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New Design Method for the Formed Suction Intake in Axial–Flow Pumps with a Vertical Axis

Andrzej Błaszczyk
Adam Papierski
Mariusz Susik
Lodz University of Technology
Institute of Turbomachinery
adam.papierski@p.lodz.pl

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A concept of the formed suction intake design obtained with an algorithm for vertical axial–flow pumps is presented. The design methodology is a part of works conducted within project no. N N513 460240 supported by the Polish National Science Center. The proposed procedure is used to optimize intakes. The results of steady flow numerical computations in the suction intake as well as applications of the design optimization in the aspect of fulfilling two objective functions are discussed. The objective functions given by the authors concern the optimal inflow of the fluid into the impeller.

Keywords: suction intake, multiobjective optimization, CFD.

1. Introduction

The formed suction intake is a final element of inlet channels in pumps with a vertical axis (Fig. 1). Most often, these pumps are mixed–flow or axial-flow pumps characterized by large capacities (over 15000 m^3/h) and quite low pump heads. In formed suction intakes, changes in the water flow direction from horizontal to vertical occur. Such a radical change in the water flow direction generates inconvenient hydraulic phenomena.

In Fig. 1, a scheme of inflow channels of the cooling water pump is shown.

The real pumping station facility (Fig. 1) consists of: a screen chamber (1), where there are trash screens (2) used to purify roughly the water supply flowing in from the high–water source, (3) a rotary screen whose task is to purify roughly water from pollutions, an open wet well (4), a formed suction intake (5) and cooling water pumps (6).

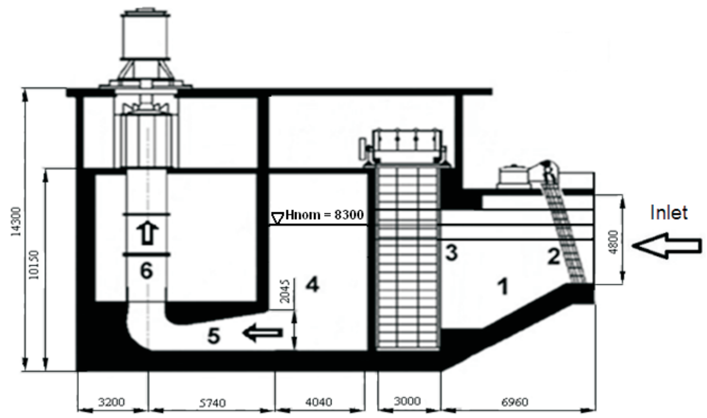

Figure 1 Real facility - system of inflow channels for the cooling water pump (458 MW unit in Ptnw II Power Plant, Poland) [8]

Comparison to the suction intake in the 360 MW unit in Bechatów Power Plant, Poland According to standard [1], the outflow of water from the formed suction intake should fulfill the following conditions:

- the angle of fluid swirl in the pump inlet cross-section, denoted as Θ and time-averaged in the period of 10 min, should fulfill the condition of $\Theta \leq 5°$; a momentary deviation (up to 30 seconds) $\Theta \leq 7°$ is allowed;

- the non-uniformity of the velocity profile in relation to the average value from the measurement surface area less than 10% in every measurement point with a Pitot probe;

- velocity fluctuations in time, in a given measurement point with a Pitot probe, less than 10% in relation to the time-averaged duration of this measurement.

A reduction in the water swirl angle, immediately upstream of the pump inlet, whose measure is a value of the absolute velocity circumferential component , can eliminate fluctuations in the pump volume flow rate (Fig. 2).

Attaining non–uniformities of the velocity profile and velocity fluctuations permissible by the standard can improve the pump capacity and its dynamic state.

In the available literature, there is a lack of publications devoted to design methods for formed suction intakes, which would check computations at the stage of velocity non–uniformities and fluid swirls at the pump inlet.

In the publications on the liquid inflow in mixed–flow and axial–flow pumps with a vertical axis, only main dimensions of formed suction intakes in relation to the pump inlet diameter are given.

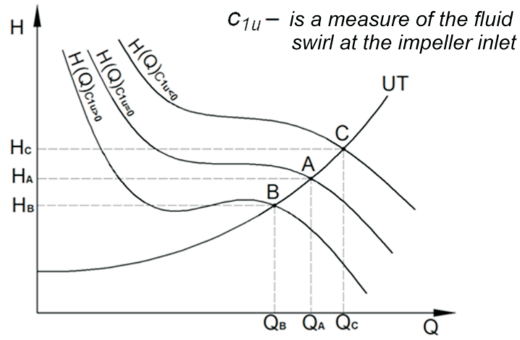

Figure 2 Characteristics of the pump flow H(Q) and characteristics of the cooling water system UT [2]

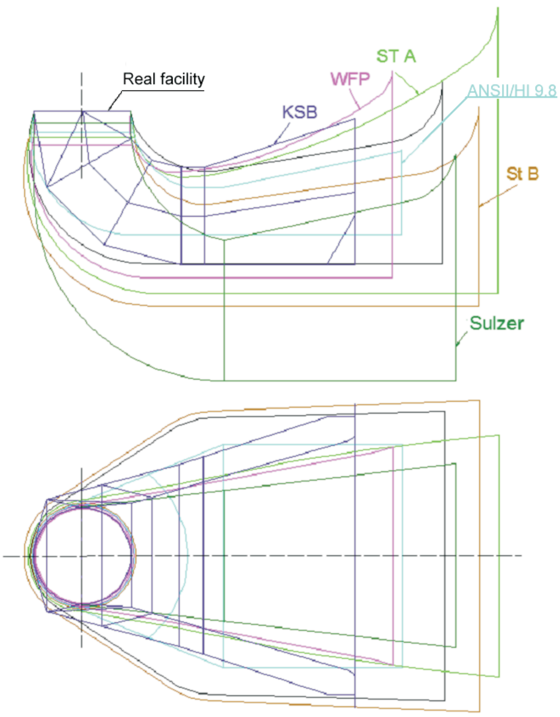

Figure 3 Meridional (a) and longitudinal (b) contours of suction intakes. Comparison to the suction intake in the 458MW unit in Ptnów II Power Plant, Poland [4]

Figures 3, 4 and 5 show dimensioned outlines of formed suction intakes proposed by the ANSI/HI 9.8-1998 standard [1], Stpniewski [10], a pump catalog of Warsaw Pump Factory [9]. They were compared to suction intakes manufactured for Pątnów, Łagisza and Bełchatów power plants. In these figures, we can see:

1. Real facility – a suction intake which was made (by ALSTOM POWER) and is still working.
2. WFP – proposals of Warsaw Pump Factory [9].
3. St A and St B – two proposals of dimensioning given in [10].
4. ANSI/HI 9.8 – recommended proposals by the ANSI/HI 9.8-1998 standard. American National Standard for Pump Intake Design [1].
5. KSB – proposals of KSB Pumps - German Pump Factory [7].
6. Sulzer – proposals of Sulzer Pumps - Swiss Pump Factory [5],

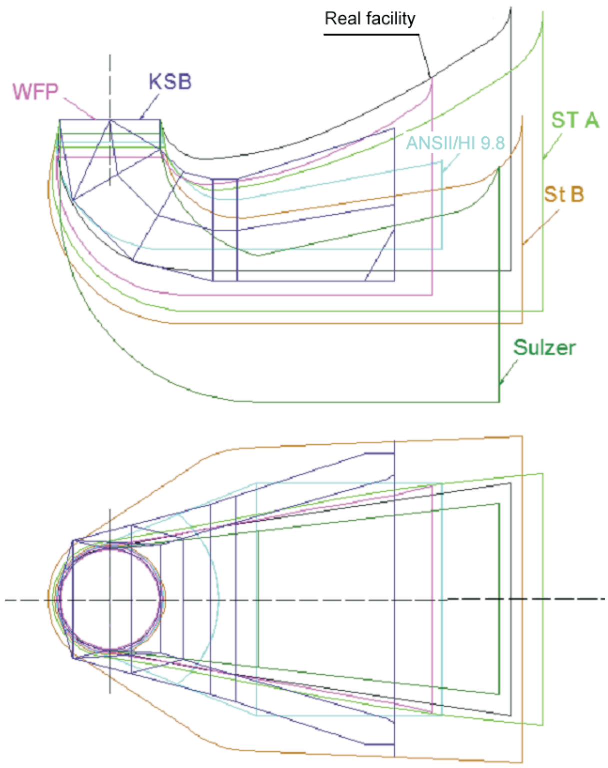

Figure 4 Meridional a) and longitudinal, b) contours of suction intakes

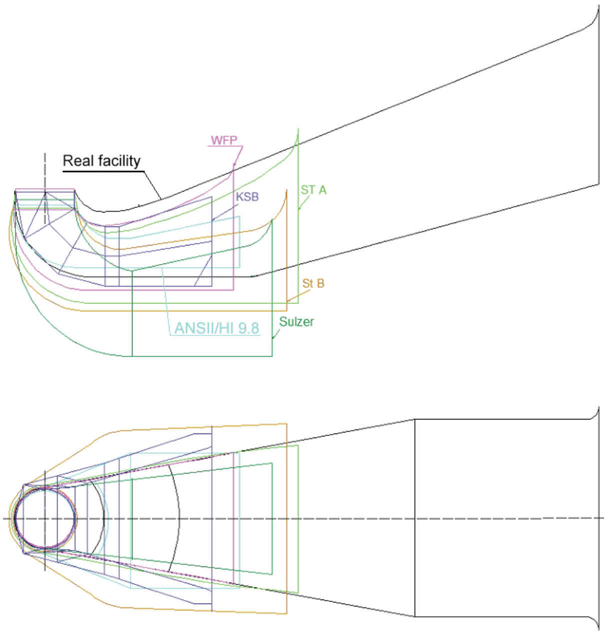

Figure 5 Meridional a) and longitudinal b) contours of suction intakes. Comparison to the suction intake in the 460 MW unit in agisza Power Plant, Poland

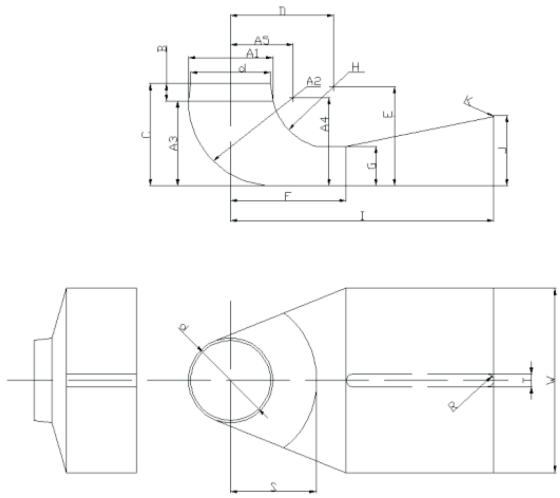

Figure 6 Main dimensions of the formed suction intake

In Fig. 6, main dimensions of the formed suction intake proposed by the authors are presented.

Differences between geometric parameters of formed suction intakes proposed in different sources and a lack of publications in the available literature devoted to design methods of formed suction intakes are due to an incoherent design methodology for formed suction intakes.

The developed methodology should enable the design of formed suction intakes in order to implement the required objective functions.

Due to this fact, the design procedure of optimal suction intakes employs results of numerical flow computations and other research works. It uses design optimization methodology in order to search for the best solution in the aspect of implementation of the required objective functions.

2. Design procedure of optimal formed suction intakes

Below, relationships and dependences used in the design method algorithm of optimal suction intakes are discussed.

Cooling water system flow parameters of the nominal point of the pump, i.e., H_N – nominal head and Q_N– nominal flow rate are the input data for the formed suction intake design.

Rotations of huge axial-flow and mixed–flow pumps fall within the range of n=300-500 rpm. Within this scope, velocity is chosen. Lower rotations cause that the pump construction is of a larger size, which has an influence on the pump price. On the other hand, cavitation phenomena are the limitation for higher number of rotations. For the required flow parameters H_N, Q_N and the assumed rotations, a specific speed from the following formula is determined:

$$n_{sq} = \frac{n\sqrt{Q_N}}{(H_N)^{3/4}} \tag{1}$$

In pump catalogs, the minimal dynamic water inflow head h_{min} (Fig. 7) is also given, besides the hydraulic parameters: H_N, Q_N, η_N (nominal efficiency), NPSH (required net positive suction head), engine power, size dimensions of the pump aggregate.

For the chosen dimensioning proportions of suction intakes, the nominal pump capacity (Q_N) and the minimal inflow head h_{min}, numerical computations of the three-dimensional flow are carried out.

In the developed algorithm, the ANSYS-CFX software is proposed (chapter 3) for the numerical computations of steady flow fluid parameters in the formed suction intake. Verification of results of the measurements, which were made for the investigated variant of the suction intake at the Institute of Turbomachinery, Lodz University of Technology, was conducted with the ANSYS CFX software package.

The results of numerical computations of the flow velocity in designed suction intakes will be used to determine the consecutive values of objective functions.

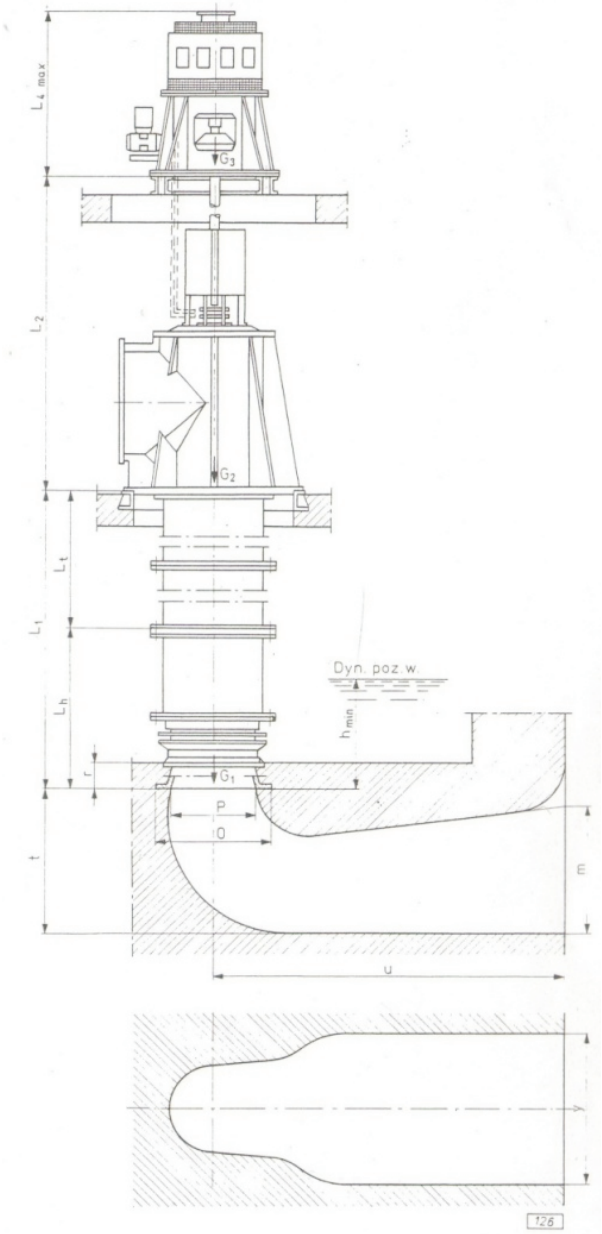

Figure 7 Scheme of the pump casing with a vertical axis [9]

Before starting the shape optimization procedure and solving N-S equations, it is necessary to make a mathematical description of the suction intake wall geometry and the method of its modification. Secondly, a generation method of the computational mesh for every acceptable geometry modifications is to be developed. A graphical representation of shape changes for the procedure control, whose aim is, for instance, to omit "significant errors" unforeseen by the computational model, is also a desirable element (although not necessary).

For the iteration optimization process to be effective, the decision variables describing shapes and sizes of the suction intake should modify automatically the geometry.

In designing the optimal formed suction intakes, the parameters of the fluid outlet plane, determining the structure of the flow at the pump impeller, are important. Pump impellers are usually designed by assuming no initial angular momentum flow (pre–rotation). The circumferential velocity is equal to zero $V_u = 0$. Consequently, both the average value V_u and its value at any point of the intake section of the pump impeller should be close or equal to zero.

On the basis of the analysis of components of the circumferential velocity distributions for different versions of the suction intake design, a proposed objective function is used to search for solutions with the lowest possible energy. The above is associated with the value V_u and restrictions resulting from the maximum fluid angle of attack $\alpha = 2 \div 6\,^{\circ}$ at the leading edge of the impeller blade.

$$F_1 = e_u = u_{lok}\,|V_{u,\,lok}| \tag{2}$$

The second objective function is proposed to attain the smallest possible value of the non-uniform velocity profile at the outlet of the formed suction intake plane (cross-section in front of the impeller). The function is closely related to the criteria specified by standard [1] for a non-uniform velocity profile. This function is calculated from the formula:

$$F_2 = \max\left\{\left|\frac{\mathrm{V}_a - (\mathrm{V}_a)_{sr}}{(\mathrm{V}_a)_{sr}}\right| * 100\%\right\} \tag{3}$$

The values (V_a) and $(\mathrm{V}_a)_{sr}$ are computed at the outlet section of the formed suction intake outlet plane (cross–section in front of the impeller) with a radius, which is less than the radius which will follow if we consider the wall thickness at the boundary layer. For these two optimization criteria defining the global objective function F_p, two weight factors w_1 and w_2 are used. The sum $w_1 + w_2$ is equal to 1.

The value of the partial objective function must be normalized by the min-max method, with the following formula:

$$F_i' = \frac{F_i - F_{i,\min}}{F_{i,\max} - F_{i,\min}} \tag{4}$$

The global objective function is calculated with equation 2.5 for different weight factors.

$$F_p = w_1 F_1' + w_2 F_2' \tag{5}$$

The preliminary calculations of the flow parameters in the formed suction intake allow one to determine the sensitivity of design variables to the objective function.

Among the parameters that describe the shape of the formed suction intake such as decision variables, five parameters indicated in Fig. 8 were also selected on the basis of these calculations, namely:

X_1 - cross-section width of the horizontal part of the suction intake,

X_2 - cross-section height of the horizontal part of the suction intake,

X_3 - distance from the pump axis to the end of the horizontal part of the suction intake,

X_4 - length of the horizontal part of the suction intake,

X_5 - diameter of the outlet from the formed suction intake.

The decision variables selected after the sensitivity analysis are shown in Fig. 8. During the optimization process, changes in the value of the objective function are observed. On the basis of these changes, a direction of the improvement in the objective function is defined by a gradient function which is opposite to the direction of increase in the value of the objective function.

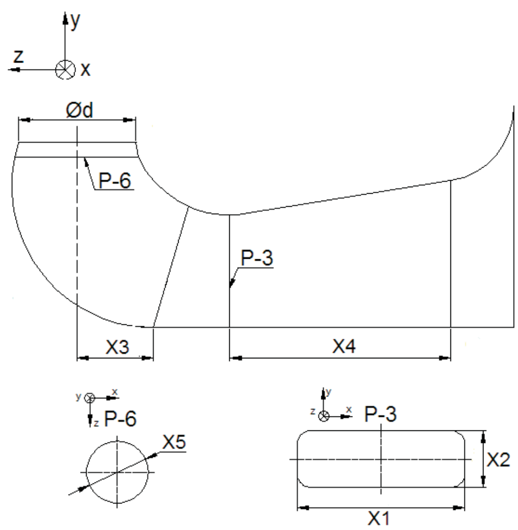

Figure 8 Design variables

This criterion occurs in the algorithm in order to determine the permissible difference between the values of successive iterations.

Figure 9 shows the developed algorithm of the design methodology for the optimal formed suction intake [11].

Due to the key meaning of the developed design method of the formed suction intake, the objective function will be described in the next chapter in detail.

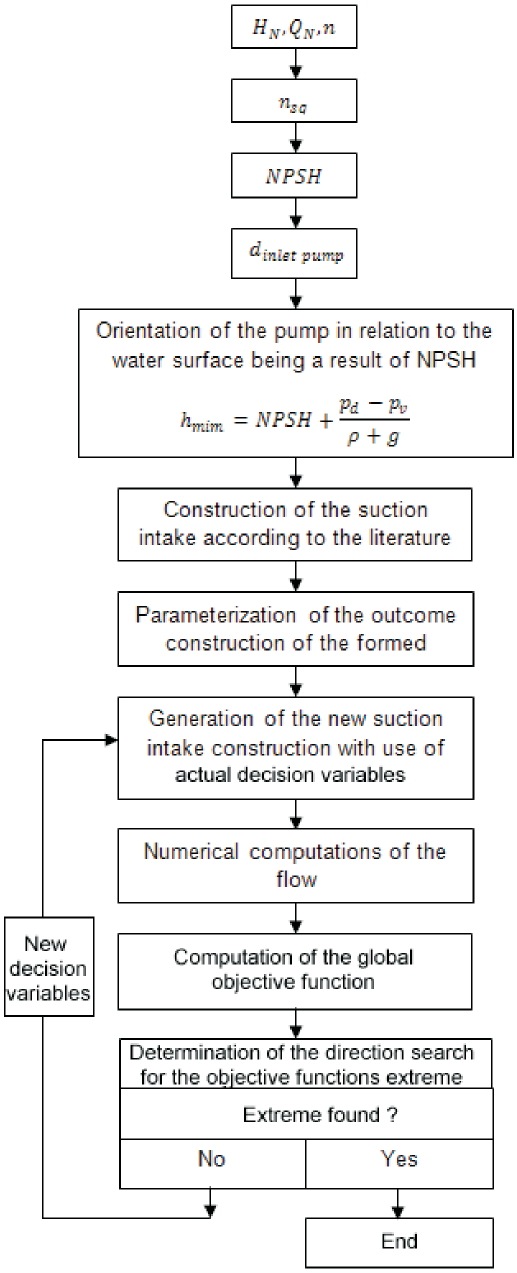

Figure 9 Design method algorithm

3. Numerical computations of steady flowsin the suction intake

3.1. *Scheme of the numerical computations*

Numerical computations of the flow in this method are proposed to be carried out with the ANSYS CFX software. This software is used in numerical computations of the flow in suction intakes, whose results were described in [3].

Numerical computations require:

- modeling of the geometry and the computational mesh generation,
- adoption of the boundary conditions.

3.2. *Geometry of channels and a computational mesh*

In order to model the geometry and generate a computational mesh for the analyzed variants of designs of suction intakes, the ANSYS CFX software is used. In Fig. 10, an example of geometry and a computational mesh of inflow channels for an exemplary suction intake construction variant are shown.

In Fig. 10, a flow direction of the liquid through the above mentioned channels is marked as well.

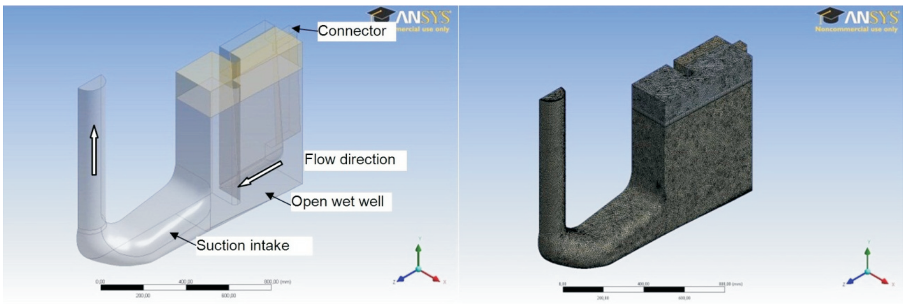

Figure 10 Geometry and a computational mesh for the connector, the open wet well and the formed suction intake

Due to the symmetry in relation to the flow direction in the suction intake, the open wet well and the connector, computational meshes for a half of the intake geometry were generated. The adopted method for the mesh generation eliminated differences of meshes for the both sides of the symmetry plane of intakes.

3.3. *Boundary conditions*

For the numerical computations of flows in the suction intake, outflow parameters from the connector of inlet channels were assumed.

In the computations of flow parameters at the outlet of the connector, the following boundary conditions were assumed:

- inlet to the inflow channels – mass flow, dependent on the investigated variant of the geometry and flow parameters of the liquid in intakes,
- outlet of the connector – opening pressure and dimensions, the assumed value of pressure is 0 [Pa],
- turbulence intensity at the level of 5%,
- zero gradient of pressure in the direction of the main flow (this condition is assumed internally by the ANSYS-CFX preprocessor).

In order to carry out the computations in inflow channels, it is necessary to assume additionally:

- walls hydraulically smooth with a slowdown of the fluid at the wall,
- a SST turbulence model,
- a logarithmic distribution of the velocity at the wall, the so-called wall function,
- constant fluid temperature,
- automatic timestep change.

For the computations in the suction intake, the following boundary conditions are proposed:

- inlet – a velocity profile distribution from the outlet of the connector,
- outlet – static pressure,
- turbulence intensity computed at the outlet of the connector.

In order to carry out the computations, it is necessary to adopt additionally:

- hydraulically smooth walls without motion,
- a SST turbulence model,
- a logarithmic distribution of the velocity at the wall, the so–called wall function,
- constant temperature of the fluid,
- automatic timestep change.

4. Optimal design of the suction intake

In order to design a formed suction intake, the algorithm shown in Fig 9 was used.

The optimization was conducted for a model of the suction intake operating in the 458MW power unit in Polish Ptnów II Power Plant. The optimization procedure used the IFFCO method described in detail in [6]. The partial objective functions F_1 and F_2 are defined by equations (2.2) and (2.3).

Figure 11 shows a multi–objective solution. Each point denotes one CFD computation in the optimization process.

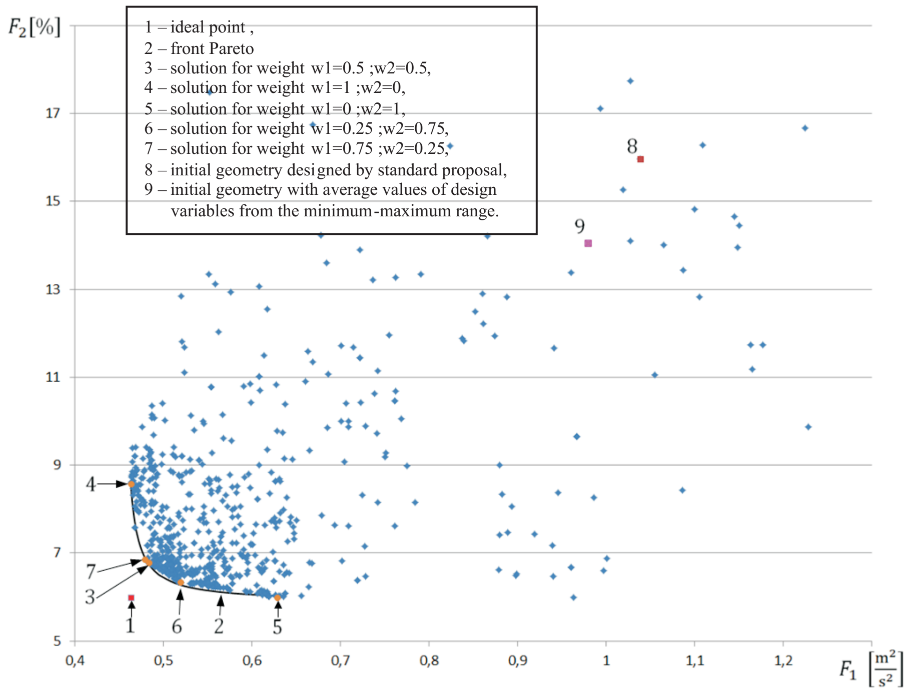

Figure 11 Pareto solution to the formed suction intakes in the domain of objective functions

A 3D model of a single solution (for the weight $w_1 = 0.5$ and $w_2 = 0.5$) of the suction intake before and after the optimization is shown in Fig. 12.

In Table T-1, decision variables and objective function values for the suction intake model before and after the optimization are collected.

On the basis of Fig. 12 and the data collected in Table T-1, it can be stated that the model geometry differs significantly before and after the optimization.

In order to explain causes of the improved fluid inflow at the pump impeller, maps of the circumferential V_u and axial components V_a of velocity, used to determine a value of the objective function, have been compared. Velocity maps for nominal operating conditions of the suction intake can be seen in figures.

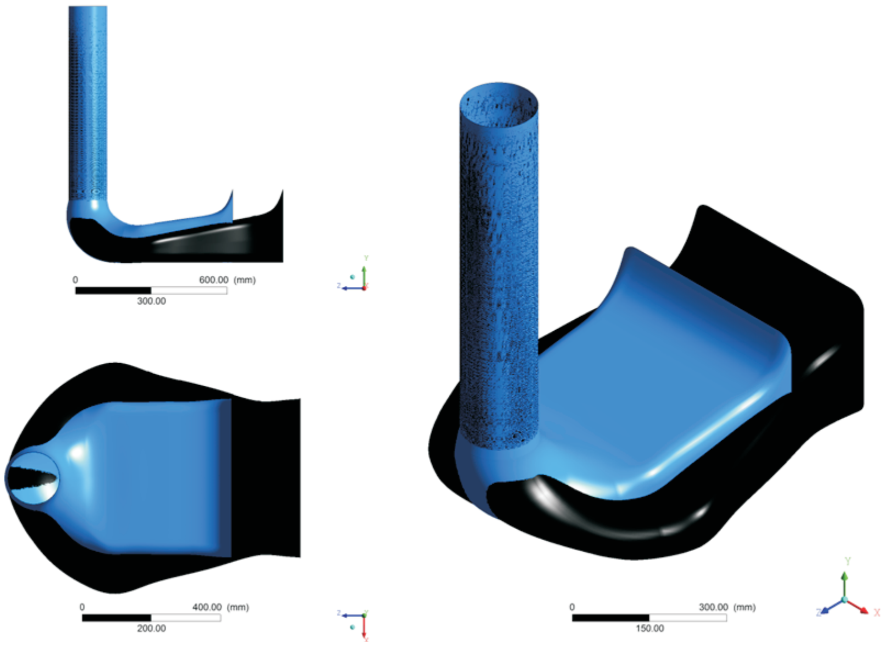

Figure 12 Suction intake before (blue) and after (black) the optimization process for the weight factor $w1 = w2 = 0.5$

In Figs 13 and 14, the flow direction of the fluid at the suction complies with the marked Z axis.

While comparing the introduced velocity distributions, significant changes in their values before and after the optimization have been noticed. These changes concern especially distributions of the velocity circumferential components V_u at the outlet of the suction intake. There are limited zones which before the optimization were present at the maximum values of V_u, and which have been equalized on the whole intake outlet surface. A similar remark refers to the velocity axial components V_a.

To summarize, one can state that the introduced parametric modifications after the optimization of geometrical parameters have caused particularly significant changes in velocity distributions, improving thus conditions of the fluid inflow at the pump impeller.

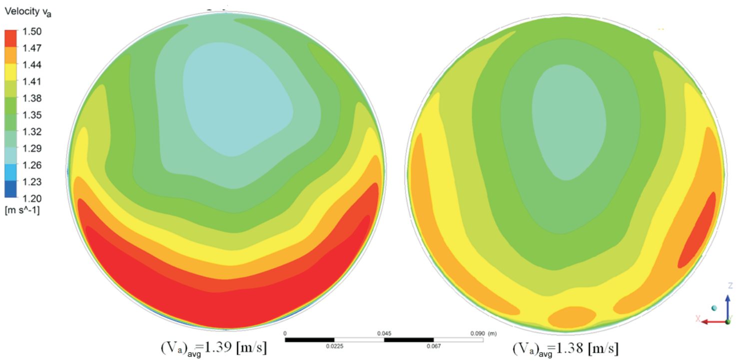

Figure 13 Distribution of the axial velocity component in a model of the suction intake before and after the optimization

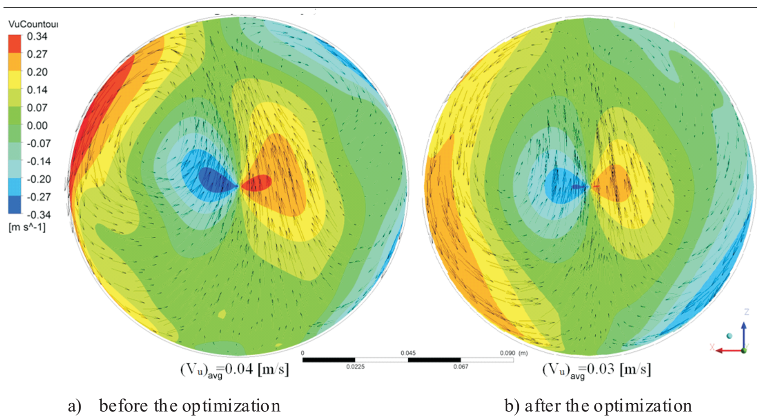

Figure 14 Distribution of the velocity circumferential component in a model of the suction intake, before and after the optimization

5. Conclusions

The developed procedure algorithm enables one to the design optimal suction intakes, which fulfill the adopted objective functions F_1 and F_2.

The intake geometries before and after the optimization are significantly different (Table T–1). The optimized intake is characterized by larger dimensions. The intake manufacturing cost is higher than before the optimization.

The final choice of a shape for the intake to be manufactured should involve its costs related to economical effects resulting from the improvement of inflow conditions at the pump impeller. Therefore, it is necessary to introduce the major objective function, whose criterion is the suction intake cost.

Decision variables before and after the optimization — *Table T-1*

		Decision variables					Objective function				
		X_1	X_2	X_3	X_4	X_5	F_1	F_2	F'_1	F'_2	F
		[mm]	[mm]	[mm]	[mm]	[mm]	[m^2/s^2]	[%]	[-]	[-]	[-]
Initial geometry (standard proposal)		147.0	438.0	106.0	247.0	160.8	1.039	15.964	0.503	0.558	0.531
Optimal geometry	w_1=0.5 w_2=0.5	101.8	668.6	126.9	424.8	149.5	0.483	6.780	0.028	0.054	0.041
	w_1=1 w_2=0	108.4	678.9	126.9	406.6	147.9	0,4630	8.5688	0.011	0.1521	0.0111
	w_1=0 w_2=1	88.2	695.8	126.8	494.0	150.9	0.629	5.985	0.153	0.010	0.010
	w_1=0.25 w_2=0.75	89.7	674.5	126.1	429.8	151.2	0.519	6.335	0.059	0.029	0.037
	w_1=0.75 w_2=0.25	103.7	668.6	126.1	424.8	149.5	0.49	6.85	0.024	0.058	0.033

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