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ANALYSIS OF TURBINES FOR MICRO-HYDROPOWER PLANTS AND USING THE TURBULENCE MODEL

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Abstract

One of the biggest challenges in the world today is access to safe and affordable electricity. As a cost-effective source of renewable energy, the use of "Micro HPP" in the flow of rivers or canals is currently becoming popular in our country. In this article, the types of micro HPP turbines and their application are technically divided into types and studied based on the turbulence model using the example of the Kaplan turbine. The rotation speed of the Kaplan turbine at different water consumption is compared with the experimental results and the results obtained in the modeling. In addition, the Comsol Multiphasic 6.1 program was used to calculate the efficiency of the studied turbine at different water consumption and water flow rates.

Keywords: Micro HPP, water consumption, water pressure, Kaplan turbine, Comsol Multiphysics 6.1.

1. Introduction

Hydropower refers to the kinetic and potential energy accumulated in the flow of water masses in channel watercourses and watercourses. A hydroelectric power plant (HPP) is a power station that converts the kinetic and potential mechanical energy of water flow into electrical energy [1-2].

The power generated in a hydroelectric power station can be determined from the following expression:

$$P = \rho g Q H_n \quad \text{(kW)} \quad (1)$$

Here P- generated power (kW), Q- water flow (m^3/s), g- gravitational acceleration (m/s^2), H_n - head (m), η_t –turbine efficiency, η_g - generator efficiency.

A large HPP is a complex technical device consisting of a large number of technological equipment, including: a dam, hydraulic turbines, electric generators, aqueducts, etc. The construction of a large hydroelectric power station is associated with long construction periods and requires a lot of money. The environmental safety of the electricity generation process at hydroelectric power plants located on low-lying rivers often carries the risk of flooding large areas. In the hydroelectric power plants near the dam, the water level rises with the help of the dam and the necessary pressure is created. The HPP building is placed in 3 different ways: 1) next to the dam; 2) far from the dam; 3) below the dam, in the riverbed. HPP built near the dam and in the riverbed create water pressure. Such hydroelectric power plants are built in the narrow places of streams and mountain rivers with a lot of water [3].

Although the classification of hydroelectric power plants is divided into types by different criteria in different countries, depending on the installed capacity, hydroelectric power plants in the world are as follows (presented in Table 1).

Table 1. Classification of hydropower plants by production capacity [4-5].

Type	Power
Pico HPP	<0.5 kW
Micro HPP	0.5 – 100 kW
Small HPP	100 - 1000 kW
Medium HPP	1 MW – 10 kW
Large HPP	> 10 kW

Currently, scientific research is being conducted on the use of renewable energy sources, including micro hydroelectric power stations, and their application to agriculture. Micro HPP refers to low-power (up to 100.0 kW) power plants used to generate electricity by converting the energy of water into electricity.

The turbine converts the energy in the water into mechanical energy. There are different types of turbine and they can be classified in several ways. According

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to the principle of operation, all types of hydro turbines used in micro hydropower plants are divided into active and reactive groups [6-7]. Active turbines mainly use the kinetic energy of open-flowing water. The simplest type of active hydraulic turbine is a water wheel driven by the energy of the water flow. It has long been used in the irrigation systems of Egypt, India, China, and other countries, and later - to drive water mills, working machines, and mechanisms of small industrial enterprises. Active turbines are high and work effectively at low pressures. Jet turbines mainly use the potential and kinetic part of the flow energy. Jet turbines are effective at low pressure and high flow rates [8]. Water pressure plays an important role in the selection of turbines. In table 2 below, the operation of turbines according to water pressure can be divided into 3 groups.

Table 2. Turbines classification according to water pressure: [8]

Turbine type	**At high pressure (> 50m)**	**At medium pressure (10-50 m)**	**At low pressure (< 10m)**
Avtiv	Pelton, Turgot	Intercurrent, Turgo	Cross-flow
Reactive	Frances	Francis Kaplan	Kaplan, Propeller

Examples of active turbines are Pelton, Turgo and Cross-flow turbines and there are various other types. Reactive types of turbines include to, Francis Propeller Kaplan turbines.

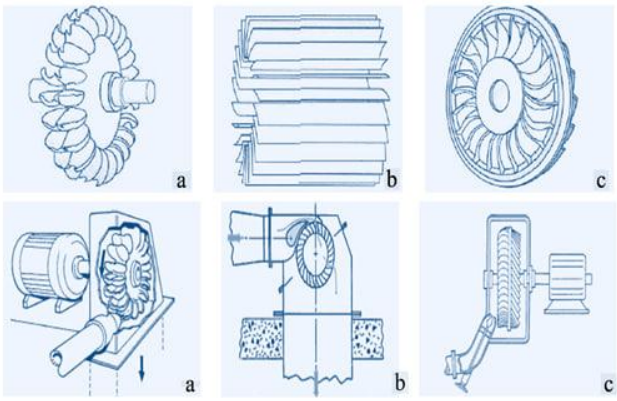


Figure 1. Types of active turbines. a- Pelton turbine and installation, b- O cross-flow turbine and installation, c- Turgo turbine and installation [9-10].

The crossflow active was invented by Professor Donat Banki of the University of Budapest. The main characteristic of cross-flow (shape b in Figure 1) is the two-way energy exchange that occurs when the water hits the blades at the inlet and outlet of the hollow rotor.

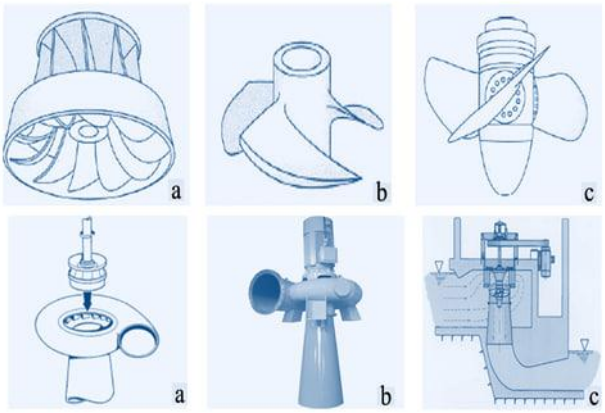


Figure 2. Types of jet turbines. d-Francis turbine and installation, e- Propeller turbine and installation, f- Kaplan turbine and installation [11-13].

The use of two working phases does not provide special advantages, except that it is a very efficient and simple method of exiting the water flow from the rotor. Cross-flow turbines are highly efficient at water pressures between 0.5 and 200 meters [14]. But Kaplan and Francis turbines are more efficient than cross-flow turbines.

The main advantages of the cross-flow turbine include its low cost, ease of operation and ease of installation due to its simple construction. The cross-flow turbine is mainly installed in small and micro hydroelectric power stations in river tributaries and streams [15].

At medium and high water pressure, Francis turbines of the jet type are used in the range of approximately 30 - 250 meters (Fig. 2 d). A Francis turbine is completely submerged in water, and when passing through the turbine, the pressure and velocity of the water decreases, and the water enters radially through the annular channel surrounding the turbine impeller, between the stationary blades that guide the turbine, and displaces it in the axial direction [16].

Francis turbine is mainly divided into two types and they are open water flow and closed water flow. The disadvantage of the open-water type turbine is that the rotating and guide vane mechanism is under water and cannot be repaired or inspected [17]. In the closed water flow type, the turbine is attached to the helical casing and water is supplied to the turbine through a water transfer pipe. The open water flow Francis turbine is used for areas with water pressure up to 10 meters. Closed water flow French turbine is used for places with water height above 30 meters.

When the Kaplan turbine (Fig. 2, form f) is operated in axial flow, the guide blades can control the flow rate by opening or closing the turbine [18-22]. When it is completely closed, the water stops completely and brings the turbine to rest [11-13]. The

Kaplan turbine is more efficient in low-pressure areas (Figure 3) with high flow rates.

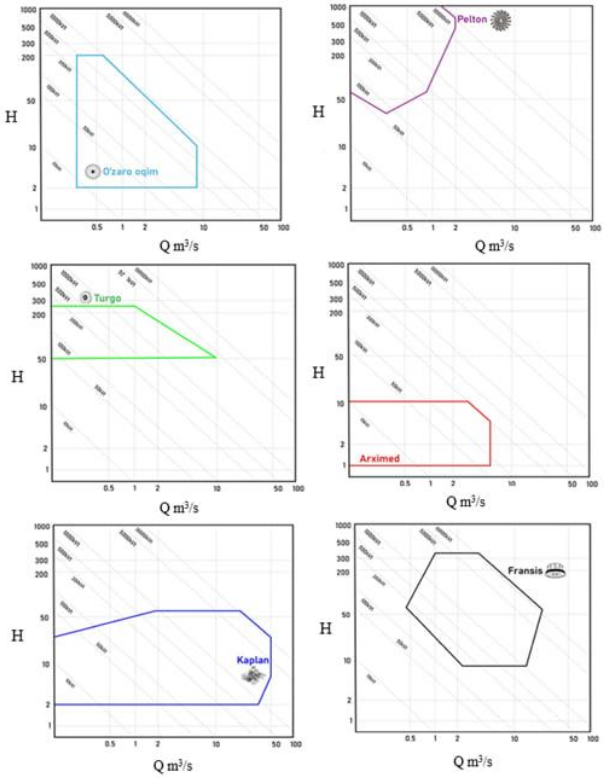


Figure 3. Graph of dependence of water pressure and consumption of turbines (based on Escher Wyss diagram).

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Kaplan turbine with water pressure from 1.5 to 35 m and flow consumption from 1.5 m^3/s to 200 m^3/s and power from 20 kW Up to 20,000 kW used in places. The main disadvantage of Kaplan turbines is their high cost.

Table 2. Kaplan turbine features:

Types of hydro turbines	vertical, horizontal (S), capsular, and Z-shaped
Working wheel diameter	From 560 mm to 5500 mm
Number of wings	3, 4, 5 or 6
Head range	From 1.5 to 50 m
Water consumption	From 1.2 to 200 m^3/s
Power	From 20 to 20,000 kW

There are 3 types of Kaplan turbines: vertical axis, horizontal axis (also called S-turbines) and capsule turbines. In addition, the Kaplan turbine is also available in the Z type, which is rarely used.

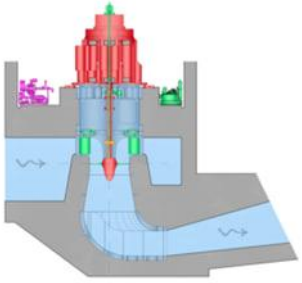


Figure 4. Kaplan turbine with vertical axis [21-22].

Vertical turbines are designed to use water energy at relatively low pressures.

Type	**Vertical axis**
Working wheel diameter	From 850 mm to 5500 mm
Number of wings	4, 5 or 6
Pressure range	From 1.5 to 50 m
Water consumption	From 3.5 to 200 m^3/s
Power	From 70 to 20,000 kW
Connection type	direct connection

Table 3. Characteristics of vertical axis Kaplan turbine

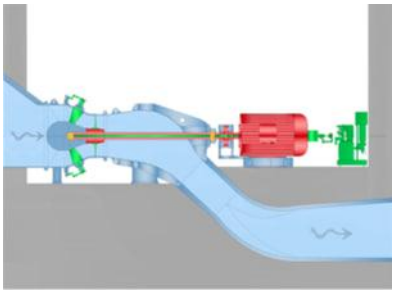


Figure 5. Kaplan turbine with horizontal axis [21-22].

Horizontal axis (Fig. 5) or "S-turbines" are preferred for higher pressure flow. These turbines are usually equipped with a gear train that connects to the generator

Table 4. Characteristics of the horizontal-axis Kaplan turbine:

Type	**Horizontal axis**
Working wheel diameter	From 560 mm to 1450 mm

Number of wings	4 or 5
Pressure range	From 1.5 to 15 m
Water consumption	From 1.2 to 14.5 m^3/s
Power	From 20 to 1750 kW
Connection type	via direct connection or reducer

Capsule type Kaplan turbines are located inside the mainstream. Horizontal axis and capsule turbines are technically slightly more efficient than vertical axis ones because they do not have to change the direction of the inlet flow, thus reducing hydraulic losses.

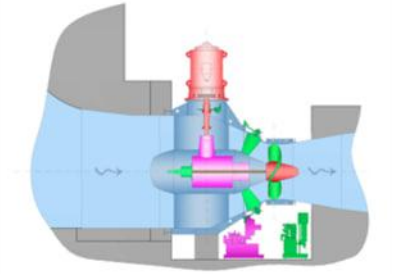


Figure 6. Capsule-type Kaplan turbine [21-22].

Table Features of capsule type Kaplan turbine:

Type	Capsule type
Working wheel diameter	From 1050 mm to 2500 mm
Number of wings	3 or 4
Pressure range	From 1.5 to 12 m
Water consumption	From 5 to 45 m^3/s
Power	From 100 to 3000 kW
Connection type	direct connection, through a reducer

The Z-type Kaplan turbine is also located inside the mainstream. Compared to the vertical axis, it is used in places with low water consumption and low power.

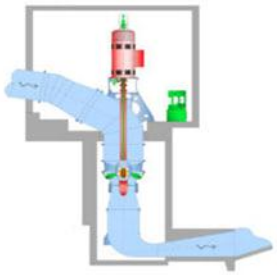


Figure 7. Z type Kaplan turbine [21-22].

Table 6. Features of the Z-type Kaplan turbine:

Type	Z type
Working wheel diameter	From 560 mm to 1450 mm
Number of wings	4 or 5
Pressure range	From 1.5 to 15 m
Water consumption	From 1.2 to 14.5 m^3/s
Power	From 20 to 1750 kW
Connection type	direct connection, through a reducer.

All of the rules of Kaplan turbines are specified for nominal operation and the best efficiency point it confirms that such design rules have hardly evolved over the past half-century. Almost all studies found in the last three decades are case studies limited to model tests or numerical simulations by CFD. Some of them mainly focus on special issues such as cavitation, hydraulic vibration, rotor-stator interaction, and abrasive erosion. As a result, no significant hydro-mechanical relationships were found in the Kaplan turbine. In addition, the study of the hydrodynamics of the Kaplan turbine lags behind that of the Francis turbine.

2. Materials and Methods

As the main parts of the Kaplan turbine, it is possible to specify the water supply parts - 1- spiral chamber, 2- guide apparatus, 3- working wheel, and 4- suction pipe. The turbine impeller is connected to the rotor by means of the 5th shaft. The shaft consists of two parts: the generator shaft and the turbine shaft. These parts are tightly fixed with each other using flanges. Vertical turbines are multi-bladed with only one wheel. Although the number of blades is 5 and 6 or more Kaplan turbines are found, it is advisable not to exceed 4 [26].

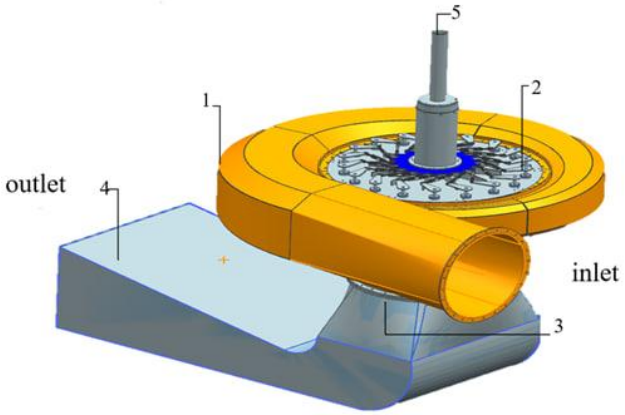


Figure 8. Kaplan turbine for micro hydropower plant.

There are two main approaches to modeling turbulence:

Physical models: These models are based on the Navier-Stokes equations that describe the motion of a liquid or gas. Such models can be very accurate, but require significant computing resources and time to solve the equations. Available models include direct numerical simulation (DNS) and Reynolds averaged equations (RANS). (Figure 9)

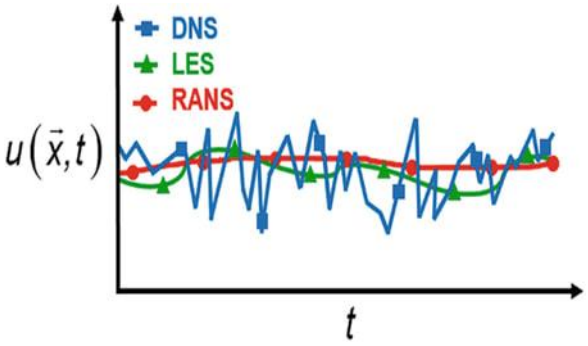


Figure 9. The main available approaches to turbulence modeling are DNS, LES, and RANS.

Statistical models: These models are based on statistical patterns observed in turbulent flows. It also looks like this when solved as a function of time. (Figure 9) They allow the prediction of mean velocity and other flow properties without the need to solve the detailed Navier-Stokes equations. Examples of statistical models are ke models and k-ω models.

Turbulence modeling capabilities are widely used in fields as diverse as aerodynamics, fluid dynamics, meteorology, and engineering applications. They help predict the behavior of turbulent flows, which can be important for design optimization or weather and climate forecasting [23-24].

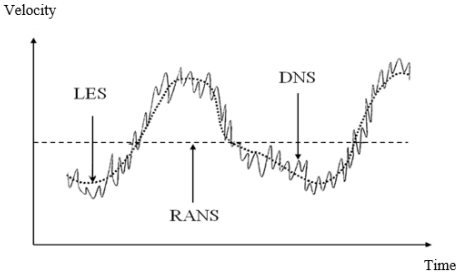


Figure 10. Time variation of the main available DNS, LES, and RANS approaches in turbulence modeling.

Turbulence modeling capabilities are widely used in fields as diverse as aerodynamics, fluid dynamics, meteorology, and engineering applications. They help predict the behavior of turbulent flows, which can be important for design optimization or weather and climate forecasting [23-24].

The most common is the Reynolds approach. Based on this approach, a system of Reynolds-averaged Navier-Stokes (RANS) equations is derived.

This paper is devoted to the modeling of hydrodynamic processes inside a micro-hydroelectric turbine, implemented on the basis of the Comsol Multiphysics 6.1 software package, where the three-parameter v2-f turbulence model is used [25].

3. Results

For process learning, the geometry is divided into 3,280,977 unstructured computational grids, which is presented in Figure 11.

For the numerical study of the given problem, the system of Reynolds-averaged Navier-Stokes equations is used [27].

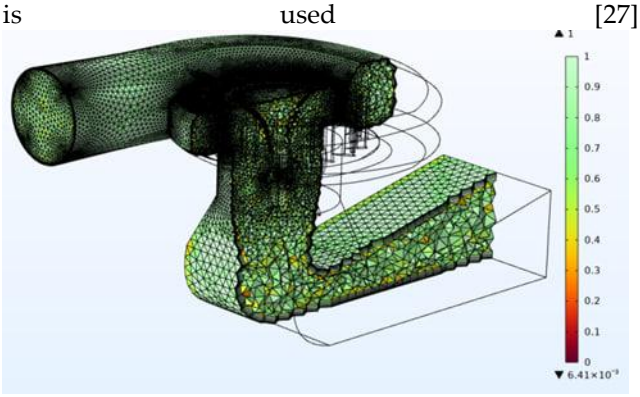


Figure 11. Unstructured computing network of micro HPP.

$$\begin{cases} \frac{\partial \rho}{\partial \tau}+\frac{\partial \rho \bar{V}_x}{\partial x}+\frac{\partial \rho \bar{V}_y}{\partial y}+\frac{\partial \rho \bar{V}_z}{\partial z}=0. \\ \rho\frac{\partial \bar{V}_x}{\partial \tau}+\rho\bar{V}_x\frac{\partial \bar{V}_x}{\partial x}+\rho\bar{V}_y\frac{\partial \bar{V}_x}{\partial y}+\rho\bar{V}_z\frac{\partial \bar{V}_x}{\partial z}+\frac{\partial \bar{p}}{\partial x}=\frac{\partial}{\partial x}\left(\nu\rho\frac{\partial \bar{V}_x}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\rho\frac{\partial \bar{V}_y}{\partial y}\right)+ \\ +\frac{\partial}{\partial z}\left(\nu\rho\frac{\partial \bar{V}_z}{\partial z}\right)-\frac{\partial \rho\overline{\vartheta_x\vartheta_x}}{\partial x}-\frac{\partial \rho\overline{\vartheta_x\vartheta_y}}{\partial y}-\frac{\partial \rho\overline{\vartheta_x\vartheta_z}}{\partial z}; \\ \rho\frac{\partial \bar{V}_y}{\partial \tau}+\rho\bar{V}_x\frac{\partial \bar{V}_y}{\partial x}+\rho\bar{V}_y\frac{\partial \bar{V}_y}{\partial y}+\rho\bar{V}_z\frac{\partial \bar{V}_y}{\partial z}+\frac{\partial \bar{p}}{\partial y}=\frac{\partial}{\partial x}\left(\nu\rho\frac{\partial \bar{V}_y}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\rho\frac{\partial \bar{V}_y}{\partial y}\right)+ \\ +\frac{\partial}{\partial z}\left(\nu\rho\frac{\partial \bar{V}_y}{\partial z}\right)-\frac{\partial \rho\overline{\vartheta_x\vartheta_y}}{\partial x}-\frac{\partial \rho\overline{\vartheta_y\vartheta_y}}{\partial y}-\frac{\partial \rho\overline{\vartheta_y\vartheta_z}}{\partial z}; \\ \rho\frac{\partial \bar{V}_z}{\partial \tau}+\rho\bar{V}_x\frac{\partial \bar{V}_z}{\partial x}+\rho\bar{V}_y\frac{\partial \bar{V}_z}{\partial y}+\rho\bar{V}_z\frac{\partial \bar{V}_z}{\partial z}+\frac{\partial \bar{p}}{\partial z}=\frac{\partial}{\partial x}\left(\nu\rho\frac{\partial \bar{V}_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\rho\frac{\partial \bar{V}_z}{\partial y}\right)+ \\ +\frac{\partial}{\partial z}\left(\nu\rho\frac{\partial \bar{V}_z}{\partial z}\right)-\frac{\partial \rho\overline{\vartheta_x\vartheta_z}}{\partial x}-\frac{\partial \rho\overline{\vartheta_y\vartheta_z}}{\partial y}-\frac{\partial \rho\overline{\vartheta_z\vartheta_z}}{\partial z}; \end{cases} \quad (1)$$

Here in the above equations $\bar{V}_x, \bar{V}_y, \bar{V}_z$ longitudinal and transverse components of the average flow velocity vector, respectively, p - hydrostatic pressure, ν- kinematic viscosity of liquid, ρ - Liquid density. This system of equations is considered open, and Bussinesque's hypothesis is used to close it.

$$-\rho\overline{\vartheta_i\vartheta_j}=2\mu_t S_{ij}-\rho\frac{2}{3}k\delta_{ij} \quad (2)$$

The last term on the right-hand side of Equation 2 represents the turbulent force per unit volume, where - turbulent dynamic viscosity, represents the pulsating speed of the liquid. Due to Reynolds stresses, the number of unknowns exceeds the number of RANS equations. Therefore, the v2-f turbulence model was used to close the equations.

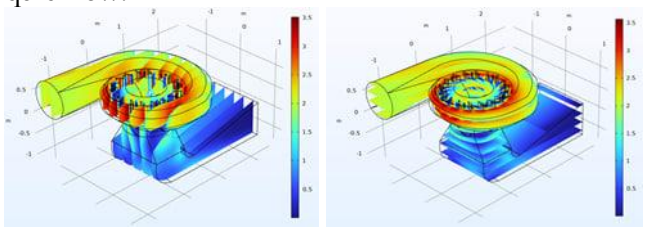
v2-f turbulence model: Near solid walls, the intensity of velocity fluctuations in the direction tangential to the wall is usually much greater than the intensity of fluctuations in the direction normal to the

wall. In other words, speed fluctuations are characterized by anisotropy. Moving away from the wall, the intensity of vibrations in all directions is the same. The velocity fluctuations are uniform or isotropic. The anisotropy of turbulent fluctuations in the boundary layer is described by introducing two additional equations solved together with the equations for the turbulence kinetic energy (k) and the kinetic energy dissipation rate (e) in the v2-f turbulence model.

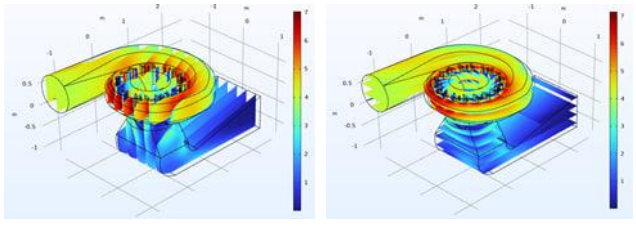
$$\begin{cases} \frac{\partial k}{\partial \tau}+\bar{V}_x\frac{\partial k}{\partial x}+\bar{V}_y\frac{\partial k}{\partial y}+\bar{V}_z\frac{\partial k}{\partial z}=P-\varepsilon+\frac{\partial}{\partial x}\left(\left(\nu+\frac{\nu^t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right)+ \\ +\frac{\partial}{\partial y}\left(\left(\nu+\frac{\nu^t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left(\nu+\frac{\nu^t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right), \\ \frac{\partial \varepsilon}{\partial \tau}+\bar{V}_x\frac{\partial \varepsilon}{\partial x}+\bar{V}_y\frac{\partial \varepsilon}{\partial y}+\bar{V}_z\frac{\partial \varepsilon}{\partial z}=\frac{1}{\tau}\left(C_{\varepsilon 1}(\zeta,a)P-C_{\varepsilon 2}\varepsilon(k,\varepsilon,a)\right)+ \\ \frac{\partial}{\partial x}\left(\left(\nu+\frac{\nu^t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\nu+\frac{\nu^t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left(\nu+\frac{\nu^t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right), \\ \frac{\partial \zeta}{\partial \tau}+\bar{V}_x\frac{\partial \zeta}{\partial x}+\bar{V}_y\frac{\partial \zeta}{\partial y}+\bar{V}_z\frac{\partial \zeta}{\partial z}=\left(1-a^3\right)f_w+a^3 f_h-\frac{\zeta}{k}P_k+ \\ +\frac{\partial}{\partial x}\left(\left(\nu+\frac{\nu^t}{\sigma_\zeta}\right)\frac{\partial \zeta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\nu+\frac{\nu^t}{\sigma_\zeta}\right)\frac{\partial \zeta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left(\nu+\frac{\nu^t}{\sigma_\zeta}\right)\frac{\partial \zeta}{\partial z}\right)+ \\ +\frac{2}{k}\left(a^3\nu+\frac{\nu^t}{\sigma_\zeta}\right)\left(\frac{\partial \zeta}{\partial x}+\frac{\partial \zeta}{\partial y}+\frac{\partial \zeta}{\partial z}\right)\left(\frac{\partial k}{\partial x}+\frac{\partial k}{\partial y}+\frac{\partial k}{\partial z}\right). \end{cases} \quad (3)$$

Here constants correspond to the creation and reduction of dissipation, respectively, and P_k is the turbulent energy production.

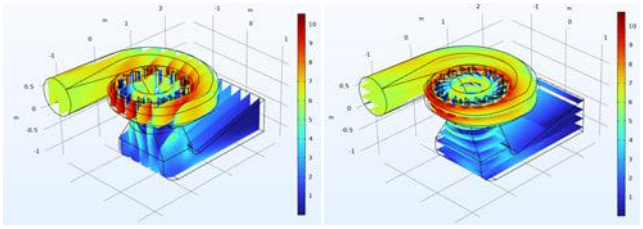
Turbulent viscosity is calculated as follows: The remaining coefficients and functions are presented in the article [7]. The main factor affecting the efficiency of micro HPP is the flow rate in the inlet pipe. Figure 12 shows isolators of the longitudinal and transverse sections of the velocity field at different speeds of the liquid flow.



Q=1 m³/s



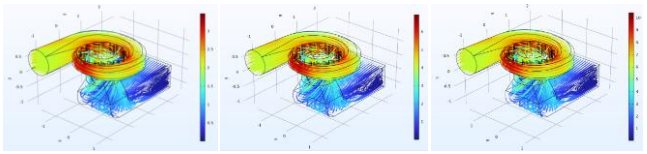
Q=2 m³/s



Q=3 m³/s

Figure 12. Isolines of the velocity field.

Figure 13 shows the streamline of the velocity field at different fluid flow rates.



Q=1 m³/s Q=2 m³/s Q=3 m³/s

Figure 13. Streamline the velocity field

Figure 14 shows the pressure drop at different flow rates.

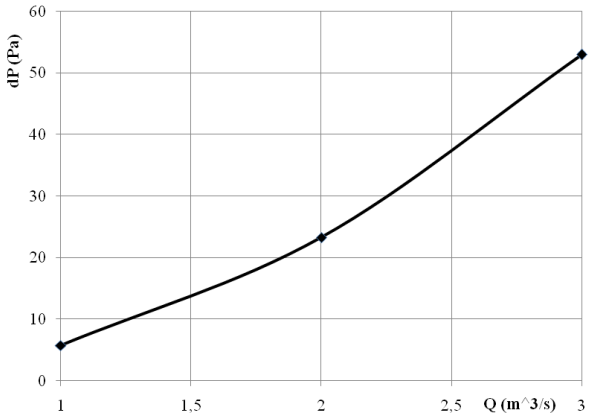


Figure 14 Pressure drop at different flow rates.

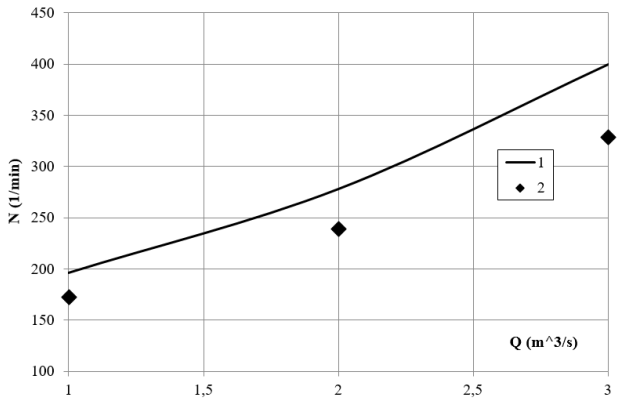


Figure 15 Pressure drop at different flow rates. 1-modeling results, 2-experimental results.

Figure 15 The number of turbine revolutions at different flow rates per minute.

5. Conclusions

Analyzing the turbines for micro hydropower, the Kaplan turbine is suitable for use at a low head of 2 m and water flow consumption of 1.5 m^3/s. In the article, water flow consumption from 1 m^3/s to 3 m^3/s the performance of a Kaplan turbine micro hydropower plant not connected to a generator was analyzed and compared with the modeling results. In the study, a numerical evaluation of micro HPP efficiency was carried out based on the modern v2-f turbulence model. According to the results of research and modeling, the number of revolutions in the Kaplan turbine is 172-180 rot/min at 1 m^3/s, 239-245 rot/min at 2 m^3/s, 328-340 rot/min at 3 m^3/s, and the modeling results are showed 196, 278, 328 rot/min respectively. The indicators allow us to determine the possibilities for this type of micro hydropower plant and to determine the influence of various parameters on their efficiency.

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