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Virtual Prototyping and Evaluation of Hydro Plant System with Crossflow Turbine †

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Abstract

The study presents an application of virtual prototyping and numerical analysis in engineering practice for an in-stream hydropower system. The performed analyses aimed to compare different design configurations of the crossflow turbine. All simulations use virtual prototypes and computational fluid dynamics to review design performance in detail under various environmental conditions. Specifics of mixed fluid flows are outlined. The major focus is on virtual prototype testing, aiming to demonstrate its ability to deliver fast results for complex, expensive structures. This work is a good example of the practical application of numerical analysis and virtual prototyping and demonstrates a specific, complex field, such as computational fluid dynamics.

Keywords: virtual prototyping; hydro plant; crossflow turbine

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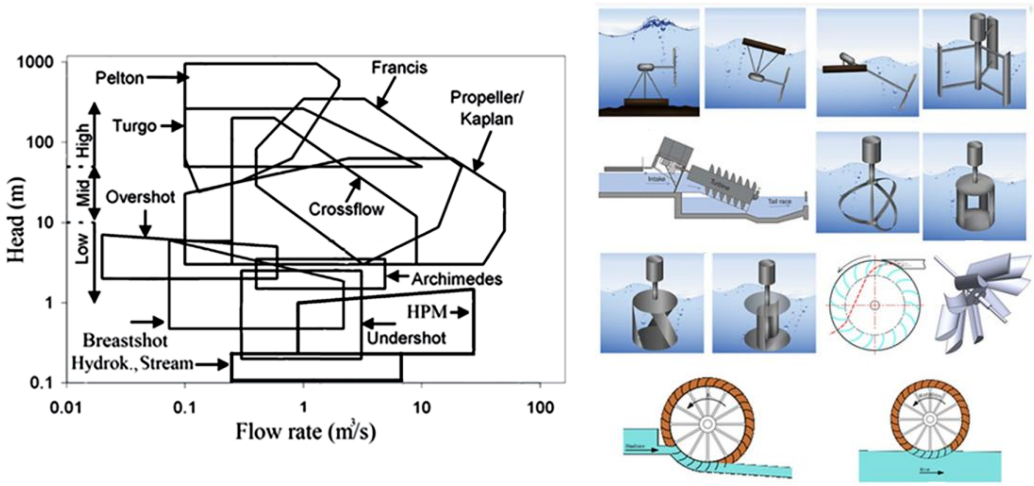
1. Introduction

The extensive use of fossil fuels (coal and oil) was predetermined by rapid industrial development. This exploitation causes severe adverse effects—environmental pollution and greenhouse gas emissions. In addition to the adverse effects of pollution on the environment and human health, it has contributed to long-term global warming. Because of this, humanity faces extreme climatic conditions much more often—excessive heat or cold, drought, floods, storms, etc. Moreover, the most essential and widely used fossil fuels—coal and oil—are non-renewable, and their reserves will ultimately be exhausted. Given the ever-increasing demand for energy and the challenges of meeting it through fossil fuels, the world is increasingly turning to renewable energy sources, especially those that produce little or no emissions and, therefore, do not contribute to pollution or greenhouse gas emissions. The most effective measure is to focus on renewable energy sources that produce little to no emissions and therefore do not contribute to the greenhouse effect [1].

A type of renewable energy source is hydropower. The amount of electricity that conventional hydroelectric plants can generate depends on annual rainfall and the amount of water, both of which flow into the estuarine basins (or reservoirs) from which Bulgaria draws most of its hydropower. Typically, hydropower is described by the energy generated by the power plant (installed capacity measured in kilowatts or megawatts) or by the hydropower category (conventional, micro-hydro, low-head, or hydrokinetic) into which the installed capacity falls. Conventional hydroelectric power plants (HPPs) use a higher head than other technologies, such as hydrokinetic systems. Micro-hydro systems can exploit lower heads and/or flows in ways that large systems cannot [2].

Hydrokinetic systems can be categorized as fluvial (river) or tidal. River systems use energy mainly from the unidirectional flow of surface water. Low-pressure turbines are used, and although the source of energy is the river's height difference, these turbines are of a different design (due to the low head) [3]. Such systems do not require the construction of dams; they do not divert water from the natural system, and they can generate power from very low heads compared to conventional hydropower systems. The applicability of the various turbine and wheel designs depends on the head and the available flow rate. A summary of the applicability of the various systems with respect to these two parameters is shown in Figure 1a [4]. Along with the popular Pelton, Francis, and Kaplan turbines operating at high and medium head values, other low-voltage turbines are also used. The diagram also covers three types of wheels, of which two—the low-pressure (undershot) and the zero-pressure water wheel (stream)—are the subject of current research as components of hydrokinetic systems.



(**a**) (**b**)

Figure 1. Types of hydropower systems and their applications. (**a**) Main parameters of various types of hydropower systems [4]; (**b**) design types of hydrokinetic systems.

Hydrokinetic systems are hydro-mechanical energy converters that convert the kinetic energy of pressure-free or low-pressure currents into other usable forms of energy. Hydrokinetic systems are those that use turbines and non-conventional power generation systems. Both types of systems use the energy from the unidirectional movement of water, with current developments and research mainly focused on turbine-based systems [5]. The developed non-conventional concepts, for the most part, are in the intensive development stage and need further research, development, and experimental work before they can be implemented [5]. Principal schematics of hydrokinetic systems are shown in Figure 1b.

Different designs have different efficiencies and applicability. Available literature on the effectiveness of the structures shows wide variation, ranging from 20% to 80% [6]. Three models of hydrokinetic systems could emerge as the most effective: the Bánki–Michell–Ossberger (BMO) turbine (crossflow), an axial turbine attached to the bottom, and an undershot water wheel.

This study focuses on crossflow turbines, also known as BMO-type turbines.

1.1. Crossflow Turbines

Crossflow turbines, or BMO turbines, are a very efficient and economical choice that offers a strong price-to-performance ratio. The crossflow water turbine is used for pressures H = 2 ÷ 200 m, but its power is usually limited to 1000 kW, which corresponds to relatively low efficiency values (up to 85%). In individual cases, the power of turbines of this type can reach up to 3000 kW (for example, the turbines of Ossberger GmbH + Co, Weissenburg, Germany) [2]. However, this type of turbine has several advantages for the specific requirements of small-power water turbines, making it competitive in the market. The most important of these advantages are:

- Extremely simple and technological construction (without special requirements for the machine equipment of the manufacturer);
- Relatively high efficiency values, in a wide range of modes;
- Provides good opportunities for manual and automatic adjustment;
- Has a low cost;
- Is characterized by a high degree of unification of components and details (a very significant advantage for the hydropower equipment of small hydropower plants).

The principal scheme of the Bánki–Michell–Ossberger turbine is shown in Figure 2, together with a typical design with a horizontal axis [7].

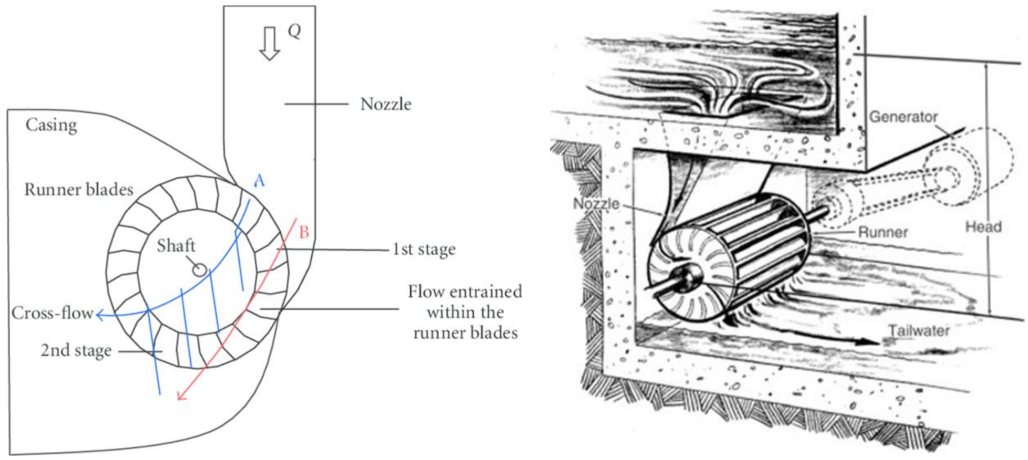


Figure 2. BMO turbine principle scheme and turbine with horizontal axis (A and B lines are flow boundaries).

1.2. Virtual Prototyping

Most existing installations of crossflow turbines use a horizontal-axis design [8,9]. This study aims to examine the concept of crossflow with a vertical axis by comparing it with the horizontal-axis type. It is performed using virtual prototyping technology.

Virtual prototyping is a useful tool for comparing concepts, as it provides detailed information on the parameters of examined variants that would otherwise require time and resources to evaluate through physical prototyping [10–12]. It involves various numerical analysis techniques that allow not only the simulation of the ongoing process but also its optimization [13,14]. The ability to follow up on internal parameters, for instance, fluid flow or pressure distribution across a cross-sectional plane, is another major feature of this technology [15]. This study uses computational fluid dynamics (CFDs) analysis, in which the turbine rotation is modeled using movable-mesh technology. It also presents mixing and interaction of two phases: liquid (water) and gas (air). These specifics require more computational time and resources but are mandatory for representing the ongoing physical process.

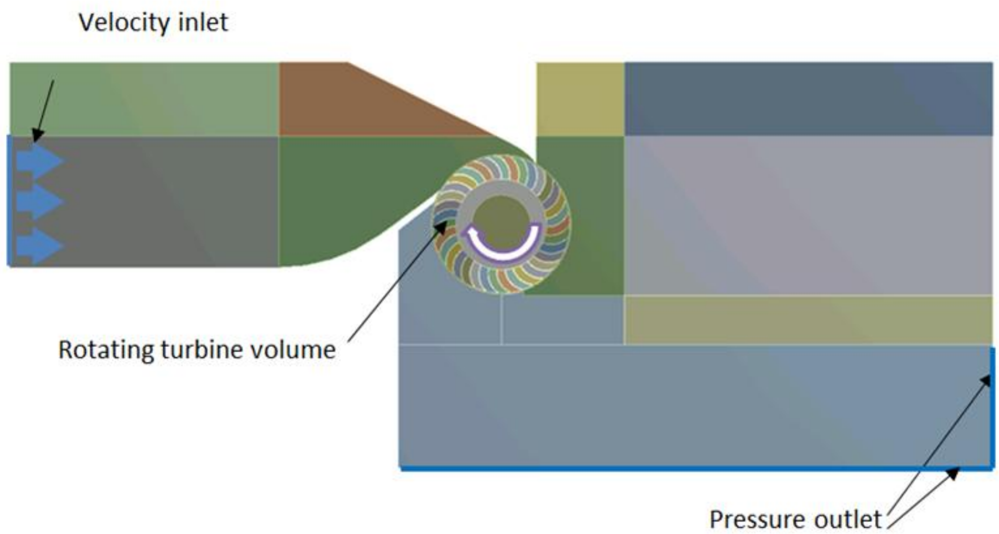
2. Materials and Methods

Two virtual prototypes of crossflow turbines are to be examined: a 2D horizontal-axis turbine model and a 3D vertical-axis turbine model. The difference in the method is due to the design specifics that allow using a 2D model for the horizontal-axis turbine, with no transverse effects requiring 3D modeling.

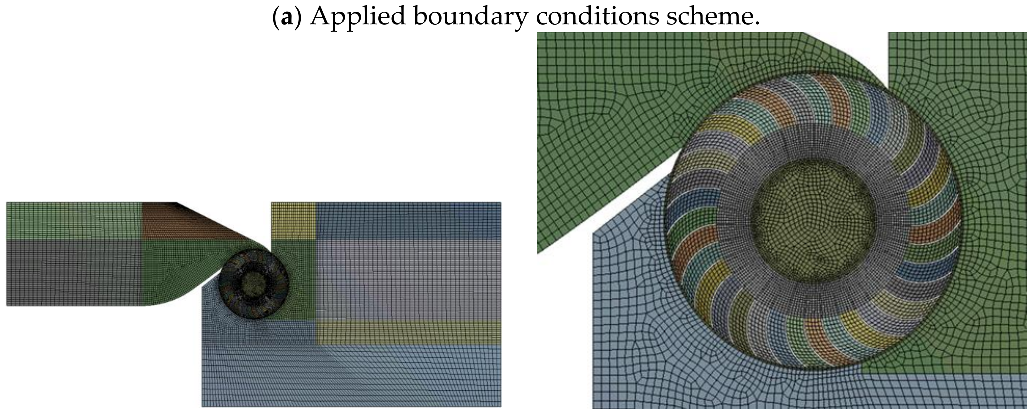
2.1. Method and Virtual Prototype for Assessment of Crossflow Turbine with Horizontal Axis

A virtual prototype is built using a sample design space, whose sizes are determined for a river application. The turbine diameter is 5.6 m, and its width is 24 m. The model and applied boundary conditions are shown in Figure 3. The rotating mesh contains the turbine and its blades. It connects to a tiny ring that is static to transfer fluid flow parameters to the surrounding environment.

The mesh is generated primarily from simple 2D quadrilateral elements. The most important feature of the mesh is the element quality. The maximal skewness for this model is less than 0.6, which allows simulation of a dynamic process as the one examined. The mesh is presented in the figure below, including general and local section views.



(**a**) Applied boundary conditions scheme.



(**b**) Mesh model.

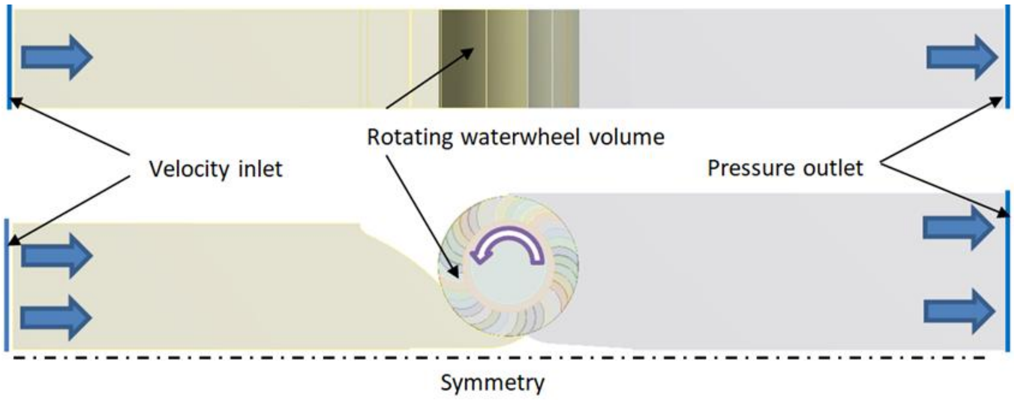
Figure 3. 2D virtual prototype of crossflow turbine with horizontal axis.

2.2. Method and Virtual Prototype for Assessment of Crossflow Turbine with Vertical Axis

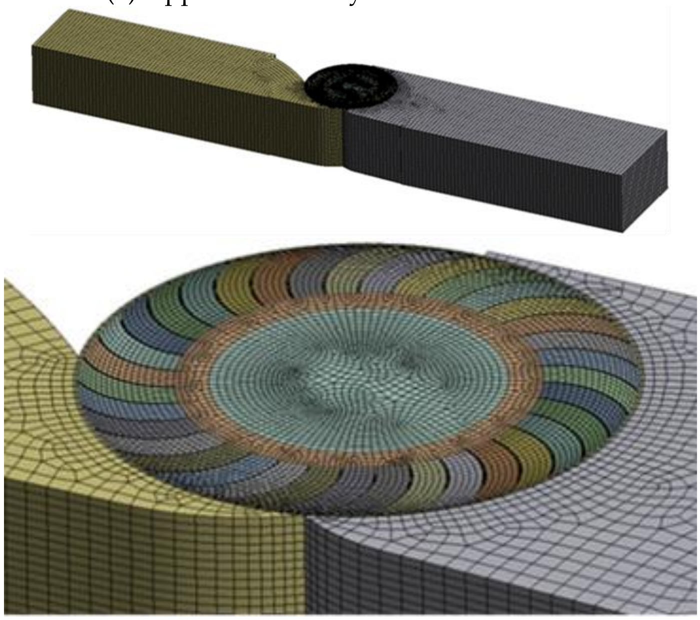
The vertical-axis prototype has similar dimensions and is applied in the same design space, again predetermined by the river site. Two turbines are modeled, with a 5.6 m external diameter. The design has 35 blades and a height of 4 m. A simulation model is built based on a virtual prototype. Further simulations of a crossflow turbine are performed, including 3D modeling.

This model uses the available design transverse symmetry and includes only one turbine. This is included in the model via the applied symmetry, as shown in Figure 4a. A

3D numerical model is presented in Figure 4b to show the mesh density and characteristics. It contains approximately 372,000 cells and 412,000 nodes.



(**a**) Applied boundary conditions scheme.



(**b**) Mesh model.

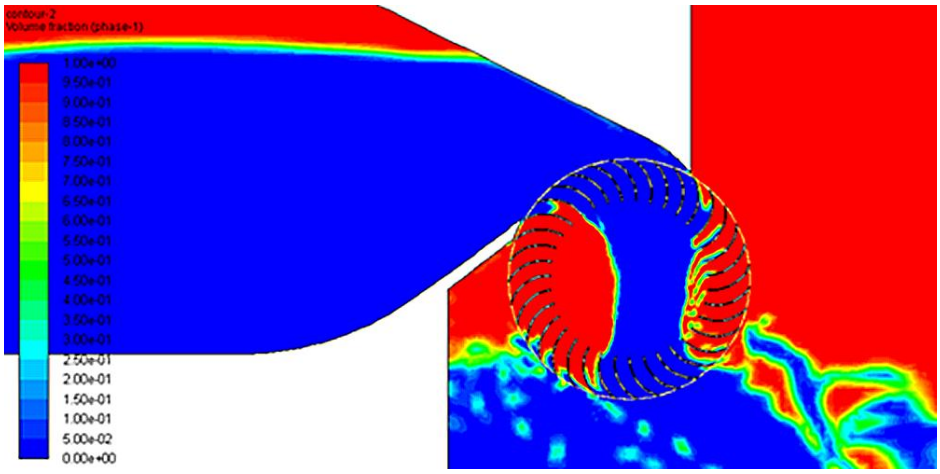
Figure 4. 3D virtual prototype of crossflow turbine with horizontal axis.

The crossflow turbine volume is defined as a dynamic, rotating mesh that interfaces with the near fluid. Its angular velocity is defined for each analysis separately.

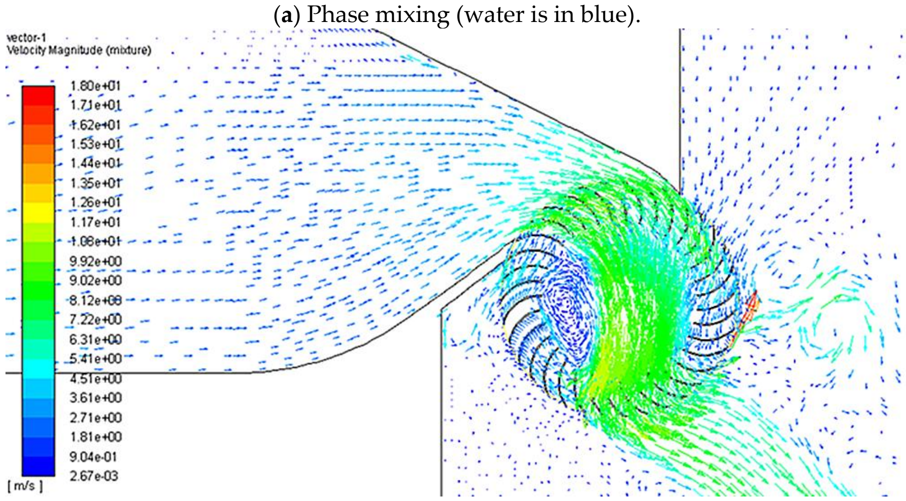
3. Results

3.1. Results for Crossflow Turbine with Horizontal Axis

Several simulations are run using different turbine rotation values at three fluid flow rates—400, 250, and 150 m^3/s. The simulation results are presented in general views, for illustration, in Figure 5. These results are for 400 m^3/s of fluid flow and provide an overall view of water mixing, splashing, and their interactions with the blades.



(**a**) Phase mixing (water is in blue).



(**b**) Velocity vectors.

Figure 5. General presentation of results for model with horizontal axis.

The results are summarized in Figure 6, where fluid flow of 400 m^3/s is examined in higher level of detail. The other two fluid flows are checked at a point.

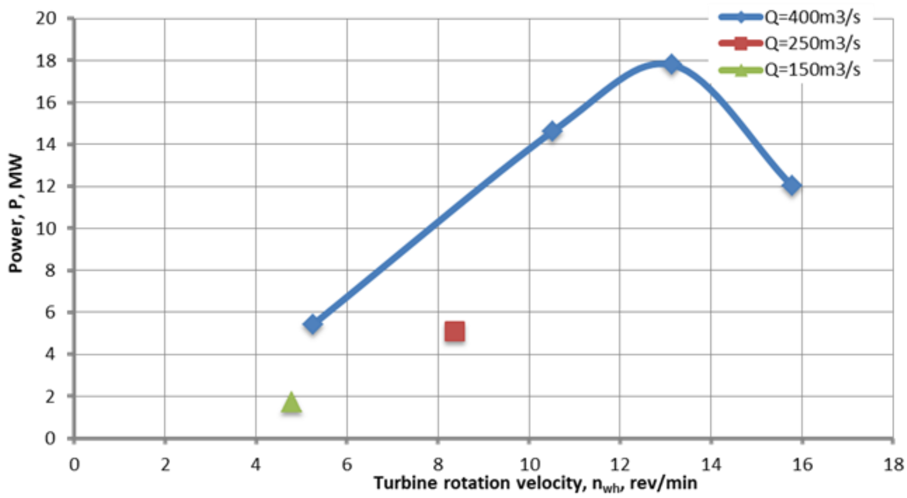


Figure 6. Generated power as function of rotational speed and fluid flow for crossflow turbine with horizontal axis.

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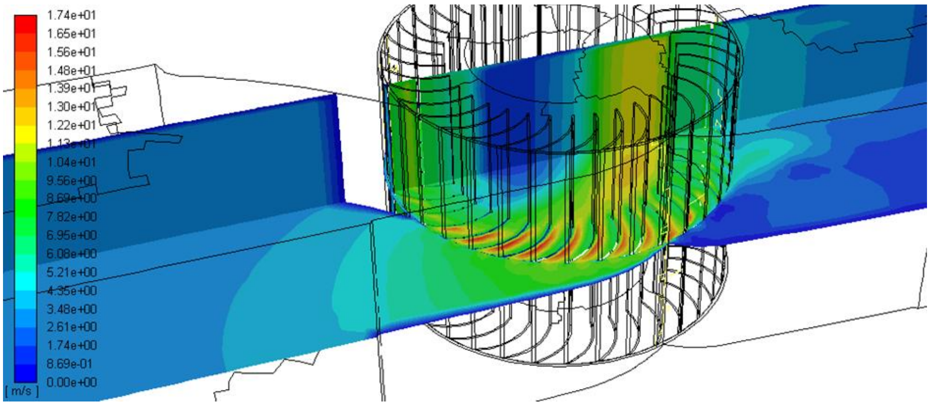
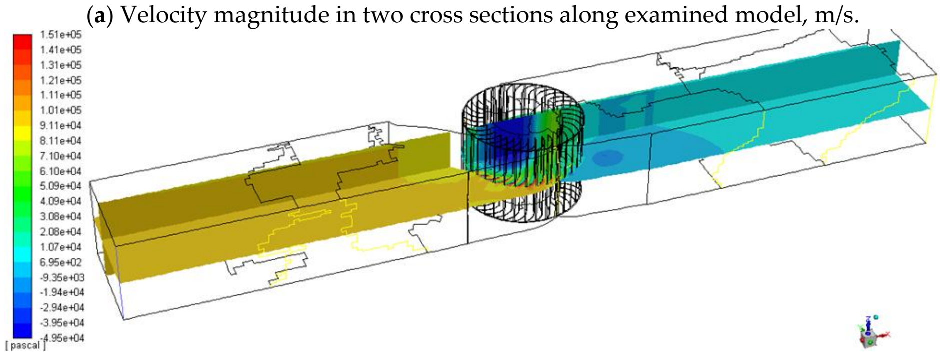
3.2. Results for Crossflow Turbine with Vertical Axis

Several simulations are run to calculate the performance of both turbines at a water flow of 100 m^3/s. This corresponds to 400 m^3/s. The target is to follow turbine performance using three parameters: harvested energy, efficiency, and inlet pressure (needed head) as functions of turbine rotational velocity.

The results are initially presented as a velocity magnitude distribution field (Figure 7a) and a total pressure distribution field (Figure 7b).



(**a**) Velocity magnitude in two cross sections along examined model, m/s.



(**b**) Pressure distribution in two cross sections along examined model, Pa.

Figure 7. General presentation of results for model with vertical axis.

All results correspond to a fluid flow rate of 400 m^3/s. Characteristics of the turbine, such as harvested energy, efficiency, and inlet pressure as functions of the rotational speed, are shown in Figure 8.

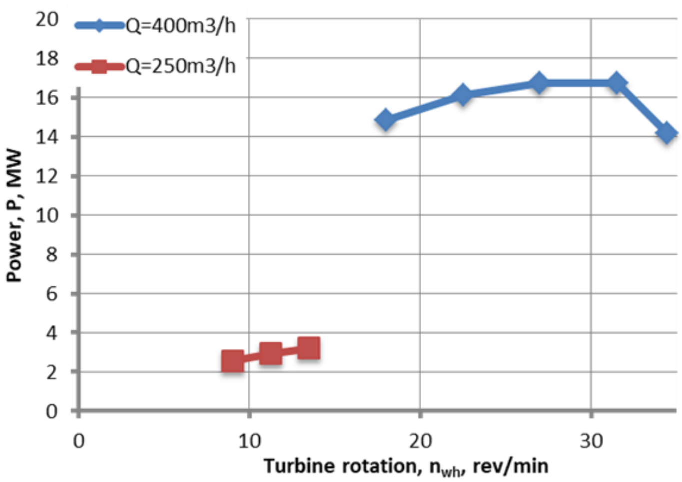


Figure 8. Generated power as function of rotational speed and fluid flow for a crossflow turbine with vertical axis.

Several comments could be made:

- The crossflow turbine is more stable in a wider rotational speed range—it produces more than 5 MW in the range from 22.5 min^{-1} to 32 min^{-1};
- Its efficiency decreases with increased rotational velocity, but harvested energy increases as well as required head;
- A good solution is to operate at 22.5 min^{-1}, with a power of nearly 5 MW and a requested head of about 6 m.

4. Discussion

The results from the virtual prototyping of a crossflow turbine with horizontal and vertical axes are compared and analyzed primarily based on the generated power.

This comparison is shown in the graph in Figure 9 for two fluid flows. Several comments could be outlined, based on this analysis:

- The crossflow turbine with a horizontal axis shows similar, but higher, harvested power at both examined water flows.
- A horizontal-axis turbine requires a certain head (minimum 1 m), which could be a barrier to further realization.
- The vertical-axis concept is more compact.
- The vertical-axis concept has more units.
- A horizontal-axis turbine requires better sealing than a vertical-axis crossflow turbine.

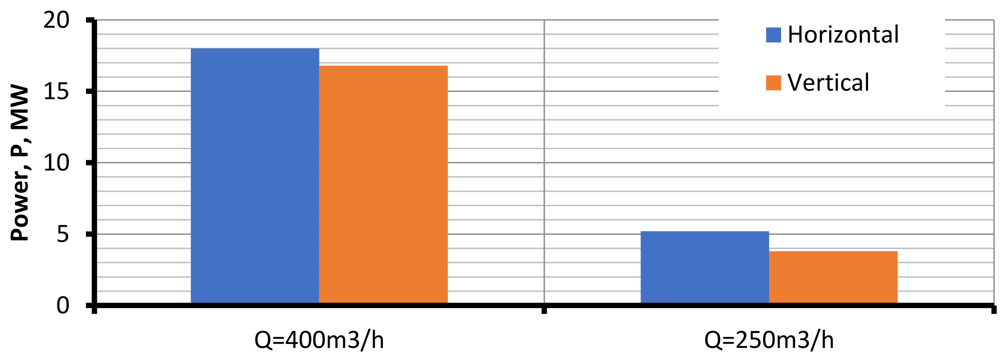


Figure 9. Comparison between crossflow turbines with horizontal and vertical axes by max generated power.

5. Conclusions

The study demonstrates the applicability of virtual prototyping to deliver fast results for complex, expensive structures, such as crossflow turbines for installation at river sites. Several major comments could be formed concerning the examined crossflow turbine concepts and the performed study:

- A possible solution for harvesting energy in open water channels is examined using virtual prototyping models.
- Two concepts are developed for crossflow turbine applications, with horizontal and vertical axes.
- Harvested power at different water flows is evaluated for both concurrent concept variants.
- The horizontal-axis crossflow turbine shows slightly better results in terms of electrical power output.
- An overall analysis of the obtained results and design parameters indicates that a crossflow turbine with a vertical axis is the better concept.
- Further detailed characterization and design are scheduled.

This work is a good example of the practical application of numerical analysis and virtual prototyping and demonstrates a specific, complex field, such as computational fluid dynamics.

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Abbreviations

The following abbreviations are used in this manuscript:

HPP	Hydroelectric power plant
BMO	Bánki–Michell–Ossberger
CFD	Computational Fluid Dynamics
2D	Two-dimensional
3D	Three-dimensional

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