This article will consider innovative methods in the design and modernization of pumping equipment using the rapid prototyping method. The research will be aimed at upgrading the impeller blade system and verifying the updated geometry, through rapid prototyping and laboratory testing of the pump with a model of the modified wheel made by 3D printing technology.

2. Research methods

The object of the study is the impeller of a brand centrifugal pump SVM (CTP) 15-4.

Pump characteristics:

Pump data
Nominal flow rate – 15 m^3/hour
Nominal head – 46 m
Rotation speed – 2850 1/min

Engine data
Rated voltage – 380 V
Rated current – 10 A

The idea of upgrading the pump is to change the blade grid to a blade grid with variable pitch and different curvature of the blades. The concept of variable pitch (Figure 1) is based on the ideas of redistributing mainly shock losses at the entrance to the impeller blade system throughout the impeller.

The implementation of such solutions involves the use of new approaches in design. In particular, the vane system of the pump is calculated not for one point (Q_{calc}, N_{calc}), but for the required feed area ($Q(Q_1, Q_2...Q_n)$, $H(H_1, H_2...H_n)$).

Thus, the hydrodynamic grid formed has different angles of inclination and channel widths. As a result, the working area of the pump expands. At the same time, a local decrease in efficiency may occur near the optimum η_{opt}, but its values increase at the boundaries of the calculated range of Q_{min} and Q_{max} feeds.Thus, the average integral efficiency of a pump with a heterogeneous blade system is higher than that of analogues with a classical (homogeneous) blade system.

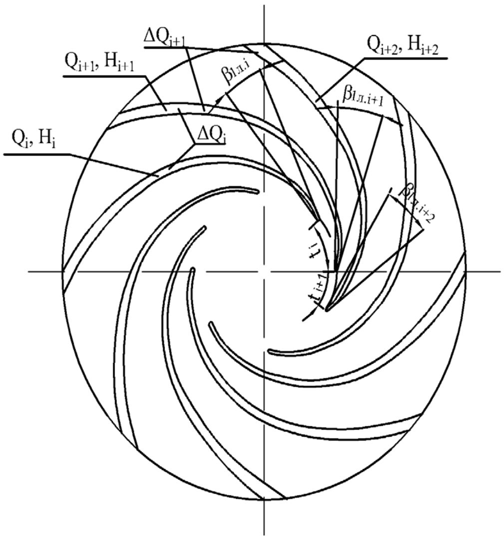


Figure 1. Diagram for calculating the parameters of a heterogeneous grid

The prototype of the wheel with an upgraded blade grille was manufactured by SLA (Stereolithography) technology. Stereolithography is a rapid prototyping process based on focusing a beam of ultraviolet light generated by a high-intensity LED with a wavelength of 405 nm on a layer of photosensitive resin located in a tank with a transparent bottom. Thus, the part is printed in the reverse bottom-up position. The product is created on a platform that is immersed in resin until it reaches the bottom of the tray, and will rise as the thickness of the "layer" increases. We can distinguish between the "base layers" that are kept under longer exposure to ultraviolet light to create a stronger base that does not come off the aluminum plate in the printer. Because of these release efforts, we had to choose the right position for printing so that there would not be many larger surfaces to separate from the bottom of the tray than the surface of the base. An Anycubic Photon monochrome printer will be used to print a prototype of a wheel with a heterogeneous grid. The main characteristics of the printer are: the working space of the printer is 130x80x165mm, the resolution in the XOY plane is 0,051mm, the step between the layers (layer resolution), on the OZ axis, is 0,01-0,15 mm, the connection is a USB drive.

The choice of printing the prototype with SLA technology was made for the following reasons:

– low roughness of 3 microns compared to the widely used FFF technology;

– sufficient strength limit of the photopolymer resin, so we used the Fotocentric High Tensile material.

Tensile strength of 80 MPa (after exposure at elevated temperature), elongation at break of 5.6% in Figure 2, the position of the workpiece on the printer table, modeled in the Photon Workshop 64 program:

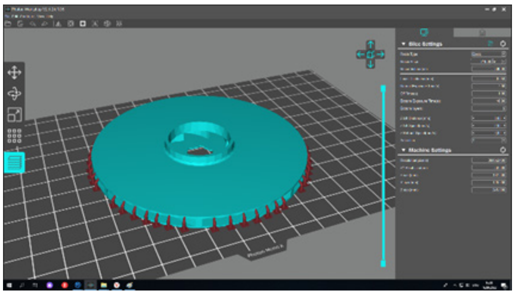


Figure 2. The position of the workpiece on the printer table

The created model will be saved in the KOMPAS program in a file in the stereolithography file format (STL). The STL file will be opened using the Photo Workshop 64 program, in which the print position Figure 3 and the location of the substrate will be set. This file will be copied to a USB drive, which will be inserted into the Anycubic Photon mono printer.

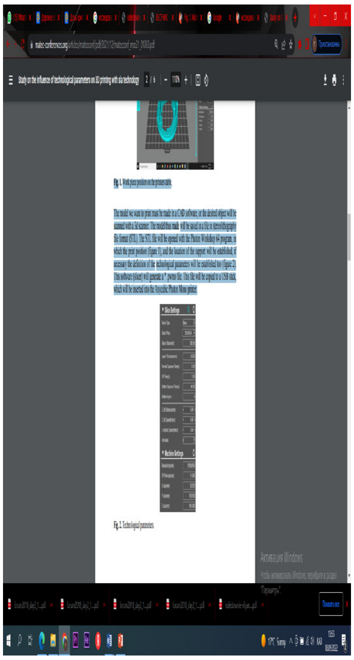


Fig. 1. Work piece position on the printers table.

The model we want to print must be made in a CAD software, or the desired object will be scanned with a 3d scanner. The model thus made will be saved in a file in stereolithography file format (STL). The STL file will be opened with the Photon Workshop 64 program, in which the print position (figure 1), and the location of the support will be established, if necessary the definition of the technological parameters will be established too (figure 2). This software (slicer) will generate a *.pwmo file. This file will be copied to a USB stick, which will be inserted into the Anycubic Photon Mono printer.

Fig. 2. Technological parameters

Figure 3. Technological parameters

The research was carried out on various printed objects, varying the technological parameters one by one. The samples were measured using an optical scanner with an accuracy of 0,004 mm. The recommended printing parameters are shown in Table 1.

Table 1. Printing parameters

Intervals Parameters	Minimum value	Maximum value
Printing speed of the main layers (mm/s)	5	15
Printing speed of current layers (mm/s)	5	15
Thickness of layers (mm)	0,02	0,15

To study the influence of the orientation position, all technological parameters were maintained at the same value, changing only the position of the sample, obtaining two marks in one print, one in a horizontal position and one in a vertical position. The orientation of the parts and the support for the support can be seen in Figure 4.

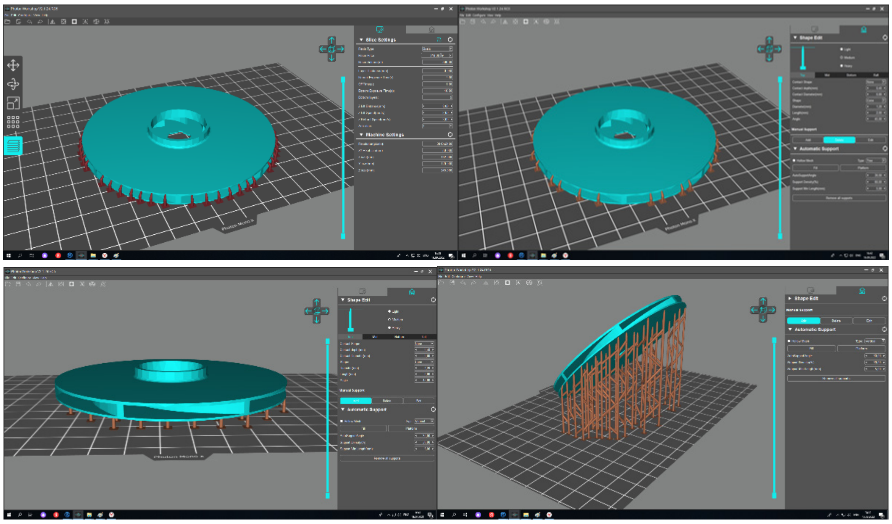


Figure 4. Various support options

The dimensions measured after printing were selected depending on their influence on the flow kinematics, so 5 points were selected, which are indicated in the drawing of the wheel (Figure 5).

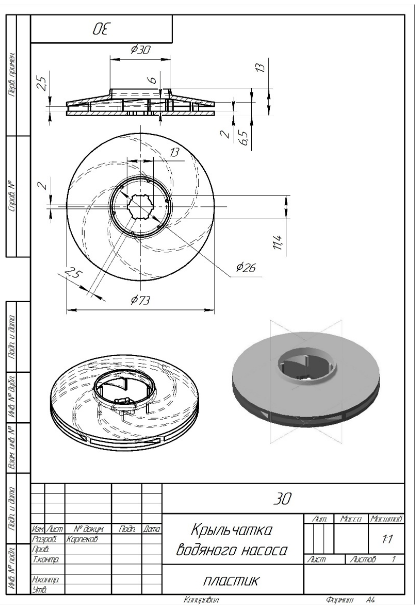


Figure 5. Dimensions to be studied

The dimensions were measured at 5 different points, the resulting size to be entered into the tables is the arithmetic mean of the measurements. The measured size values depending on the position of the part at the type of printing are shown in Table 2:

Table 2. Deviation from the original dimensions

Размер исходный Ориентация	b_{21} 2 mm	b_{22} 2 mm	b_{23} 2 mm	b_{24} 2 mm	b_{25} 2 mm
Вертикальная	1.7	1.9	1.8	1.6	1.7
Размер исходный Ориентация	b_{21} 6 mm	b_{22} 6 mm	b_{23} 6 mm	b_{24} 6 mm	b_{25} 6 mm
Вертикальная	5.5	5.4	5.5	5.3	5.6

According to the results of experiments, it was revealed the effect of the feed rate on the OZ axis, an increase in speed will lead to lower surface quality, higher roughness. The distance between the layers is 0,15 mm/s, getting a roughness of Ra 6,3 microns, and in the right case we used a distance of 0,05 m/s between the layers, getting a roughness of Ra1,6 microns. The printed samples are shown in Figure 6.

Figure 6. The effect of the feed rate on the OZ axis

The analysis of the effect of exposure time showed that there was no dependence on the thickness of the layer and the speed of exposure. If the exposure time from the bottom is not long enough, the print may slip off the plate, and the printing process must be stopped.

Experiments have also been conducted on the effect of exposure time at the UV chamber, the hardness is slightly lower than usual if the curing time by UV radiation is too short and the curing temperature is too low.he results of the hardness test for various curing parameters are shown in Table 3.

Table 3. Dependence between the curing parameters

Current parameter		Shore Hardness
Time	Temperature	
5	30	60
5	100	63
15	30	76
15	100	79
30	30	75
30	100	89

Verification of the printed geometry with the original geometry was performed by reverse engineering technologies.

Reverse engineering in mathematical modeling and evaluation of the geometric accuracy of the part. In modern production based on digital product data, precision control systems (PCS) are used, which can be divided into contact (coordinate measuring machines or CMM) and non-contact (optical and laser 2D/3D scanning systems). The first group of PCS is suitable for solid materials. The second group allows you to work with both soft and hard materials. In both cases, the result is a set of points having an unambiguous coordinate definition in two– or three-dimensional space [12].

The main working elements of an optical 2D/3D scanner are a light source and cameras that allow you to obtain a stereoscopic image. To date, there are no universal cameras that would allow obtaining high-precision macromodels (over 1 meter), mesomodels (less than 1 meter) and micromodels (less than 1 mm) of objects. When comparing the dimensions of a manufactured part, in the case of 2D scanning, a comparison is made with a drawing, and in the case of 3D scanning with a solid-state model. Moreover, the drawing and the solid-state 3D model are developed in external CAD programs. Sometimes, when 3D scanning large objects, photogrammetry tools are used, allowing you to create a reference network relative to which individual scans obtained during 3D scanning are positioned.

The scanning of the centrifugal wheel was carried out by an optical scanner EX Scan Pro_V3.7.0.3. According to the following algorithm, Figure 7 shows a photo of the work on the scan of a project employee.

1. Performing calibration;
2. Scanning mode: manual high-precision;
3. Table turns 8 steps were selected;
4. To increase the accuracy of capture and increase the accuracy, we scan one part several times at different angles, create 16 fragments;
5. After scanning in the EX Scan Pro_V application, we combine 16 scans (choosing with 3 or 4 points);
6. Edit the resulting point cloud. Remove excess, clean up noise and save the file in a suitable format;
7. Globalization of the grid. This process helps to improve the quality of the scan;
8. Creating a polygonal grid (stl model).

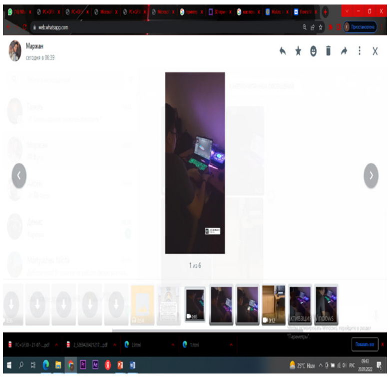


Figure 7. Photo report of scanning work

Figure 8a shows a part of the "centrifugal wheel", Figure 8b shows its polygonal model.

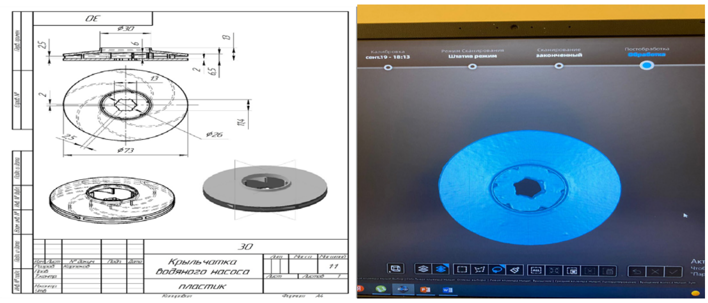


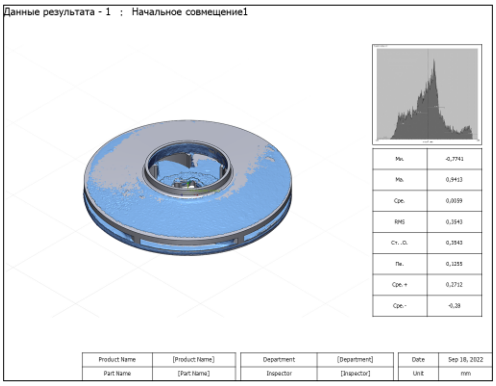
Figure 8. Wheel model a) geometric model b) polygonal model

The Geomagic Design X program was used to evaluate the printing accuracy of centrifugal wheels. 3D scanning data processing software allows you to create virtual three-dimensional models of physical objects in order to perform geometry control and reverse engineering in CAD/CAM/CAE systems [13-16].

This program allows you to:

– correct errors in the scanned model;
– create polygonal grids and full-fledged parametric solid-state models;
– analyze possible changes and errors;
– conduct a comparative analysis;
– perform size and quality control of physical objects.

Figure 9 shows a model of the initial geometry of the centrifugal wheel with a printed model.



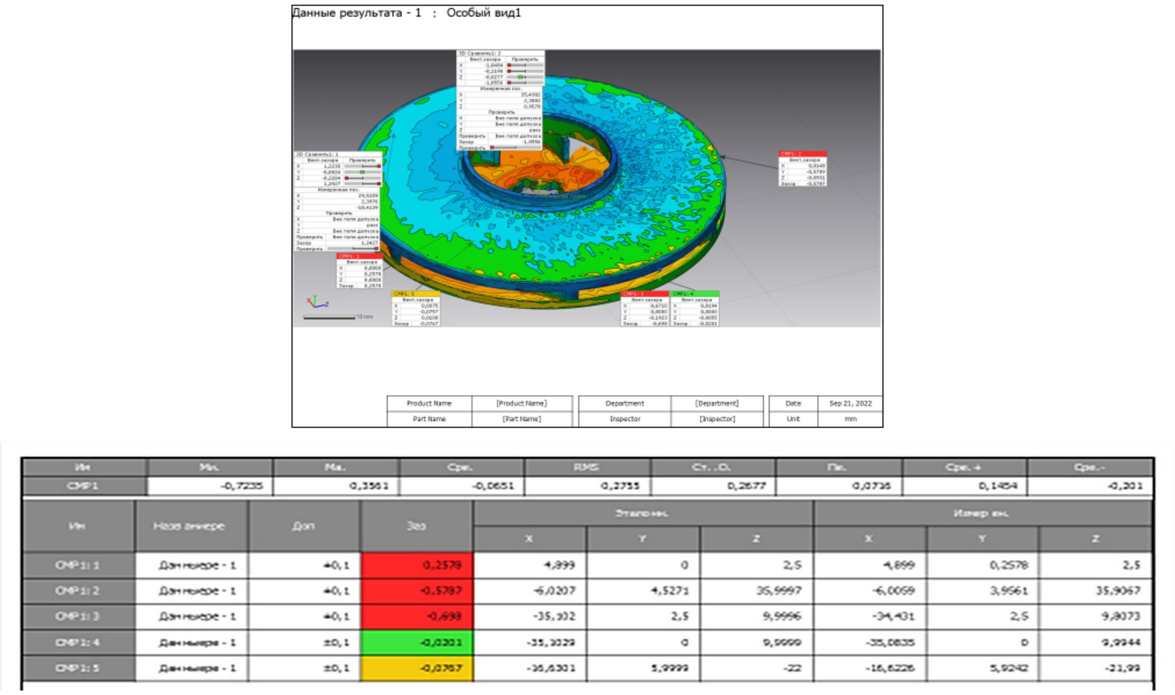
Данные результата - 1 : Начальное совмещение1

Мн.	-0,7741
Мв.	0,9413
Сре.	0,0059
RMS	0,3543
Ст. .О.	0,3543
Пе.	0,1255
Сре. +	0,2712
Сре. -	-0,28

Product Name	[Product Name]	Department	[Department]	Date	Sep 18, 2022
Part Name	[Part Name]	Inspector	[Inspector]	Unit	mm

Figure 9. Combining a 3D model (KOMPAS) and a printed model with SLA technology

The construction of a map of deviations of geometric dimensions before compensation and after compensation of geometry is shown in Figure 10.



Данные результата - 1 : Особый вид1

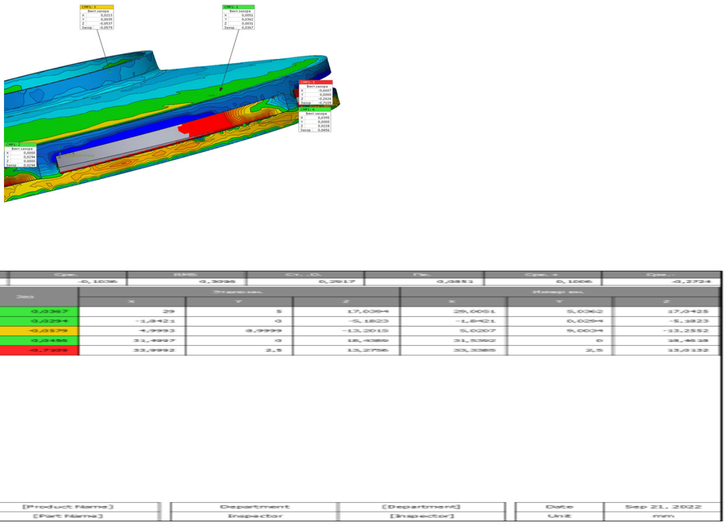
Product Name	[Product Name]	Department	[Department]	Date	Sep 21, 2022
Part Name	[Part Name]	Inspector	[Inspector]	Unit	mm

Им	Ми.	Ма.	Сре.	RMS	Ст. .О.	Пе.	Сре.+	Сре.-
СМР1	-0,7235	0,3561	-0,0651	0,2755	0,2677	0,0736	0,1454	-0,201

Им	Назв анкере	Доп	Зaз	Эталон ек.			Измер ек.		
				X	Y	Z	X	Y	Z
СМР1: 1	Дан нкере - 1	±0,1	0,2578	4,899	0	2,5	4,899	0,2578	2,5
СМР1: 2	Дан нкере - 1	±0,1	-0,5797	-6,0207	4,5271	35,9997	-6,0059	3,9561	35,9067
СМР1: 3	Дан нкере - 1	±0,1	-0,698	-35,102	2,5	9,9996	-34,431	2,5	9,8073
СМР1: 4	Дан нкере - 1	±0,1	-0,0201	-35,1029	0	9,9999	-35,0835	0	9,9944
СМР1: 5	Дан нкере - 1	±0,1	-0,0767	-16,6301	5,9999	-22	-16,6226	5,9242	-21,99

Figure 10. Measurement results of 3D model and printed wheel model

After certain deviations due to the 3D printing error, a newly compensated geometric 3-dimensional model of the wheel was created, but taking into account the printing error. The results of measurements of the compensated geometry are shown in Figure 11.



Им	Ми.	Ма.	Сре.	RMS	Ст. .О.	Пе.	Сре.+	Сре.-
СМР1	-0,7923	0,3251	-0,1036	0,3096	0,2917	0,0851	0,1006	-0,2724

Им	Назв анкере	Доп	Зaз	Эталон ек.			Измер ек.		
				X	Y	Z	X	Y	Z
СМР1: 1	Дан нкере - 1	±0,1	0,0367	29	5	17,0394	29,0051	5,0362	17,0425
СМР1: 2	Дан нкере - 1	±0,1	0,0294	-1,8421	0	-5,1823	-1,8421	0,0294	-5,1823
СМР1: 3	Дан нкере - 1	±0,1	-0,0579	4,9993	8,9999	-13,2015	5,0207	9,0034	-13,2552
СМР1: 4	Дан нкере - 1	±0,1	0,0456	31,4997	0	18,4389	31,5392	0	18,4618
СМР1: 5	Дан нкере - 1	±0,1	-0,7309	33,9992	2,5	13,2756	33,3385	2,5	13,0132

Product Name	[Product Name]	Department	[Department]	Date	Sep 21, 2022
Part Name	[Part Name]	Inspector	[Inspector]	Unit	mm

Figure 11. Measurement results of the 3D model and the compensated printed wheel model

Repeated scanning of the compensated geometry determined the maximum error of the printed part δ_{max}= 0,05mm, which will not significantly affect the kinematics of the fluid flow in the wheel during pump tests.

According to the experimental data on the influence of technological parameters of printing on the quality of the model and the measurement results, the regression equation (1) was derived

$$y = -0{,}17X_1{}^2 + 0.0603X_2 + 0.2681 \tag{1}$$

where: X_1 and X_2, respectively, print speed and layer thickness.

3. Results and discussion

Experimental studies within the framework of this work were carried out at the test stand of the Department of Mechanical Engineering, which was assembled and automated, the finished stand and the window of measurement results are shown in Figure 12.

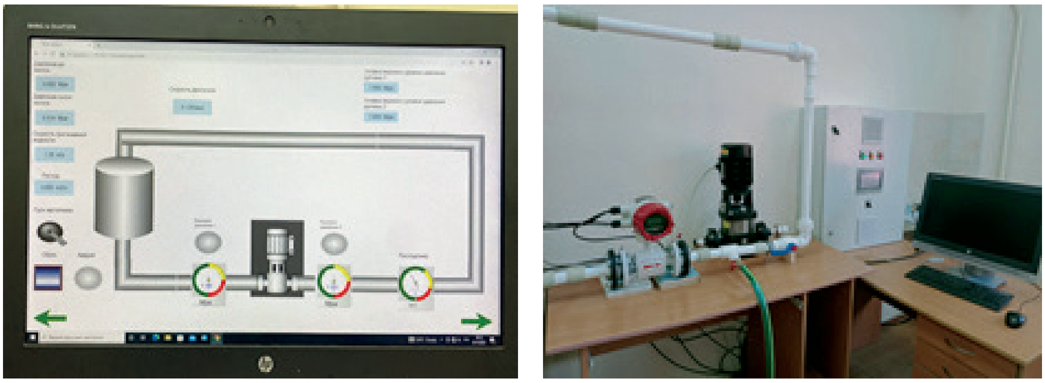


Figure 12. Diagram and readings on the laboratory stand

The stand is filled from the technical water supply and operates on a closed liquid circulation system. The installation of the stand consisted of an experimental pump of the SVM 3 with an engine, a tank with a capacity of 0,05 $м^3$, measuring equipment, a pipeline system with shut-off and control valves, as well as a control box.

The drive of the experimental pump was an adjustable electric motor with a power of 0,8 kW. The maximum speed of the electric motor is 2850 rpm. The flow meter records the flow values.

Digital pressure gauges controlled the pressure drop at the pump inlet and outlet. The supply of the experimental pump was regulated by means of a valve on the pressure line. The measuring equipment provided the ability to remove energy characteristics in accordance with existing requirements and was transmitted via wi-fi to a stationary computer.

In general, the method of testing the pump to remove their pressure and energy characteristics corresponded to the developed recommendations in [17]. Further, only general provisions are noted in determining the quantities necessary to determine experimental dependencies

$$H = f(Q),\ N = f(Q),\ \eta = f(Q)$$

The flow was measured by a flow meter.

The pressure of the experimental pump was calculated from the readings of pressure gauges measuring the pressure in the inlet and outlet dimensional sections, calculated by the formula (2)

$$H = \frac{P_D - P_S}{\gamma}, \text{М}, \tag{2}$$

where: P_S, P_D – are the readings of pressure gauges in the suction and discharge dimensional sections, respectively, γ – specific gravity of water;

The power on the shaft of the experimental pump was determined using

$$N_S = U \cdot I \cdot \eta_E \cdot \eta_N \cdot cos\varphi \cdot 10^{-3}, \tag{3}$$

where: U – is the mains voltage, V;
I – the current strength of the consumer from the network, A;
η_E – engine efficiency, $\eta_E = 0,9;$
η_N – network efficiency, $\eta_N = 0,95$.
$cos\varphi = 0,87$

$$\eta = \frac{9,8 \cdot Q \cdot H}{3,6 \cdot N_S}, \text{Вт} \tag{4}$$

The measurement results of the equipment are shown in Table 4

Table 4. Measurement results

№	Q m^3/h	P MPa	H m	U V	I A	V m/min
1	3.3	0.018	1.836735	228	3.2	1.01
2	3.1	0.1	10.20408	226.8	3.18	0.89
3	2.9	0.18	18.36735	226.3	3.15	0.77
4	2.5	0.28	28.57143	226	3.1	0.72
5	2	0.335	34.18367	225.5	3.05	0.54
6	1.5	0.385	39.28571	225	3	0.49

Estimation of measurement result errors. The results of field studies inevitably contain errors of various origins, when conducting experimental studies, it is mandatory to assess the accuracy of the measured values. Taking into account [38], it can be concluded that systematic errors are decisive in the experimental study of centrifugal pumps.

The relative margin of error in determining the feed was determined by the formula:

$$\Delta Q = \sqrt{\delta Q^2 + \delta n^2}, \%, \tag{5}$$

where: δQ^2 – relative marginal error of feed measurement, %.
δn^2 – relative marginal error of measuring the engine shaft speed
σ_Q – the average quadratic relative error of the feed measurement.

The errors of direct and indirect measurements are given in Tables 5 and 6.

Table 5. Errors of direct measurements

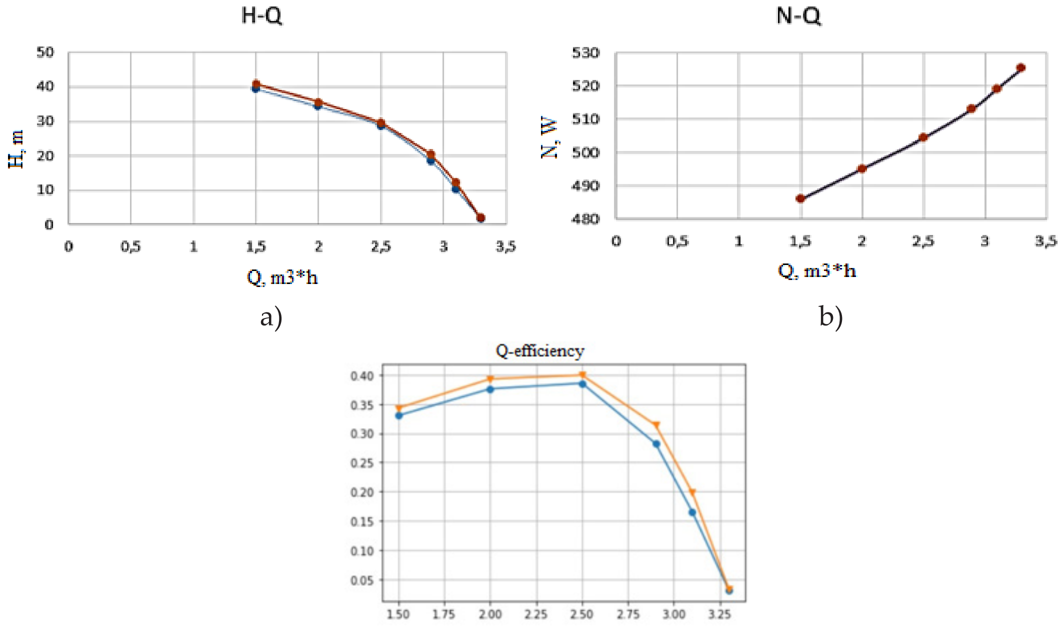
Measured parameter	Absolute margin of error,%	Relative margin of error,%	RMS relative error,%
Pressure drop at the pump Δ_{pu}, MPa	0.4	0.51	0.24
Mains voltage, V	0.3	0.41	0.16
Current strength, A	0.4	0.32	0.16
Supply Q, m^3/h	0.4	0.2	0.1

Table 6. Errors of indirect measurements

The determined value	Permissible limit error of the test, %	Relative margin of error,%	RMS relative error,%
Supply Q, m^3/s	3.0	1.79	0.9
Pressure H, m	3.0	0.91	0.48
Power N, W	3.0	1.02	0.51
Efficiency η, %	5.0	2.14	1.07

Based on the analysis of the data in Tables 5, 6, it can be concluded that the errors in determining the pressure parameters of the experimental pump according to [18] did not exceed the permissible limits.

Graphs of the pressure and energy characteristics of the impeller model with a heterogeneous grid are shown in Figure 13.



a)

b)

c)

a) characteristic head (blue line for pump with initial wheel geometry, red line for pump with heterogeneous grid) b) characteristic of the power on the pump shaft

c) efficiency characteristic (blue line for a pump with the original wheel geometry, red line for a pump with a heterogeneous grid)

Figure 13. Pressure and energy characteristics of the pump

Analyzing the pressure and energy characteristics of a pump with a factory impeller and a prototype of a wheel with a modified grid, it can be concluded that the discrepancy in the results of the pressure is about 4%. At the same time, the maximum efficiency values diverge by 3%.

4. Conclusion

Based on the results of the research presented in the article, the following conclusions were made:

– Rapid prototyping technology made it possible to create a modified centrifugal pump impeller with 3D printing technology using the SLA method;

– Coefficients regression equation of the dependence of the geometric deviations of the printed wheel on factors such as the printing speed of the main layers, the printing speed of the current layers, the thickness of the layers indicates a greater influence of the printing speed factor;

– A technique for optimizing the geometry accuracy of printed impellers using reverse engineering technology has been created;

– The tests of the pump with modified impellers showed an increase in pressure by 4%, and an increase in efficiency by 3%.

The prospect of using rapid prototyping for mechanical engineering is economically obvious, since these devices significantly accelerate the process of developing new products, significantly reduce the risks of design errors, reduce the cost of obtaining a layout, and are already available to most Kazakhstan enterprises at their prices.

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Сорғы құрылысында жылдам прототиптеу технологиясын қолдану

Аңдатпа. Мақалада тиімділікті арттыру мақсатында орталықтан тепкіш сорғының жұмыс дөңгелегін өзгерту кезінде жылдам прототиптеу технологиясын қолдану нәтижелері келтірілген. Технологияны іске асыру нәтижесінде негізгі қабаттардың басып шығару жылдамдығы, ағымдағы қабаттардың басып шығару жылдамдығы, қабаттардың қалыңдығы сияқты параметрлердің басып шығарылған өнімдердің геометриялық дәлдігіне әсері зерттелді. Эксперименттердің нәтижелері бойынша беру жылдамдығының OZ осіне әсері анықталды, жылдамдықтың жоғарылауы бетінің сапасының төмендеуіне, кедір-бұдырдың жоғарылауына әкеледі. Қабаттар арасындағы қашықтық 0,15 мм/с құрайды, Ra 6,3 мкм кедір-бұдырды алады, ал оң жақта біз қабаттар арасында 0,05 мм/с қашықтықты қолданып, Ra1,6 мкм кедір-бұдырды аламыз. Мақалада басып шығарылған өнімдердің қаттылығына ультрафиолет камерасындағы экспозиция уақыты мен экспозиция уақытының әсерін талдау нәтижелері келтірілген. Мақалада оптикалық сканерді қолдану негізінде реверсинг технологиясы негізінде прототиптердің геометриясын анықтау және өтеу әдістемесі келтірілген. Модификацияланған доңғалақ прототипі бар орталықтан тепкіш сорғының сынақтары жаңа өнімдерді жобалау циклін қысқарту, сондай-ақ оларды әзірлеу құнын төмендету үшін жылдам прототиптеу сияқты инновацияларды қолдану қажеттілігін растайды.

Түйін сөздер: жылдам прототиптеу, сандық егіздер, 3D принтерлер, басып шығару параметрлері, тиімділік, орталықтан тепкіш сорғы және кері инженерия.

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Применение технологии быстрого прототипирования в насосостроении

Аннотация. В статье приведены результаты применения технологии быстрого прототипирования при модификации рабочего колеса центробежного насоса в целях повышения КПД. В результате реализации технологии были изучены влияние параметров, таких, как скорость печати основных слоев, скорость печати текущих слоев, толщина слоев на геометрическую точность напечатанных изделий. По результатам экспериментов было выявлено влияния скорости подачи на ось OZ, увеличение скорости приведет к более низкому качеству поверхности, более высокой шероховатости. Расстояние между слоями 0,15 мм/с, получая шероховатость Ra6,3 мкм, а в правом случае мы использовали расстояние 0,05 мм/с между слоями, получая шероховатость Ra1,6 мкм. В статье приведены результаты анализа влияния времени экспозиции и времени выдержки в УФО-камере на твердость напечатанных изделий. В статье приведена методика определения и компенсации геометрии прототипов на базе технологии реверсинжениринга на основе применения оптического сканера. Проведенные испытания центробежного насоса с прототипом модифицированного колеса подтверждают необходимость применения таких инноваций, как быстрое прототипирование для сокращения цикла проектирования новых изделий, а также снижения себестоимости на их разработку.

Ключевые слова: быстрое прототипирование, цифровые двойники, 3D-принтеры, параметры печати, эффективность, центробежный насос и обратный инжиниринг.

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