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A Study on Design of Micro-Hydropower Plant for Run-off Water Sources in Bangladesh

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Abstract

Hydropower has been one of the most used energy sources in the world since historic times. Electricity production from hydropower has been there for decades, particularly in isolated regions. Studies have shown that 232 rivers in Bangladesh can be used for micro-hydropower generation and energy security for isolated communities with a reasonable flow rate. The run-off water from these rivers can be used as a clean energy source for running micro-hydro power plants. The main objective of this study was to investigate and justify the potentiality of micro-hydropower in Bangladesh and design a cross-flow turbine to harness power from these rivers. This study considered several design considerations, and a theoretical analysis was performed to create a cross-flow turbine. Then, a turbine was developed, and numerical analysis was conducted using ANSYS-CFX software. Results show that the turbine can achieve a peak efficiency and shaft power of 84.60% and 4.68 kW, respectively. Results indicated that a site with 100-150 liter/s of flow rate and a head of 5-6 meters could easily produce around 3-5 kW of power supply, considering all kinds of losses. The current study is expected to provide helpful information for improving hydropower-based electricity generation in Bangladesh.

1. Introduction

Bangladesh is the fastest-growing economy compared to the rest of the world; however, development is an essential part of any country's continued growth, and the primary driver of that development is energy. Energy has become one of the most essential components in improving Bangladesh's economic advancement and people's lives (SREDA, 2013; Hydrocarbon Unit, 2021). According to various reports from the hydrocarbon unit of the MPEMR Bangladesh, the main energy resources of Bangladesh are domestic natural gas, coal, imported oil, liquid

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petroleum gas, hydropower, and imported liquid natural gas, imported electricity (Hydrocarbon Unit, 2021).

Renewable energy is being used instead of gas, coal, and oil worldwide, and it is critical for long-term growth and environmental protection by reducing carbon emissions. Bangladesh also uses renewable energy, but the percentage is much less than what is truly needed (Hydrocarbon Unit, 2021). Therefore, numerous feasibility studies on micro-hydropower plants have been conducted at different times. The Water Development Board (WDB) and the Ministry of Power (MOP) jointly researched the country's small/mini-hydropower potential in 1981. The group looked over nineteen potential locations for modest hydropower plant installation. In 1984, the authors identified twelve prospective locations for constructing a mini-hydropower facility (ESCAP, 2015; Wazed *et al.*, 2008). In 2004, in another study by Sustainable Rural Energy (SRE), the local government engineering department (LGED) investigated some effective micro-hydro sites in Chittagong, which is illustrated in Table 1(Wazed *et al.*, 2008).

Table 1: Potential micro-hydro sites in Chittagong identified by SRE in a study in 2004 (Wazed *et al.*, 2008).

SI No.	Description site	Expected power generation (kW)
01	KhagrachariNunchari, Tholipara	3
02	Bandarban	30
03	Bangchari	25
04	Liragoan	20
05	Kamalchar in Rangamati	20
06	ThangKhrue in Rangamati	30
07	Monjaipara	7.5

Table 2: Potential sites identified by IFRD of BCSIR (Wazed *et al.*, 2008).

SI No.	Waterfall name	Avg. Discharge (ltr/s)	Approx. Flow Duration/Month	Approx. Fall for Hydropower /m	Electric Power Generation (kW)	Annual Energy Produced (kWh)
01	Sailopropat in Banderban	100	12	6	5	43800
02	Madhobkundu in Moulvibazar	150	12	10	15	131400

Moreover, the Institute of Fuel Research Development (IFRD) of the Bangladesh Council of Scientific and Industrial Research (BCSIR) has conducted a feasibility study on the research and development of renewable energy such as solar, wind, and micro-mini-hydro power in Bangladesh. Then, the collected data was explored in various prospects at the RET laboratory of IFRD. Table 2 shows part of the data (Wazed *et al.*, 2008). A large and growing body of literature has investigated the potential of hydropower in Bangladesh. Miskat *et al.* (2020) studied different types and technologies used for hydropower generation, and they observed that small-scale hydropower was the most practical way for Bangladesh to produce sustainable electricity according to an economic and environmental assessment.

Most researchers have based their studies on small-scale hydropowerplant technologies. One of which was done by Ali *et al.* (2021), who explored the feasibility from a technological standpoint of mini-hydropower potentiality from sewage water in four districts of Dhaka city. The study has analyzed technical, economic, and environmental criteria while taking into account the waterfall's head and the sewage system's flow rate.This study also shows the potential of small-scale hydro-powerplants and how they can be suitable in conditions like drain water systems.This study also shows the potential of small-scale hydro-powerplants and how they can be suitable in conditions like drain water systems. Doost *et al.* (2020) studied the potential and design procedures of Archimedes Screws Turbines (ASTs), which may create up to 355 kW of power with low water heads (less than around 5 m) and a wide variety of flow rates, with realistic efficiencies of 60% to 80%. Woldemariam *et al.* (2017) investigated improving a micro-cross-flow turbine CFD-driven design optimization approach. Rakibuzzaman *et al.* (2021) designed a small-scale hydropower turbine to use the wastewater from fish farms on the seas. The study developed a small-scale hydropower plant with propeller-type tubular turbines and a permanent magnet synchronous generator. Park *et al.* (2021) studied the unsteady fluid flow and its effect on the performance of rotating machines such as turbines. Mehr *et al.* (2021) numerically optimized the cross-flow turbine and found a peak overall efficiency of 82%. This study is significant since it will help us to know better design conditions for our turbine for performance improvement. Therefore, based on the previous feasibility study and previous research, it is significant to design and develop a micro-hydro power plant in Bangladesh.

Therefore, this study focused on the applicability of a micro-hydropower plant in Bangladesh. It provides the basic data and installation process for a micro-hydropower plant in runoff water sources in Bangladesh.

2. Methodology

2.1 Design Consideration

The design of a micro-hydro-power plant requires many design considerations, including site study and selection, measuring flow rate and head, civil work components (dam, trash rack, and penstock), turbine type, size, power generation, etc. In recent years, many scholars have designed and optimized hydro turbines using computational fluid dynamics. This study considered the turbine-specific speed to determine the runner diameter, which is written as.

$$N_s = \frac{N(rpm)\sqrt{Q(m^3/s)}}{H^{3/4}(m)} \tag{1}$$

where N is the turbine rotational speed, H is the net head, and Q is the flow rate. The blade rotational speed mainly depends on the generator and the type of driver used (Drtina, 1999; Morteza & Behnam, 2017). The hydraulic power generation (lost from water potential energy) is given as (Nasir, 2014).

$$P_h = \rho g Q H \tag{2}$$

where, P_h is the power in kW generated by hydraulic force. Once the hydraulic power has been obtained, the turbine power can be calculated as

$$P_t = P_h \eta \tag{3}$$

where, P_t is the shaft power, η represents the efficiency of a turbine. It should be remembered that the head of an impulse turbine is measured at the point of jet impact, which is always above the downstream water level. This results in a head decrease. When comparing the performance of impulse turbines with reaction turbines that employ the whole available head, the difference is not inconsequential for low-head designs. The turbine efficiency must be multiplied by the efficiencies of the speed increase (if any) and the alternator to get the total efficiency of the micro-hydro-power plant. Based on the theory and references, we have selected a cross-flow turbine because the head is below 10 m and the flow rate is 0.1 m^3/s.

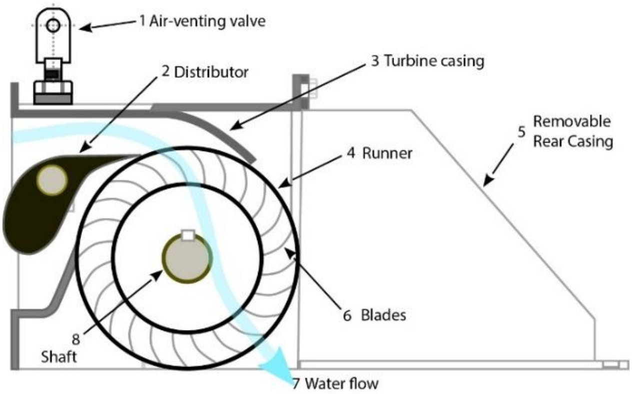


Figure 1: Block diagram of the cross-flow turbine.

Cross-flow turbines are a subcategory of impulse turbines, and water enters the runner tangentially, passes through it transversely, and leaves it radially. The main reason for this classification is that these turbines do not submerge like reaction turbines and function in the air. Cross-flow turbines are better suited for remote areas (Boyle, 1996). Although these turbines are helpful for a wide range of hydraulic heads and power outputs, they are most efficient when the heads and power outputs are low. So, for 0.1 m^3/s flow rate and 6 m of the head, we have selected the cross-flow turbine for three reasons: firstly, the cross-flow turbine is a low-head turbine. Secondly, this is a very simple, low-cost turbine in this low-head region. Finally, a micro hydropower plant has already been installed in

Bamerchara Lake for comparison purposes. In which a cross-flow turbine is being used. Cross-flow turbines can be used in pico, micro, and small power plants, with power outputs ranging from 1 kW to 5 MW (EERE, 2024). Figure 1 shows the schematic diagram of a cross-flow turbine.

2.2 Theoretical Analysis

This study theoretically calculated the turbine design parameters such as net head, flow rate, efficiency, runner diameter, power output, etc. To determine the net head of the turbine, mathematically, the net head, H, is written as

$$H = H_g - H_t \tag{4}$$

where H_t is the head equivalent for various losses in pipelines, channels, etc. This loss amounts to around 6 percent of the gross head. H_g is the gross head at the turbine's intake. Then, the water volumetric flow rate, Q, was calculated using the following formula:$Q = A \times V$. The turbine efficiency can be estimated using the formula (Mockmore & Merryfield, 1949; Penche, 1998):

$$\eta = 0.5 \times C^2(1 + \psi) \times cos^2\alpha \tag{5}$$

where α is the blade angle of attack, ψ is the blade roughness, and C is the nozzle roughness. The hydraulic power was calculated using Eq. (2). Then the turbine rotational speed N was determined and expressed as (Mockmore & Merryfield, 1949)

$$N = 513.25 \times \left(H \times 0.745/\sqrt{P_t}\right) \tag{6}$$

Following the equation determined the turbine runner's outer diameter D_o:

$$D_0 = 40 \times \sqrt{H}/N \tag{7}$$

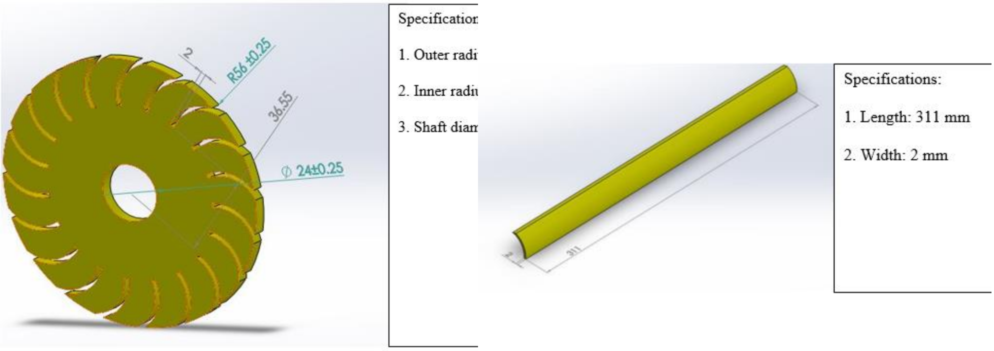
Then, turbine blade spacing t_b was calculated using the following formula $t_b = 0.174 \times D_0$. Also, the number of blades in the runner n was estimated using the following equation:

$$n = \pi \times D_0/t_b \tag{8}$$

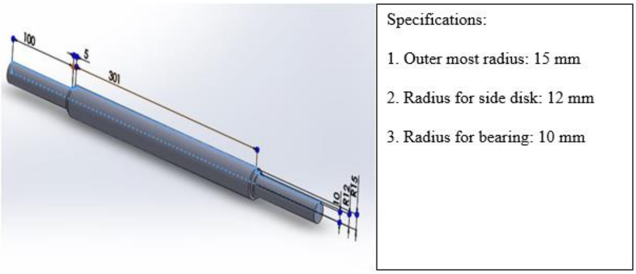
Also, the runner length, inner diameter, blade radius curvature, shaft diameter, etc., were calculated, and the turbine model was finally designed.

2.3 Model Development

For the project calculation, a cross-flow turbine has been selected. The model of the cross-flow turbine was designed according to the calculated value using the 64-bit SolidWorks 2016 Software. The model is developed into different parts: side disk, runner blade, shaft, casing, and nozzle. Figure 2 shows the cross-flow turbine and its components. The final runner assembly and the cross-flow turbine assembly are shown in Figure 3. The primary design specifications of the cross-flow turbine are presented in Table 3.

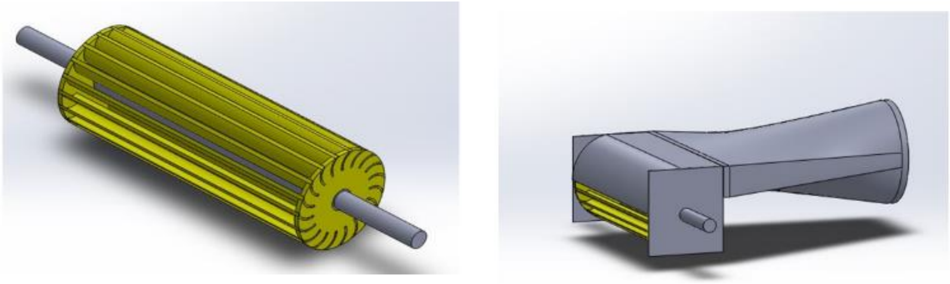


(a) Runner side disk (b) Runner blade



(c) Shaft

Figure 2: Design of a crossflow turbine and its major components (a) runner side disk, (b) runner blade, (c) shaft.



(a) Runner assembly (b) Crossflow turbine

Figure 3: Crossflow turbine (a) runner assembly, (b) crossflow turbine assembly.

Table 3: Design specifications of the cross-flow turbine.

SI No.	Descriptions	Dimension (unit)
01	Gross head, H_g	6 m
02	Net head, H_n	5.64 m
03	Discharge, Q	0.1 m^3/s
05	Turbine power, P_t	4.87 kW
06	Turbine speed, N	850 rpm
07	Runner outer diameter, D_o	112 mm

08	Blade spacing, t_b	19.48 mm
09	Radial rim width, a	19.48 mm
10	Number of runner blades, n	19
11	Runner length, L	301 mm
12	Runner inner diameter, D_i	73 mm
13	Blade radius curvature, r_b	18 mm
14	Diameter of shaft, D_s	24 mm

2.4 Numerical Analysis

A three-dimensional geometry of a horizontal propeller-type turbine was used to study and conduct the numerical analysis of flow characteristics on the cross-flow turbine. Figure 4 shows the geometry and dimensions of the turbine. Then, the model was meshed by using ANSYS ICEM-CFX (21R2, ANSYS Inc., Canonsburg, PA, USA, 2021) software.

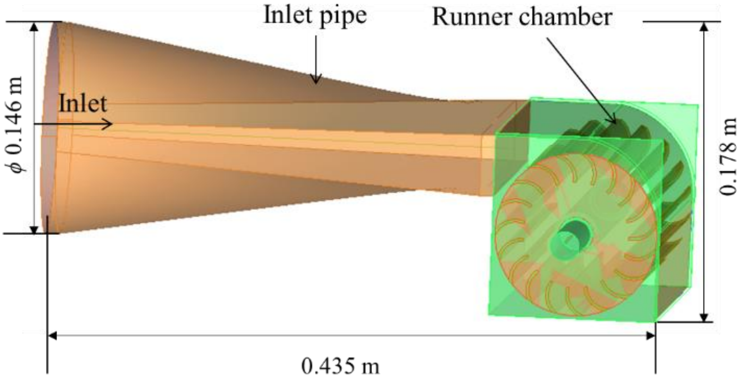


Figure 4: Three-dimensional geometry of the crossflow turbine.

The hydraulic turbine's flexible design made it possible to use the unstructured prism tetrahedral grid system to create the grid based on the finite volume method. The turbine model was segmented into two components: inlet pipe and runner with turbine housing. Figure 5 displays the prism tetra-meshing grids for the unstructured processes. To control the near-wall treatment of a cross-flow turbine, the number of prism layers was chosen to be six, the initial prism layer height was 0.25 mm, and the height ratio was 1.2. Therefore, the total prism layer's height was 2.4825 mm, respectively. The y+ value was considered in the range of y+<300. The y+ contours are shown in Figure 6. Then, a grid verification test was performed to verify the impact of meshing grids on the calculation results at a flow rate of 0.1 m^3/s. Five various grids were generated to check the convergence results. The grid independence test results are shown in Figure 7. It is observed that the simulated turbine efficiency tended to converge with increasing grid numbers. Results also found that the relative error at 1.165 million was 0.10587%, as shown in Table 4. Thus, the model grids were selected for 1.165 million nodes and 4.127 million elements, respectively.

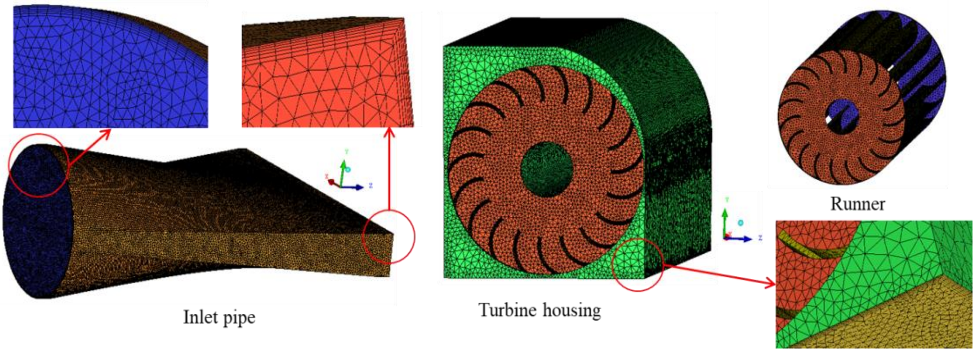


Figure 5: Unstructured prism-tetrahedral meshing grids.

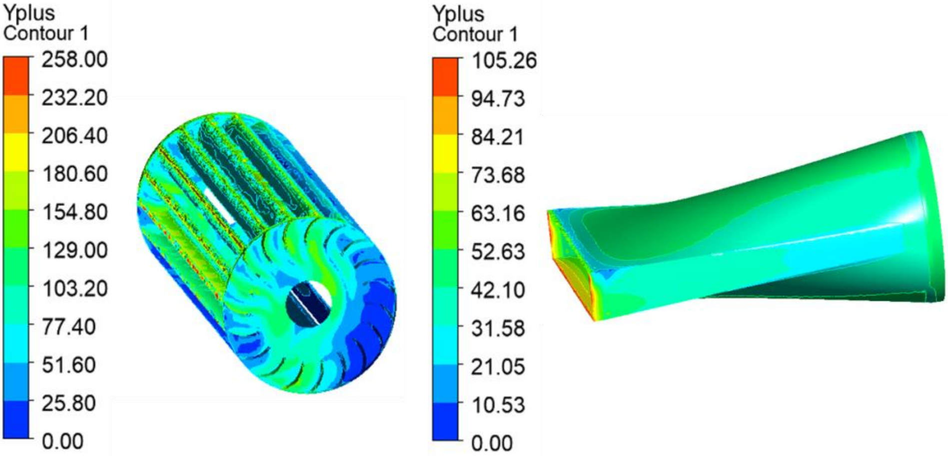


Figure 6: Three-dimensional geometry of the crossflow turbine.

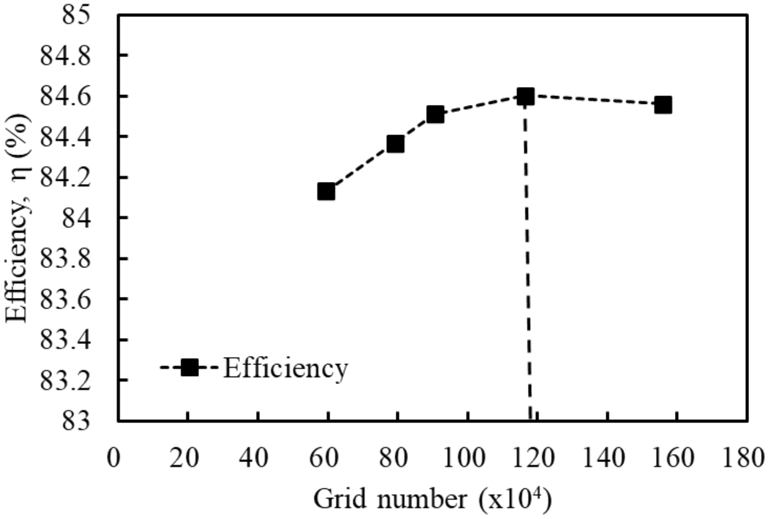


Figure 7: Grid independence test of a cross-flow turbine.

Table 4: Meshing grids and relative errors of the cross-flow turbine.

SI No.	Nodes (x10^4)	Grid ratio	Efficiency (%)	Relative error (%)
01	59.3891	-	85.132	
02	79.1855	1.1006	85.369	0.2789
03	90.5247	1.0456	85.511	0.1657
04	116.589	1.0880	85.602	0.1058
05	155.879	1.1016	85.561	0.0480

This study considered continuous phase, steady state, and incompressible flow to run the computer simulation. Then, Reynolds Average Navier-Stokes (RANS) governing equations were accounted for calculating the flow analysis of the turbine. The governing equations of the continuity and momentum equations are written as (Ansys Inc., 2021; Anderson *et al.*, 1949)

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{9}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S \tag{10}$$

where, u_i is the velocity vector, x represents the component of the position vector, p is the scalar pressure, ρ is the density of the fluid, τ_{ij} designates the stress tensor, S is the source term, and $i$and $j$are the tensor notations. The eddy viscosity was added to calculate the turbulent flow. The SST (shear stress transport turbulence) model was used to estimate the fluid's turbulent shear stress (David, 1994; Menter, 1994). The k-ω-based SST model was developed by Menter (1994) and can effectively blend the robust and accurate formulation of the model in the near-wall region. This model is widely applicable in turbomachinery and can also predict the onset of flow separation under an adverse pressure gradient. Therefore, the SST model was chosen for this study.

The turbine housing and inlet pipe were stationary while the runner was rotating parts. This study utilized the multi-reference frame (MRF) to solve the internal flow field in the turbine. The computational domain selected the frozen-rotor interface between the stationary and rotating frames. Figure 8 shows the turbine prototype domain for analysis data and its frozen-rotor interface. The turbulence model was set as an SST model with boundary conditions, mass flow rate for the inlet, and static pressure in the outlet. The reference pressure was 1 atm. Automatic wall functions were assumed to be treated near the wall boundary. The boundary conditions were taken as smooth wall surfaces with rotation speeds of 850 rpm. The residual value was set to 1 × 10^{-5} to converge the numerical simulation.

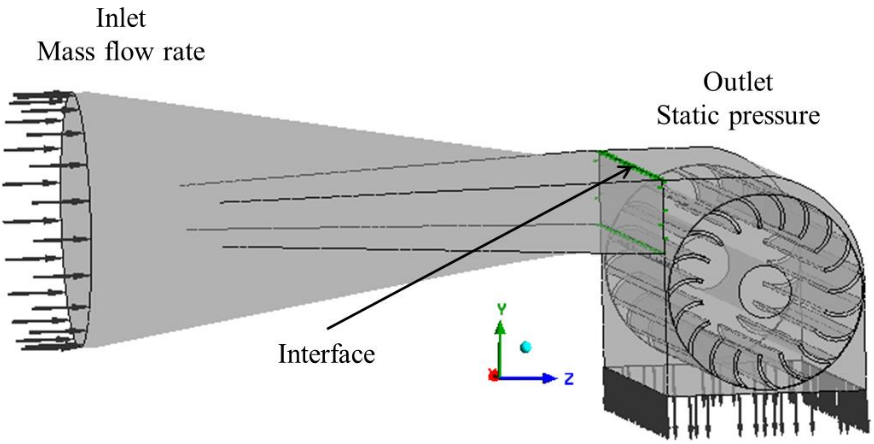


Figure 8: Computational domain for data analysis.

3. Results and Discussion

3.1 Performance Characteristics of Cross-flow Turbine

As said earlier, a micro-hydropower plant is already at BamercharaLake, Banshkhali, Chittagong. Therefore, Table 5 compares the existing micro-hydro power plant with theoretical results. The theoretical design results are similar to those of the existing turbine.

Table 5: Design specification comparison of existing hydro and theoretical designed.

SI No.	Descriptions	Bamerchara Hydro Unit	Theoretically Designed Unit
01	Type of turbine	Crossflow	Crossflow
02	Net Head	6 m–10 m	5.64 m
03	Flow rate	150 liter/sec	100 liter/sec
04	Turbine Power	4 kW- 6 kW	4.87 kW

3.2 Performance characteristics of cross-flow turbine

This analysis found that the turbine produced a power of 4.68 kW with 84.60% efficiency at 0.1 m^3/s flow rate, as shown in Figure 9. The efficiency drops with the flow rate increase and decrease. The effects of pressure and velocity are shown in Figure 10. From Figure 10(a), the pressure contour shows maximum pressure around the inlet and rotating wheel. In Figure 10(b), the velocity contour again shows higher velocity around the runner housing and the outlet side. The velocity is minimum at the blade pressure side. Limited water is circulating at the runner's backside, reducing the water pressure and velocity (Mehr *et al.*, 2021). Figure 11 shows the velocity vector, where it is noticed that around the down-right side, a velocity circulation is created, resulting in energy loss.

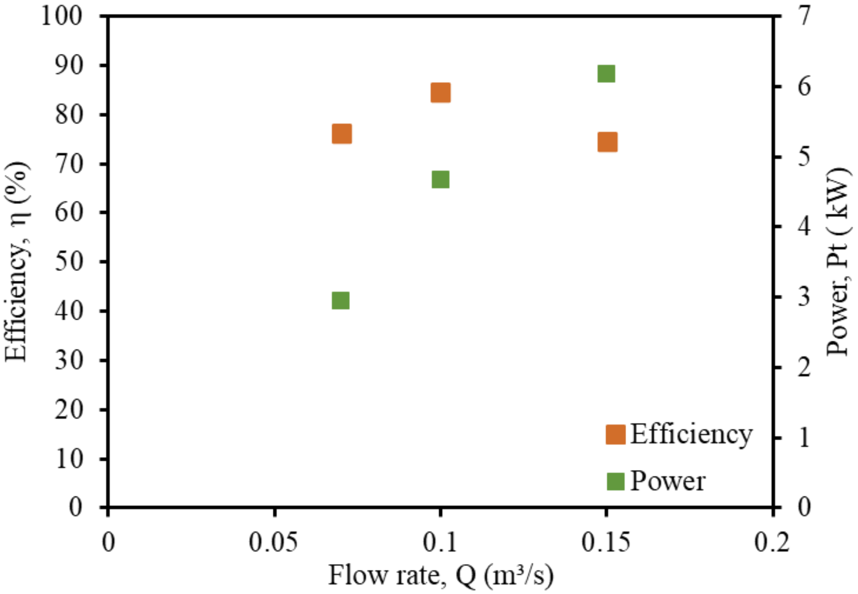
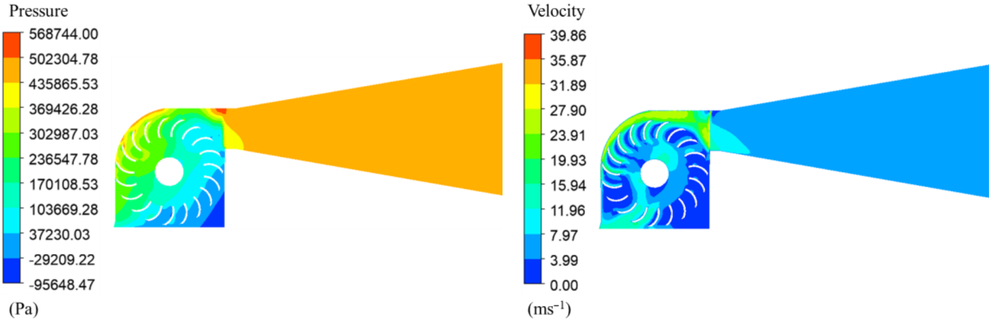


Figure 9: Computed hydraulic performances of the cross-flow turbine.



(a) (b)

Figure 10: (a) Pressure contour of the cross-flow turbine, (b) velocity contour of the cross-flow turbine.

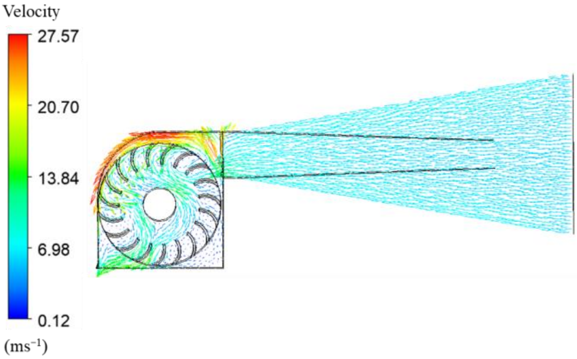


Figure 11: Velocity vector of the cross-flow turbine.

4. Conclusion

The micro-hydro power plant is significant in the world's total electricity supply. Particularly in rural areas, it provides a dependable and cost-effective power source. It has a decent potential within the northeastern hilly regions of Bangladesh. Because of the sufficient waterfalls, rivers, and canals, Bangladesh has good run-off water micro-hydro potential. Nevertheless, it has yet to be investigated. Parameters to line up a new micro-hydro plant have been considered. As the hydro powerhouse does not use non-renewable energy, it can assist in preserving a lot of other energy resources. This study showed that the targeted site's theoretical result was 4.87 kW, which was approximately similar to the site's estimated value. Although there were some considerations in the theoretical part, like the material's roughness, the turbine's efficiency, penstock length, etc., the study showed that this kind of project could be possible by the authority of the proposed area, which already has been discovered. Based on the survey, a site with 100-150 liter/s of flow rate and a head of 5-6 meters could easily produce around 3-5 kW of power supply considering all kinds of loss. Finally, correct parameter consideration to examine possible places may motivate interested individuals and provide an incentive to decide on micro-hydro plants for local usage.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have completely witnessed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy.

Author's contribution

The study conceptualization, methodology, and data analysis were performed by M. Rakibuzzaman, A. A. Kauser Amin; A. Islam performed the draft preparation; and M. Rakibuzzaman; A.K.M. P. Iqbal reviewed and editing the paper. Also, L. Zhou advised on the project work.

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