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DESIGN AND OPTIMIZATION OF THE TWO-CHANNEL CENTRIFUGAL WASTEWATER PUMP IMPELLER

Bostan Viorel [1], Petco Andrei [2, 3]

[1] Technical University of Moldova, Faculty of Computers, Informatics and Microelectronics, Studenților Str. 9/7, Chisinau, Republic of Moldova
[2] Technical University of Moldova, Faculty of Mechanical, Industrial and Transport Engineering, Technical University of Moldova, Studenților Str. 9/7, Chisinau, Republic of Moldova
[3] S.R.L. "CRIS", Meșterul Manole str. 7, Chisinau, Republic of Moldova

Corresponding author: Petco Andrei, andrei.petco@tcm.utm.md

Abstract: The efficiency and reliability of pumping systems play a key role in wastewater treatment systems as well as in wastewater disposal systems in general. This paper considers the optimisation of a two-channel centrifugal pump impeller for wastewater applications. The purpose of the study is to increase the hydraulic efficiency of the pump by optimising the geometric parameters of the impeller. The optimisation criterion is increasing the impeller hydraulic efficiency. The original impeller geometry was obtained using CFturbo software. Numerical simulation was carried out in ANSYS CFX. Optimisation of the impeller geometry was performed in the ANSYS optiSLang software package using the Response Surface method. The Evolutionary Algorithm was used as the optimisation algorithm, which allowed an efficient analysis of the design parameter space and finding the optimal solution. As a result of optimisation, an impeller with a hydraulic efficiency of 61.2% was obtained, which exceeds the required hydraulic efficiency of 60% specified in the technical conditions. It should also be noted that the resulting geometry allows wastewater bodies with a diameter of Dp=100 mm to pass through.
Key words: Centrifugal pump, wastewater pump, CFD, Impeller Optimisation, Blade

1. INTRODUCTION

Centrifugal pumps are widely used in wastewater treatment systems, primarily due to their robustness, adaptability to changing pumping conditions, and relative simplicity [3, 12]. However, these pumps often encounter difficult operating conditions characterised by liquids containing significant amounts of solids, which creates difficulties in terms of performance degradation, reduced efficiency, and increased wear on the impellers. Since wastewater treatment plants and associated pumping systems are significant energy consumers [8], improving pump efficiency is a critical challenge [1, 2, 4, 5].

Optimising wastewater centrifugal pumps plays a key role in improving their efficiency, reliability, and durability [9, 11]. Key optimisation parameters usually include impeller geometry, channel width, and blade shape, which affect hydraulic losses, cavitation levels, and the potential for clogging. Modern optimisation techniques use CFD modelling to analyse fluid flow, pressure distribution, and flow velocity, which in turn allows the determination of parameters that maximise efficiency [6, 10]. In addition, recall surface and evolutionary algorithms are used to find optimal solutions from multiple simulations. As a result of the optimisation process, pump efficiency can be improved, energy consumption can be reduced, and equipment life can be extended.

This study considers the impeller optimisation of a dual-channel centrifugal pump designed to operate under demanding wastewater treatment conditions. The pump under study is to provide a flow rate of 600 (m^3/h) and a head of 17 (mH_2O) at a rotational speed of 1800 (rpm). The main objective of this study is to obtain a pump wheel with increased hydraulic efficiency of the pump by systematically optimising the critical geometrical parameters of the impeller. Considering the operational difficulties associated with wastewater, namely containing solids, the optimisation process includes explicit design criteria aimed at the efficient movement of solids up to Dp=100mm diameter (value provided in the specification received from the customer), which in turn is also a limitation of the optimisation. This capability is necessary to prevent clogging for the reliable operation of wastewater conveying stations.

2. MATERIALS AND METHODS

The optimisation process combines CFD with response surface optimisation and weaving with Evolutionary Algorithms as described below. The initial aim of the optimisation is the efficiency of the impeller of the wastewater pump, with the characteristics presented in Table 1. An initial geometry was generated in the CFturbo software, and CFturbo was also used to generate the geometric model during the optimisation process.
Samples were generated using the Latin HyperCube (LHS), a statistical method used for generating a near-random sample. For each geometry in the obtained dataset, CFD modelling (Ansys CFX) was performed to obtain the fluid flow characteristics and determine the corresponding criterion values.
A Response surface (RSM) was based on these simulation results. The resulting model allowed the optimisation algorithm to efficiently determine the geometry that maximises the selected criteria function. In the final step, a validation calculation in CFD was carried out.

Table 1. Requested pump parameters

Parameters	Value
Pumps Head at BEP (Best Efficiency Point), H	17 m
Volume flow rate, Q	600 m^3/h
Maximum wastewater body size, dp	100 mm
Impeller rotational speed, n	1800 min^{-1}

The initial geometric model of the impeller was developed using the specialised pump design software CFturbo (Figure 1). This software is adapted to the design of turbomachines, has an intuitive interface, and allows for integration with CAE systems such as ANSYS (ANSYS WorkBench), enabling automatic geometry optimisation. and replaces the geometric model building step in modules such as ANSYS DesignModeler.
To ensure the accuracy and reliability of the computational fluid dynamics (CFD) analysis, a high-quality structured mesh was created using ANSYS TurboGrid (Figure 2), a tool specifically designed for turbomachinery. The structured mesh provides improved accuracy in determining flow characteristics near the walls. This type of mesh also allows the description of complex three-dimensional flow patterns, which is critical for accurate prediction of impeller hydraulic performance. The mesh was created to obtain the desired parameter y+ equal to 1. The expected Reynolds number of fluid flow in the pump impeller was assumed to be $5 \cdot 10^5$ for the mesh calculation.

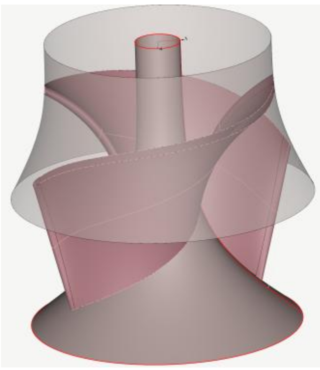


Fig. 1. Geometrical model obtained in CFturbo

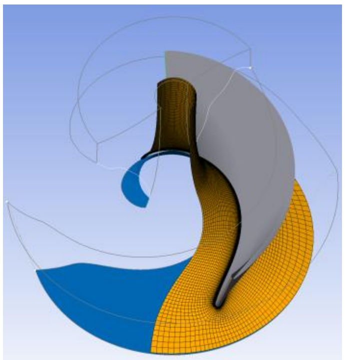


Fig. 2. Discretization mesh

The steady-state CFD modelling was carried out in the ANSYS CFX software environment using the Reynolds-averaged Navier-Stokes (RANS) equations. These equations are widely used in turbomachinery due to the balance between computational cost and accuracy required to solve practical engineering problems. This model, the Menter Shear Stress Transfer (SST) model (eq. 1-2) [7], combines the advantages of the accuracy of the k-ω model near the wall and the stability of the k-ε model in free flow, making it particularly suitable for the complex turbulent flow conditions present in centrifugal pumps operating in different operating conditions.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho \omega k + \frac{\partial(\rho k)}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right] \tag{1}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{v_t} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\frac{\rho \sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{2}$$

where x_j are partial coordinates, with the subscript j denoting spatial direction (x, y, z), ρ is fluid density, u_j - mean flow velocity components in direction j, k - turbulence kinetic energy, ω - specific dissipation rate, μ represents dynamic viscosity, μ_t is turbulent viscosity (eddy viscosity), ν_t - turbulent kinematic viscosity and P represents turbulence production term.

Initial and boundary conditions are presented in Figure 3 total pressure of 10^6 Pa is set at the inlet of the computational domain, with the flow direction set perpendicular to the boundary. At the outlet, a nominal mass flow rate of 1.75 (kg/s) is given, and the flow parameters are calculated by the solver using the Zero Gradient condition. The domain is rotated at 1800 rpm. A no-slip condition is specified for the walls, assuming zero velocity at the boundaries. The roughness of the surfaces is not considered in the model. The Periodic Interface condition is applied on the lateral boundaries of the design domain to account for the cyclic symmetry of the structure. The simulation uses Physical Timescale with a step of 0.002 s.

Due to limited computational resources, in research was carried out in a steady-state model, which allows us to obtain a stable solution at a reasonable computational cost, while preserving the main physical effects of the flow.

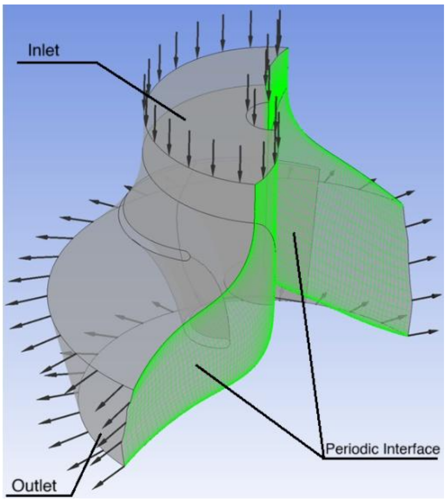


Fig. 3. Initial and boundary conditions scheme

The blade geometry was parameterized by varying the wrap angle θ, with the blade thickness distribution ranging from 8 mm at LE to 6 mm at TE. For the given study, the 2-bladed wastewater pump impeller scheme was chosen. Also, the shape of the flow area is formed by the following parameters Impeller DiameterDimp, Outlet width b2, Impeller light Δz, LE position on hub LEh, LE position on Shroud LEs, impeller TE angle α (fig.4).

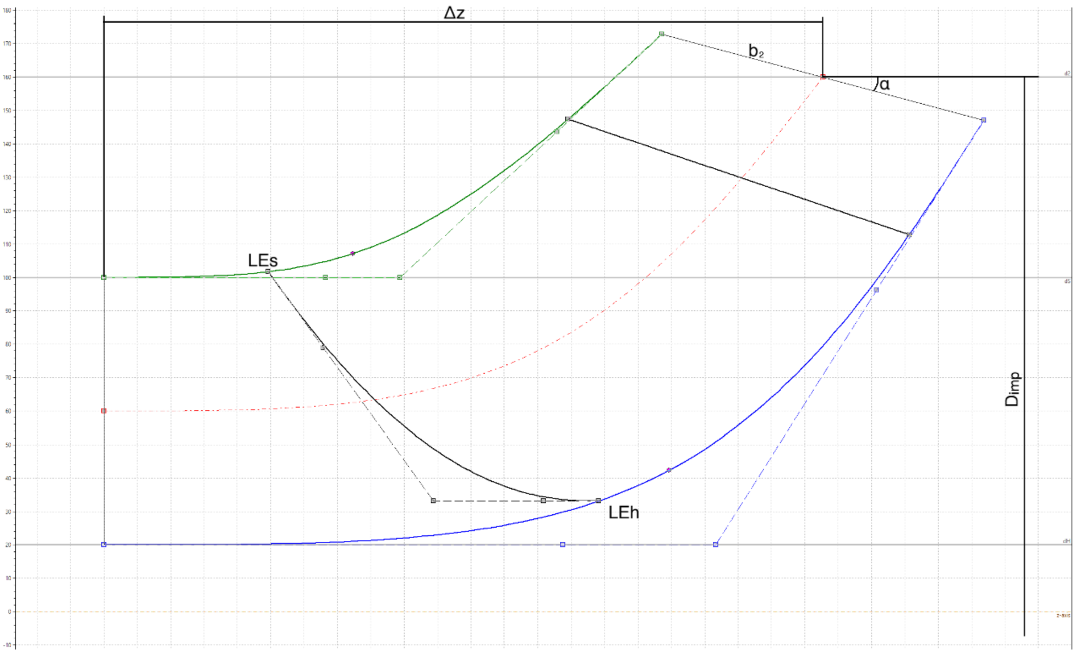


Fig. 4. Parameterisation scheme

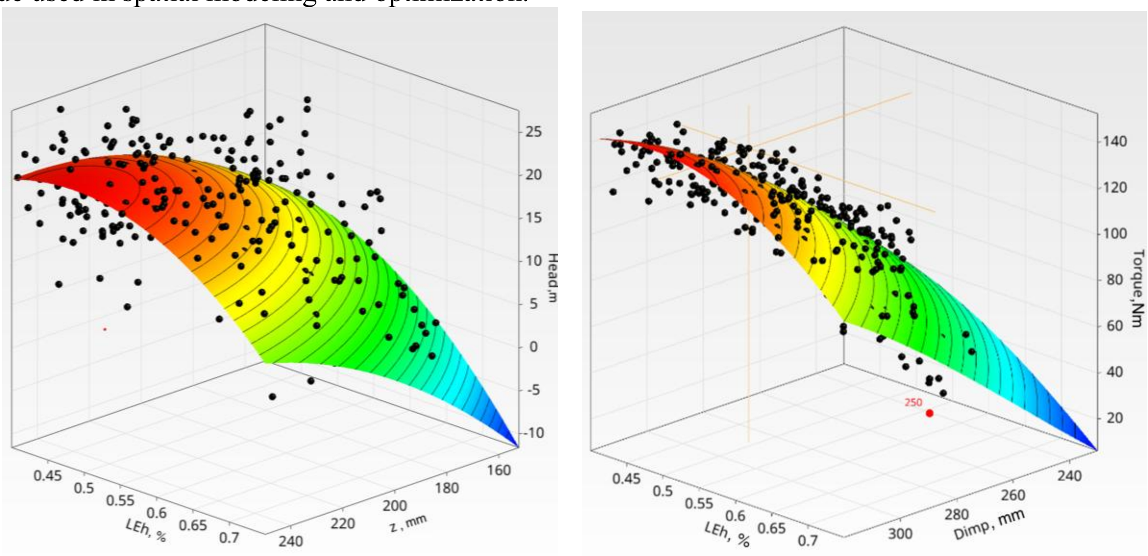
The limits of variation of the geometric parameters are indicated in Table 2. The limits were chosen so as to cover the widest possible range of geometries.

Table 2. The limits of variation of the geometric parameters.

Outlet width b_2, [mm]	Impeller Diameter D_{imp}, [mm]	Impeller TE angle, α [°]	Impeller light Δz, [mm]	LE position on Hub LEh, [mm]	LE position on Shroud LEs, [mm]	Wrap angle, θ [°]
100-120	230-320	0-20	150-250	0.4-0.75	0.25-0.6	90-180

3. RESULTS AND DISCUSSION

Following the optimization process, the response surface was obtained (Figure 5), based on which the Evolutionary Algorithm was applied in order to obtain the geometry that will show the value of the maximum criterion function. The response surface was obtained by applying the Kriging algorithm, a statistical interpolation technique used in spatial modeling and optimization.



(a) (b)

Fig. 5. Response surface: a) representation for parameters affecting Torque, b) representation for parameters affecting Head

A coefficient of performance (COP) matrix was obtained (Figure 5). It should be noted that for Torque, the main influence is the pump impeller diameter D. The pressure, in turn, is influenced by the position of the leading edge LE (LEh and LEs) and the number of blades z.

The following analysis of the correlation matrix of the centrifugal pump impeller parameters (Table 3) presents the relationship between the geometric characteristics of the centrifugal pump impeller and the key performance parameters of the pump, namely head and torque, which, in the case of this optimisation process, represent the Optimisation Criterion and Constraint. These data also allowed the geometry of the impeller to be adjusted after the optimisation process to meet the impeller passage criterion Dp of wastewater bodies.

Analysing the representation in the material matrix, it can be observed that the impeller diameter Dimp was the dominant geometric factor showing a strong positive correlation (0.77) with the pump impeller torque, which may be because an increase in the impeller diameter significantly increases the torque due to the large fluid forces acting on the enlarged blades. The impeller diameter showed a weak positive correlation (0.15) with the pump head, which does not quite coincide with the data on classical centrifugal pumps [1]. The weakness of this correlation may be due to the small number of blades Z = 2 and the small maximum level of the girth angle θ = 180°, so that the increase in impeller diameter itself gives a limited increase in head.

The impeller axial height (z), defined as the height from the impeller inlet to the midpoint of the outlet, showed a marked positive correlation (0.52) with pump head; it also slightly increases the torque requirement (correlation 0.14), collectively indicating that axial height is also a favourable optimisation parameter. The leading-edge positions at the hub (LEh) and at the shroud (LEs), in turn, show a moderate negative correlation with pump head (-0.36 and -0.37, respectively). This may be related to the suction capacity of the impeller.

The geometrical parameters obtained during the optimisation process are presented below (Table 4). It should also be noted that the geometry was partially modified in order to meet the criterion of maximum passable wastewater body.

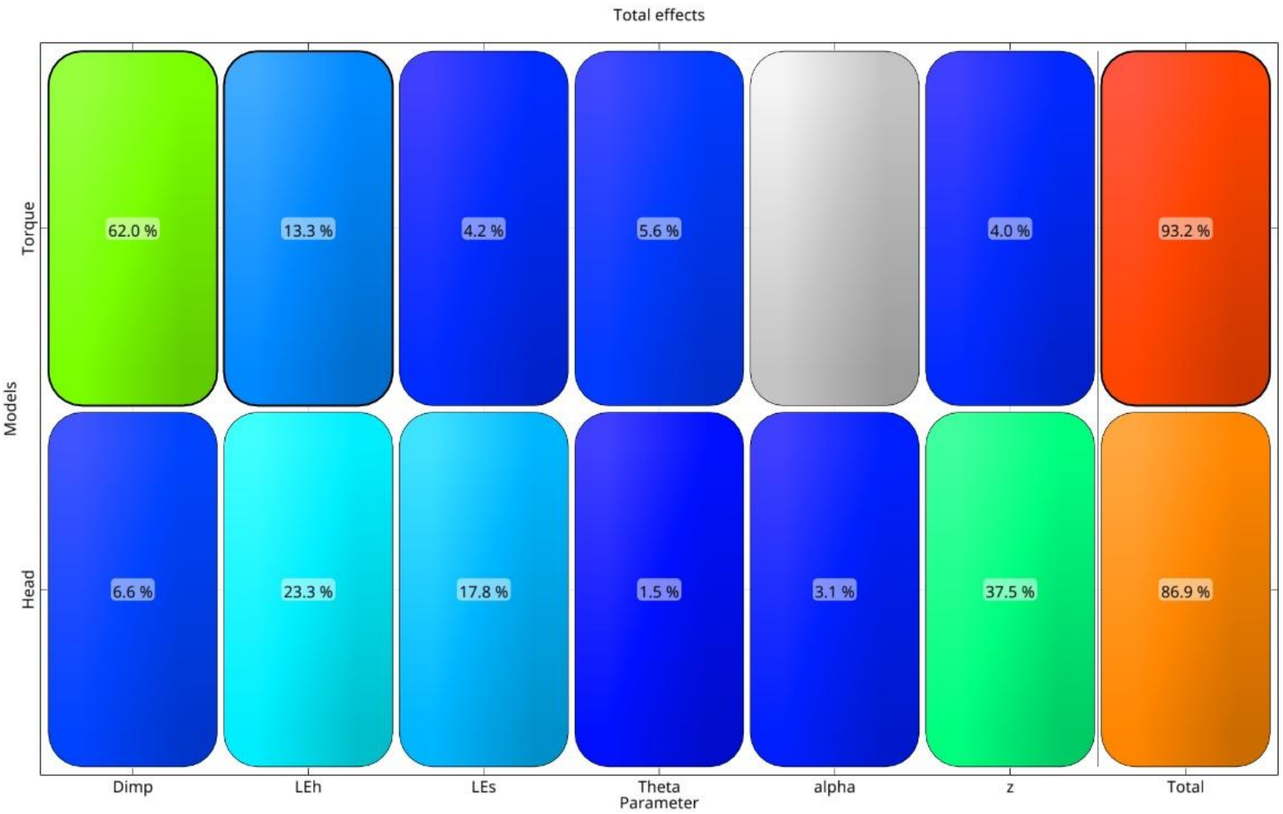


Fig. 5. Coefficient of performance matrix (COP)

Table 3. Correlation matrix

	b_2	D_{imp}	LEh	LEs	θ	α	Δz	Head	Torque
Pump Torque	0.041	0.772	-0.152	-0.133	-0.095	0.28	0.139	0.492	1
Pump Head	0.025	0.149	-0.359	-0.372	0.042	-0.014	0.519	1	0.492
Impeller light Δz	0.0616	0.1	0.084	0.091	-0.061	0.065	1	0.519	0.139
impeller TE angle α	-0.067	0.1	-0.111	0.034	-0.014	1	0.065	-0.014	0.28
Wrap angle θ	0.029	0.007	0.016	-0.077	1	-0.014	-0.061	0.042	-0.095
LE position on Shroud LEs	-0.019	-0.05	-0.064	1	-0.077	0.0345	0.0916	-0.372	-0.133
LE position on Hub LEh	0.0696	0.336	1	-0.064	0.016	-0.111	0.084	-0.359	-0.152
Impeller Diam. D_{imp}	0.005	1	0.336	-0.05	0.007	0.1	0.1	0.149	0.772
Outlet width b_2	1	0.005	0.069	-0.019	0.029	-0.067	0.061	0.025	0.0418

Table 4. The geometrical parameters after optimisation process

Outlet width b_2, [mm]	Impeller Diameter D_{imp}, [mm]	Impeller TE angle α, [°]	Impeller light Δz, [mm]	LE position on Hub Leh, [mm]	LE position on Shroud Les, [mm]	Wrap angle θ, [°]
118.82	252.77	6.9	200.5	0.474	0.263	166.23

The results of the CFD simulation validation are presented in Figure 6. It should be noted that the pressure distribution is similar to other optimised pump results. When analysing the velocity field, it is possible to notice the response of excess vortices or recirculation.

The optimisation process resulted in a significant improvement in hydraulic efficiency, fully satisfying the target specifications. An impeller with an efficiency of 61.2% was achieved. It should also be noted that the obtained head value is almost identical to the requested one, unlike the model obtained in CFturbo. The optimised impeller geometry demonstrated a reduction in internal pressure losses, increased fluid flow stability, and improved overall flow pattern.

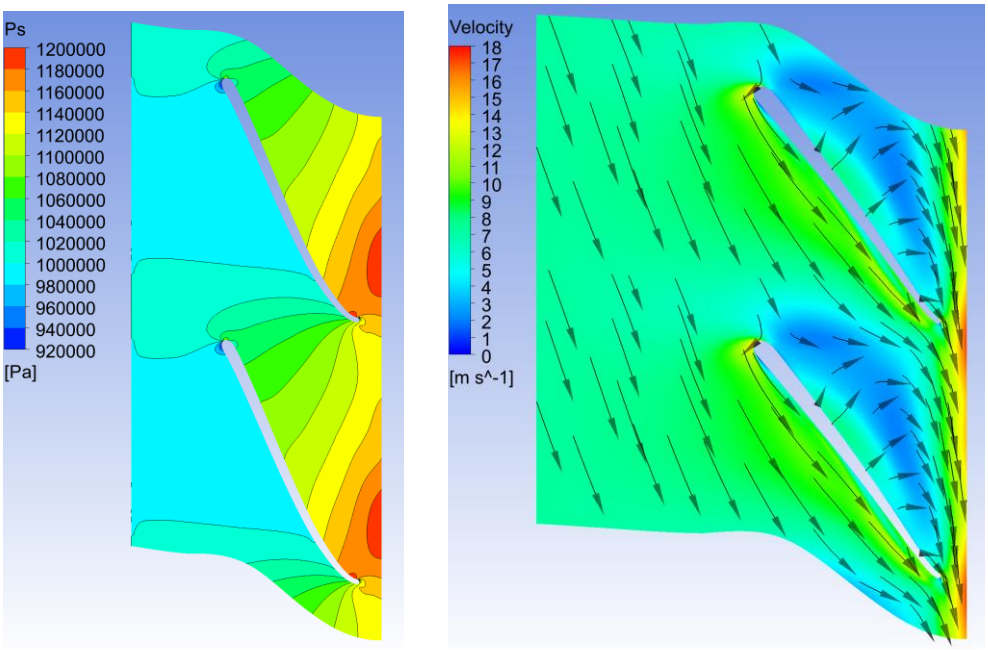


Fig. 6. Blad-to-blade plot of pressure and velocity distribution

5. CONCLUSIONS

During this study, the geometry of the two-channel impeller of a centrifugal pump designed for use in wastewater treatment systems was successfully optimised. It should be noted that the following was achieved:
Increased efficiency: The optimised impeller achieved a hydraulic efficiency of 61.2%, exceeding the initial target of 60%.
Efficient computational approach: The use of CFturbo for the initial geometry design, ANSYS CFX for numerical simulation, and ANSYS optiSLang with evolutionary algorithms proved to be extremely effective in determining the optimal impeller geometry.
Improved hydraulic performance: The redesigned geometry significantly reduced internal pressure losses, resulting in improved hydraulic stability and fluid flow characteristics. At the same time, operational capabilities have been maintained: The optimised geometry successfully meets critical operational criteria, including the passage of wastewater bodies with a diameter of up to 100 mm.
Although, unfortunately, no experimental testing has been carried out and research is continuing as part of the current R&D programme, the results clearly indicate significant potential for further development and wider implementation. The practical application of the optimised design is planned at CRIS Hermetic Pumps in Chisinau, Republic of Moldova, which will provide a solid foundation for future research in this field.

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Conflicts of interest: There is no conflict of interest.
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