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Optimization of Microturbines for Combined Energy Sources Based on Microhydropower Plants

A. V. Volkov, A. A. Vikhlyantsev, A. A. Druzhinin, A. V. Ryzhenkov, S. N. Pankratov, B. M. Orahelashvily, A. K. Lyamasov

Abstract*: This work discusses design issues of microturbines for combined energy sources based on microhydropower plants for the heads H≤20 m and the flow rates Q ≤1.20 m3/s. It is proposed to optimize microturbines. The main approaches to the formulated problem are described, optimization algorithm is analyzed exemplifying its embodiments for separate elements of microhydroturbines. The proposed approach has been verified. Experimental results of microhydroturbine optimization for simulated combined energy source based on microhydropower plant with the available head H =1.1 m, flow rates Q ≤0.021 m3/s and rotation frequency of electric generator n = 1000 rpm have been presented. On the basis of numeric simulation, the hydraulic efficiency of hydroturbine has been increased by 5.4% as a consequence of the proposed approaches.

***Keywords*: hydroelectric engineering, renewable energy sources, green technologies, combined energy sources, microhydroturbine.**

I. INTRODUCTION

Nowadays power supply facilities capable to accelerate and to implement distributed power generation become more and more popular. These facilities are based on the principle of combined generation of electricity and heat, cogeneration, preferably on the basis of renewable energy sources [1].

Among numerous renewable resources, the most important is hydroelectric engineering which is characterized by the most steady power potentials and, at the same time, by higher independence on destabilizing natural factors.

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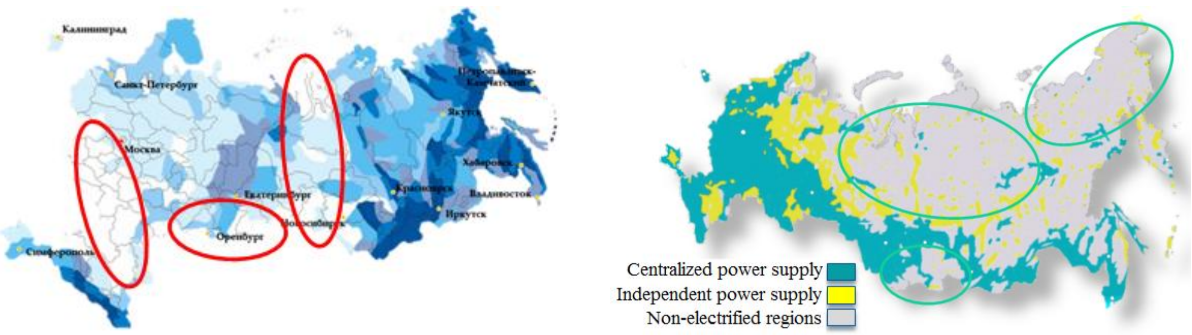
* Correspondence Author
A.V. Volkov*, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
A.A. Vikhlyantsev, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
A.A. Druzhinin, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
A.V. Ryzhenkov, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
S.N. Pankratov, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
B.M. Orahelashvily, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.
A.K. Lyamasov, National Research University 'MPEI' (NRU 'MPEI'), Moscow, Russia.

II. METHODS

A. General description

Most settlements with decentralized power supply in Russia are located in regions with the main hydropower potential presented by minor lowland rivers, hydraulic facilities and retention hydraulic systems (Fig. 1). In particular, such water resources are characterized by low available heads ($H \leq 20$ m) and low flow rate in river bed ($Q \leq 1.20$ m^3/s), which significantly hinders development of efficient power engineering equipment [2].



a) b)

Fig. 1: Modern state of water resources in Russia and opportunities of their efficient use: a) statistical analysis of Russian water resources; b) statistical data on independent consumers in the vicinity of water bodies and level of electrification.

At present combined energy sources based on microhydropower plants are under intensive development for operation in such environments. Taking into account their moderate power, the issue of reduction of payback periods is of great importance. This issue should be solved simultaneously in four fields:

- automation of operation process, self-diagnosis systems, and remote control;
- design optimization and decrease in equipment costs;
- development of energy efficient flowcharts;
- improvement of energy performances of hydroelectric units.

The latter field for combined energy sources based on microhydropower plants at present is one of the most important fields. The analysis of application fields of various types of hydroturbines demonstrated that upon low flow rates and delivery capacity, the most often applied were millwheel hydroturbines and free-stream hydroelectric units [3] characterized by low RPM. In order to provide the required quality of electricity, electric generator drive powered by such hydroturbines should be equipped with multiplier, and this fact concerning overall microhydropower plant can lead to significant increase in prime cost of the equipment comparable with expenses for erection of overall microhydropower plant.

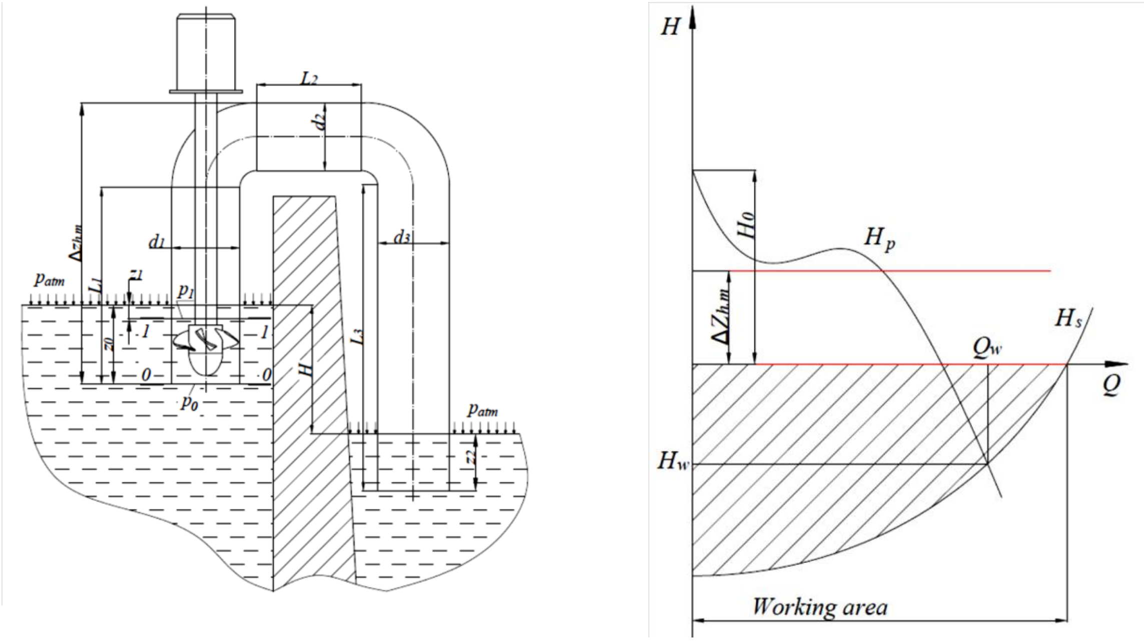
Application of axial hydroturbines in such situations eliminates the necessity to use multipliers, however, as evidenced in practice, their energy performances are rather low. For instance, axial hydroturbine designed for operation in microhydropower plant with available head $H = 1.1$ m, according to conventional procedures, can be characterized by hydraulic efficiency $\eta_{h.t} = 40$ %, although, according to various theoretical estimations, ultimate hydraulic efficiency of such hydroturbine varies in the range of $\eta_{h.t} = 60 \div 75\%$ or does not satisfy operability conditions of microhydropower plant. Existence of such high unachieved energy potential and additional requirements to hydroturbine evidence necessity to develop efficient optimization methods of hydroturbine regarding low flow rates and delivery capacity (microhydroturbine) for operation in combined energy sources based on microhydropower plant

B. Algorithm

Startup of facility is a crucial moment for energy source based on microhydropower plant. In microhydropower plant with water conduit in the form of siphon (Fig. 2*a*), microhydroturbine is actuated in pump mode and provides filling of the water conduit with subsequent transition to energy generation due to vacuum formation in the cross section 1-1 after microhydroturbine.

Moreover, most of the time microhydroturbine operates in the mode of energy generation (turbine mode), the most urgent issues are comprised of energy efficiency. Therefore, on the one hand, optimization of geometrical parameters of microhydroturbine requires for solution providing maximum hydraulic efficiency in operating mode Q_w at preset rpm of motor shaft n and available head H, and on the other hand, operability conditions are satisfied (Fig. 2*b*): microhydroturbine head required for water conduit filling is provided in pump mode $H_0 \geq \Delta Z_{h.m}$ at preset designed parameters Q_d , H_d and vacuum is formed after microhydroturbine for steady operation in energy generation mode. The latter of these conditions can be presented as follows: $H_w < 0$.

In terms of formulation, such problem is comparable with designing of reversible hydraulic machine which includes designing of hydroturbine such that minimum required head is provided in pump mode. However, upon such approach, the optimum turbine mode with maximum hydraulic efficiency $\eta_{h.t}$ can deviate significantly from operation mode. Using numerical simulation software in combination with multivariate optimization makes it possible to solve this problem in the most efficient way.



a) *b)*

Fig. 2. Operation principle of microhydropower plant with water conduit in the form of siphon: a) analytical flowchart; b) operability conditions.

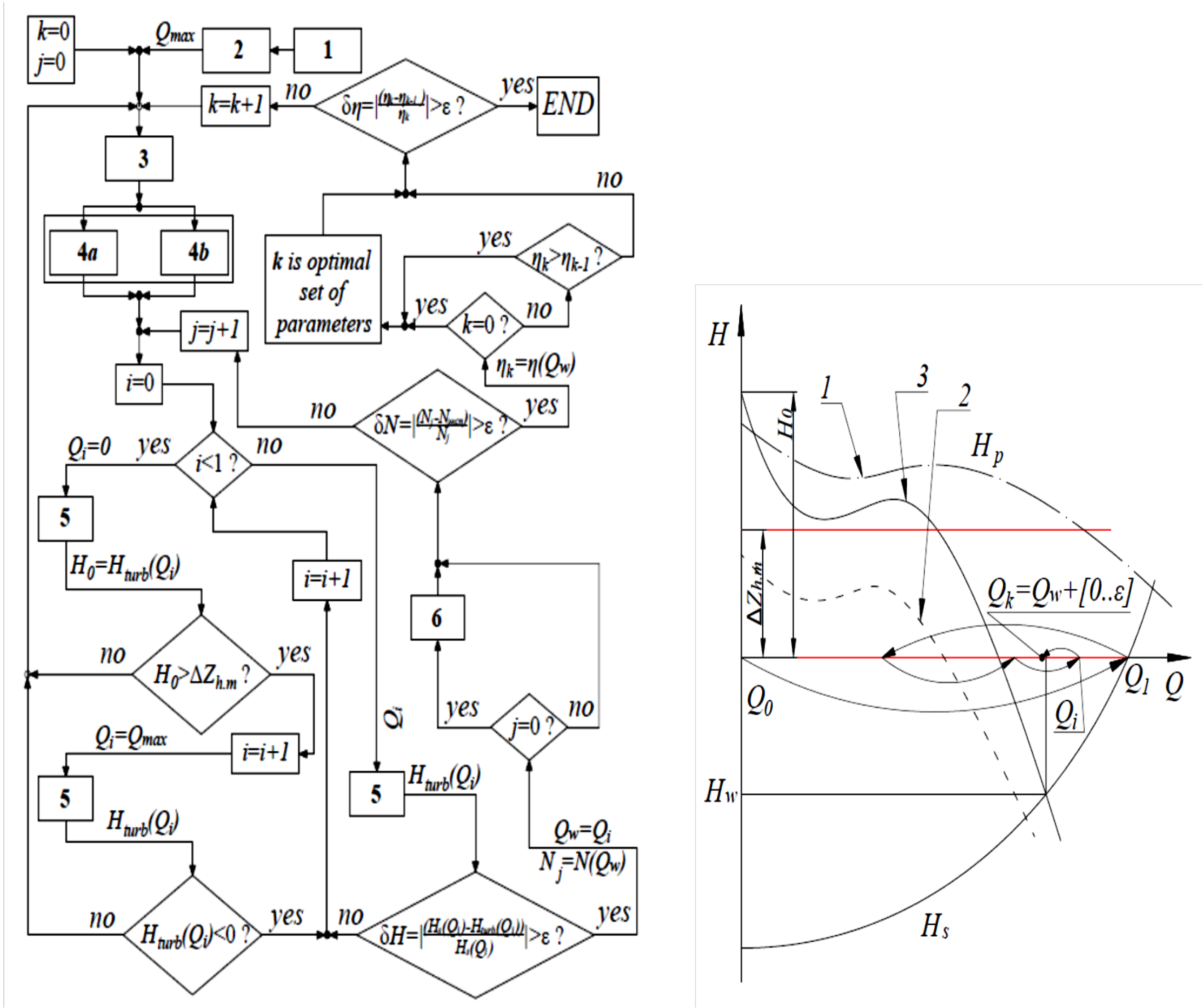
Figure 3*a* illustrates schematically iterative optimization algorithm of microhydroturbine. According to it, the optimization is performed in four stages:

1) Analysis of microhydropower plant system;
2) Definition of initial conditions;
3) Verification of analytical model;
4) Searching for optimum geometry.

At stage 1, on the basis of input data 1: available head H, RPM of generator shaft n, immersion depth of water conduit in upstream Z_0 and downstream Z_2, immersion depth of microhydroturbine Z_1, upper section of water conduit $\Delta Z_{h.m}$ and geometrical parameters of water conduit $L_1, L_2, L_3, d_1, d_2, d_3$ (see Fig. 2*a*), the characteristic $H_s(Q)$ of microhydropower plant system is plotted 2 (Fig. 2*b*) and boundary of working delivery capacities Q_{max} is determined (see Fig. 2*b*).

At stage 2, initial designed parameters of microhydroturbine 3 are preset: working variables (delivery Q_{d_0} and head H_{d_0}), geometrical variables depending on them (blade angles at wheel inlet β_{1_0} and outlet β_{2_0}, wheel diameter D_{1_0}, hub-tip ratio $\bar{d}_{hub_0}$, etc.), and additional variables: polynomial coefficients of equations determining regularities of variation of flow section area $F_0(L_3)$, blade angle $\beta_0(L_3)$, and angle of meridional projection $\lambda_0(L_3)$ along the length of water conveyance system. It should be mentioned that selection of initial conditions effects the time of searching for extreme value of target variable, thus, it is important to obtain good first approximation. With this aim, the first approximation should be based on experimental recommendations to designing of hydroturbine. Then, the first approximation of the microhydroturbine in meridional projection 4*a* and blades 4*b* are designed.

At stage 3, the numerical simulation 5, verification and adjustment of analytical model are carried out so that to provide maximum agreement with the experiment 6. It is important for elimination of errors at subsequent stage upon searching for extreme solution



a) b)

Fig. 3: Optimization of microhydroturbine:
a) schematic view of optimization algorithm; b) verification of boundary conditions.

As can be seen, such approach assumes numerous computations and design works. Computations can be minimized by stochastic methods of multivariate optimization for searching of extreme solutions. Design works can be minimized by approaches to designing of microhydroturbine elements which would allow simultaneously to automate the design process based on existing CADs and to expand possibilities to improve $\eta_{h.t}$ by means of fine tuning based on preset regularities of variation geometrical parameters. Such approach reflects modern trends in pump engineering [4-6], this experience should be applied for designing of hydroturbines and reverse hydraulic machines.

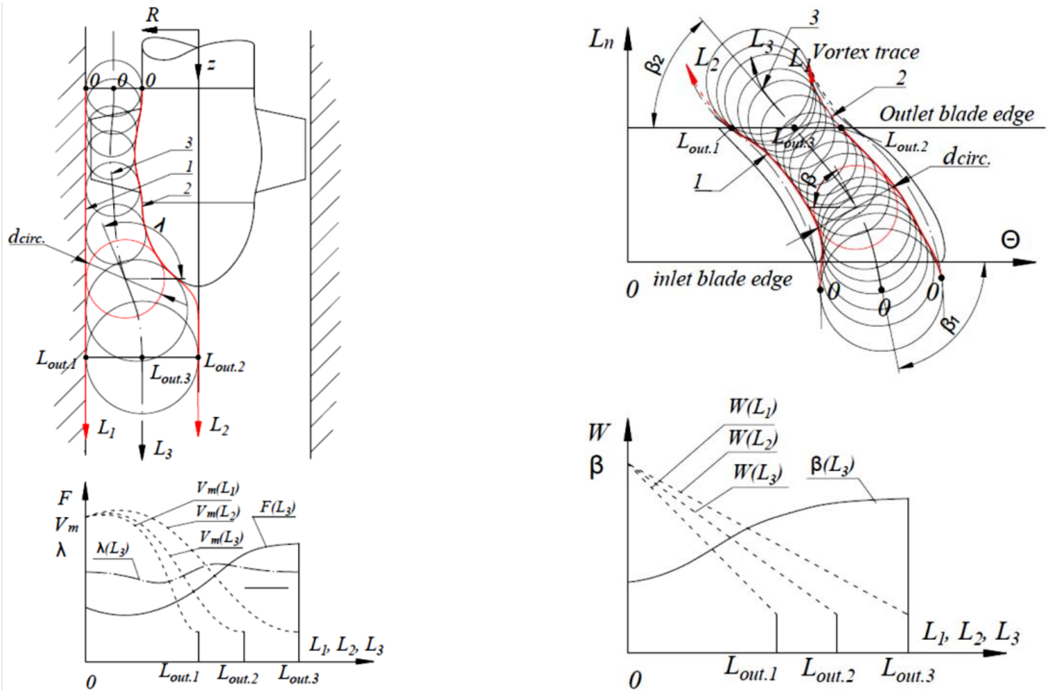
The essence of these approaches is in plotting of element walls in flow section of microhydroturbine (lines 1 and 2 in Fig. 4) by rolling circumference of variable diameter along flow center line (line 3 in Fig. 4) presented by parametric curve (1):

$$f = \begin{cases} R(s) \\ z(s) \end{cases}, \qquad (1)$$

where $s = 0 \div 1$ is the parameter; R, z are the coordinates of flow center line in cylindrical coordinates.

The variation law of circumference diameter $d_{circ.}(s)$ which is expressed by polynomial of the n-th order, Eq. (2), and geometry of the flow center line are directly related with flow hydrodynamic parameters: with meridional constituent of absolute velocity $V_m(L_{1,2,3})$ and relative velocity $W(L_{1,2,3})$, hence, they determine hydraulic losses and hydraulic efficiency of microhydroturbine $\eta_{h.t}$.

$$d_{circ.} = \sum_{m=0}^{n} a_m s^m \qquad (2)$$



a) *b)*

Fig. 4: Designing of sections of microhydroturbine:
a) meridional projection; b) flat pattern of cylindrical blade row

III. RESULT AND DISCUSSION

In the frames of the R&D project (unique identifier: RFMEFI58618X0060), the microhydroturbine was developed for prototype model of combined energy source based on microhydropower plant. Initial input data were based on design sizes of a typical for Russia low-head microhydropower plant with available head $H = 1.1\ m$ for commercial generator with n = 1000 rpm: $Z_0 = 0.230$ m, $Z_1 = 0.015$ m, $Z_2 = 0.080$ m, $\Delta Z_{h.m.} = 0.1$ m, $L_1 = 1.4755\ m$, $L_2 = 0.3905$, $L_3 = 0.430\ m$, $d_1 = d_2 = d_3 = 0.082\ m$. The designed parameters were assigned in accordance with the aforementioned recommendations. The results of designing were used for verification of operability conditions (Fig. 2*b*). The first approximation meeting these conditions was characterized as follows: $Q_{d_0} = 0.01$ m^3/s and $H_{d_0} = -0.12$ m with respective geometrical parameters: $\beta_{1_0} = 57° \div 37°$ and $\beta_{2_0} = 11° \div 27°$ (from hub), $D_{1_0} = 0.08$ m and $\bar{d}_{hub_0} = 0.5$. The meridional projection of microhydroturbine, according to the designed parameters, should satisfy the properties of classical axial turbine (*of Kaplan*), hence, the following law was adopted: $\lambda_0(L_3)$ and $F_0(L_3)$ described by Eqs. (3)÷(4). The law $\beta_0(L_3)$ in the first approximation was assumed to be linear:

$$\lambda(L) = \begin{cases} 90°, 0 \le L \le L_{hub} \\ 0{,}5(\lambda_{max} - 90°)\left[\sin\left(1{,}5\pi + 2\pi\left(\frac{L - L_{hub}}{L_{out} - L_{hub}}\right)\right) + 1\right] + 90°, L_{hub} \le L \le L_{out} \end{cases} \quad (3)$$

where L_{hub} was the length of microturbine hub; L_{out} was the coordinate of microhydroturbine outlet along the flow center line (Fig. 5*a*); λ_{max} was the maximum inclination angle of center line.

$$F(L) = \begin{cases} F_{in}, 0 \le L \le L_{hub} \\ k(L - L_{hub})^2 + F_{in}, L_{hub} \le L \le L_{out} \end{cases}$$

(4)

where $F_{in} = \frac{\pi D^2 (1 - \bar{d}_{hub}^2)}{4}$ was the flow section area at microturbine inlet; $F_{out} = \frac{\pi D^2}{4}$ was the flow section area at microturbine outlet; $k = \frac{F_{out} - F_{in}}{(L_{out} - L_{hub})^2}$ was the coefficient of polynomial of the second order *F(L)*.

After determination of initial conditions, the analytical model was verified (Fig. 5*a*) on the basis of designed microturbine in the first approximation satisfying operability conditions (Figs. 5*b*÷5*c*). The computational region includes the tank simulating upstream and a fragment of water conduit with microhydroturbine. The parameters and boundary conditions of the analytical model were preset in accordance with the recommendations [7-9] as summarized in Table 1.

Table 1: Variables of analytical model

Turbine model	RPM, n		Boundary conditions, (see Fig. 5*a*)		Number of analytical cells
			Surface description	BC	
SST	Downstream	0	Inlet	Pressure	700,000
			Inlet	Flow rate	

			Wall	Rough wall	
			Microhydroturbine inlet (side 1)	Sliding surface	
	Microturbine	150÷1,000	Wall	Rough wall	
			Wall	Rotating rough wall	
			Microhydroturbine inlet (side 2)	Sliding surface	
			Microhydroturbine outlet (side 1)	Sliding surface	
	Pipe to upstream	0	Outlet	Flow rate	
			Wall	Rough wall	
			Microhydroturbine outlet (side 2)	Sliding surface	

Predictions and experiments were compared with respect to $N(n)$: torsion torque on generator shaft of microhydroturbine without consideration for electromechanical losses. Verification results (Fig. 5*d*) are in good agreement with experiment, thus, it has been concluded that the applied analytical model is reliable.

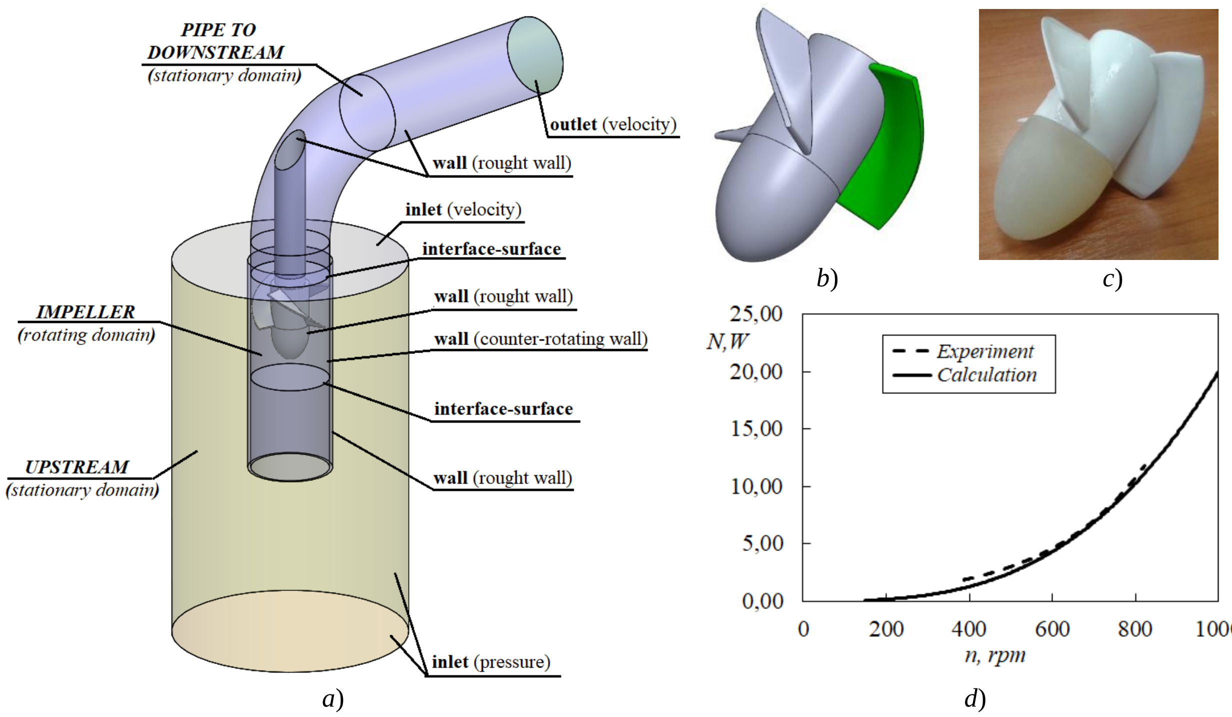
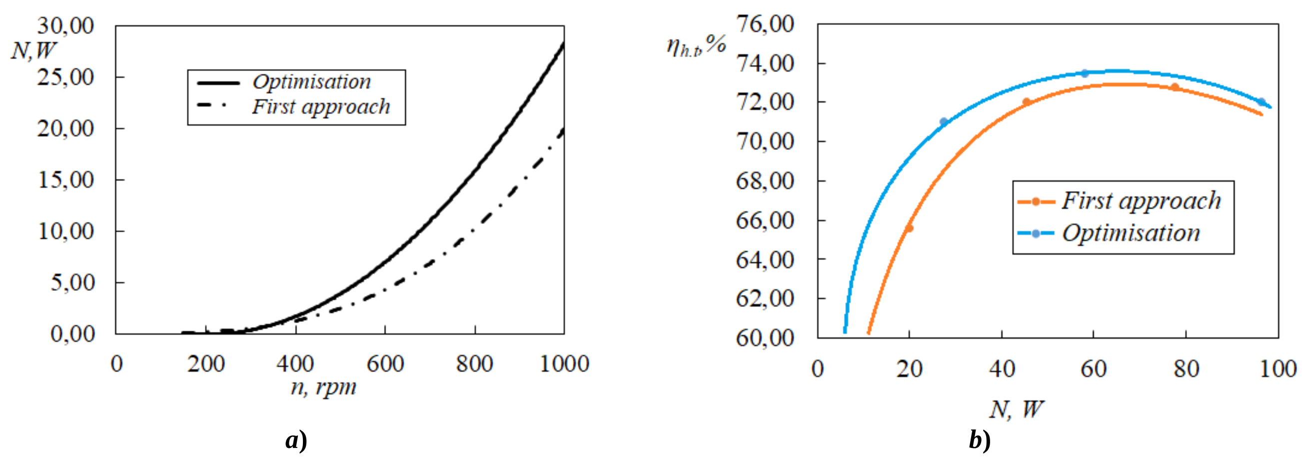
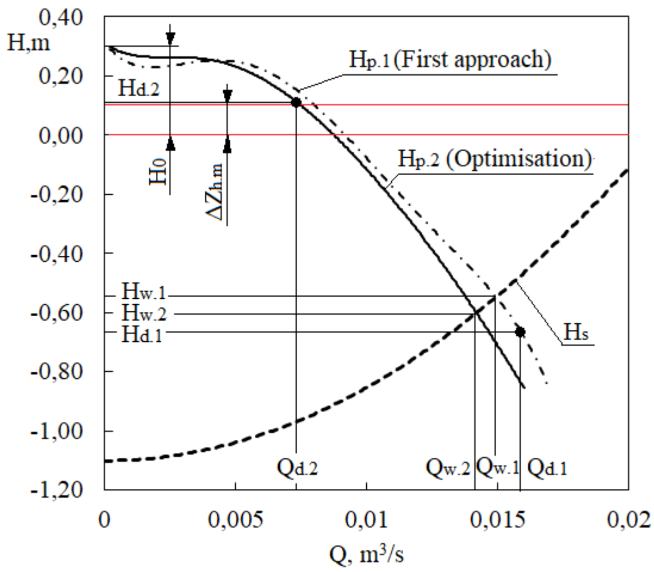


Fig. 5: Experimental verification of analytical model: a) boundary conditions of analytical model; b) 3D model of microhydroturbine; c) prototype model fabricated by FDM technology; d) N(n) of microhydroturbine.

A series of subsequent predictions made it possible to optimize microhydroturbine and to provide better energy performances in comparison with the first approximation (Figs. 6*a*-6*b*). As shown by the predictions, the maximum hydraulic efficiency of the first approximation of microhydroturbine is 71% in comparison with 65.6% of its optimized variant. Herewith, as illustrated in Fig. 6*c*, operability conditions are satisfied.





c)

Fig. 6: Optimization of microhydroturbine: a) N(n) of microhydroturbine; b) performance $\eta_{h.t}(N)$; c) flow rate/drop performance

IV. CONCLUSION

The obtained experimental results make it possible to conclude that the considered optimization of microhydroturbine can be successfully applied to combined sources based on microhydropower plant with the heads $H \leq 20$ m and the flow rates of $Q \leq 1.20$ m^3/s.

In the frames of the project, the input data have been analyzed, the initial conditions for optimization have been formulated, the analytical model has been verified using the first approximation of microhydroturbine with subsequent iterated optimization. On the basis of numerical simulation, the hydraulic efficiency of hydroturbine has been increased by 5.4% in comparison with the first approximation.

It should be mentioned that, since the verification results are in good agreement with the experiments, analysis of the predicted trends is sufficient background to expect similar experimental trends.

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