Research on Engineering Structures & Materials
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Research Article

CFD analysis on horizontal axis tidal current turbine

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Article Info

Article History:

Received 03 May 2025

Accepted 05 Aug 2025

Keywords:

Tidal energy;
Tidal current turbine;
Torque;
Thrust;
Power;
CFD analysis

Abstract

In response to the escalating global demand for sustainable energy and the environmental toll of fossil fuel dependency, this study presents a high-resolution Computational Fluid Dynamics (CFD) analysis of a Horizontal Axis Tidal Current Turbine (HATCT) designed for deployment in the Passur River, Khulna, Bangladesh, a region characterized by strong and predictable tidal flows. The CFD methodology is applied with a validated 3D turbine model, enabling precise evaluation of hydrodynamic performance metrics such as thrust, torque, and power output. The process supports optimization of blade geometry and operational parameters, contributing to the design of efficient tidal energy systems tailored to site-specific conditions. The turbine was tested across multiple mesh configurations to ensure numerical stability and mesh independence. Key findings indicate a consistent energy yield of approximately 3 kWh per tidal cycle, demonstrating the turbine's viability for localized renewable energy generation. These results highlight the practical application of CFD in marine energy engineering and underscore the potential of HATCTs to support Bangladesh's transition toward sustainable power infrastructure. The study offers a data-driven foundation for future experimental validation and large-scale implementation of tidal energy technologies in estuarine environments.

1. Introduction

Tidal energy has gained prominence as a stable and sustainable source of power owing to its predictability and high energy density. Unlike solar and wind energy, which are affected by atmospheric variability, tidal currents are controlled by gravitational interactions between the Earth, moon, and sun, resulting in cyclic and predictable flow patterns. This makes tidal energy ideal for integrating into national power systems, especially along coastal and estuary areas [1]. At the latter half of the 20th century, the concept of employing horizontal-axis turbines for extracting energy from tidal currents gained traction, mostly due to the practical success of wind turbines. Estimating the energy potential of tidal flows and comprehending the related hydrodynamic processes were the main goals of early theoretical research. Because of its straightforward mechanical construction and inherent alignment with the direction of tidal flow [2], the horizontal-axis turbine arrangement became a popular choice by the 1990s. There was a notable shift from theory to practice in the early 2000s. In 2008, the Sea Gen project in Northern Ireland achieved a significant milestone in the commercialization of tidal energy technology by becoming the first grid-connected tidal turbine in the world [3]. Several full-scale prototypes, including Open Hydro, HS1000, and AR1000, were created during this time, effectively proving the viability of producing energy on a megawatt scale using tidal currents.

Research on turbine performance, wake interactions, generator integration, and environmental factors dominated the academic and industry interest in HATCTs between 2002 and 2012. Ten years of advancements were summarized in a thorough assessment by Ng et al. (2013), which

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DOI: http://dx.doi.org/10.17515/resm2025-866en0503rs

focused on the increasing technological maturity and potential economic benefits of horizontal-axis systems [4]. After this formative time, more recent research has looked into sophisticated design techniques to maximize turbine performance. Adaptive, variable-pitch blades are used to improve hydrodynamic efficiency and enable bidirectional flow energy capture, while diffuser-augmented systems are integrated to boost power output [5]. On the other hand, studies of wake dynamics and turbine-fluid interactions have yielded important information for enhancing array designs and overall farm efficiency [6]. As a result, Large-scale implementations like Raz Blanchard in France and the Mey-Gen project in Scotland have signaled a move towards commercial feasibility in recent years. By enhancing turbine efficiency and dependability and reducing the need for operational maintenance, these projects establish HATCTs as a viable and sustainable energy option for island and coastal areas [7]. Continuous advancements in environmental integration, control systems, and blade geometry strengthen the position of tidal energy in the world's renewable energy mix.

Currently, in line with global trends, Bangladesh, facing increasing energy demand due to its growing population, stands at a critical juncture in its pursuit of sustainable energy solutions. Its extensive river network featuring major rivers like the Padma, Jamuna, and Meghna presents a unique opportunity to harness hydrokinetic energy, particularly through the deployment of horizontal tidal current turbines. These riverine systems offer immense potential for generating clean electricity through strategically positioned turbines within natural water currents [8]. Tidal energy is a renewable energy source that produces mechanical power for generators by converting the kinetic energy of moving water into electrical energy [9]. It uses less fossil fuels and produces less CO2 emissions. It is among the numerous resources available to address climate change concerns [10]. As the world looks for cleaner and more sustainable ways to produce energy, tidal power is expected to draw more concern and attention. Tides originate from the gravitational attraction of the moon. Given that water covers 71% of the earth's surface, tides provide a large-scale means of energy capture [11]. The main benefit of tidal energy over other renewable energy sources like wind or solar power is that tides are predictable [12].

At present, the extraction of electricity from tidal currents is receiving more interest because it is currently an unexplored renewable resource. Because of their great energy density and regularity, tidal currents are a desirable renewable energy source [13]. Many systems have recently been developed to produce electrical power from the energy contained in tidal currents [14]. As its rotational axis is parallel to the tidal flow, horizontal axis tidal turbines, or HATCTs for short, only run in one direction of flow. They are also referred to as axial flow turbines. The HATCT operates on a similar basis to the horizontal axis wind turbine (HAWT). The development of computing power and computational fluid dynamics (CFD) models to represent the intricate flow surrounding the turbine has advanced significantly [15]. The mesh that is chosen to solve the fluid flow and the turbulence model that is used to depict the problem's physics are the only factors that affect the independent mesh solutions. The mesh was created using SIMCENTER STA-RCCM+, which was extremely fine in the blade wall region to produce exact results. Three meshes have been done throughout the investigation of a 1.6m diameter three-bladed HATCT and the 3D design of the HATCT has been taken from a Tidal Turbine Benchmarking Projects of Supergen [16]. A total of three simulations have been done.

Therefore, in aspect of Bangladesh, it can be a great initiative to generate power using tidal current turbines as Bangladesh has a great deal of potential for tidal energy harvesting because of its large coastline along the Bay of Bengal and its many tidal rivers. The installation of horizontal tidal current turbines is one viable method of using this resource. To comprehend the performance and optimize the design of such turbines in the context of Bangladesh's particular tidal circumstances, computational fluid dynamics (CFD) study is essential. Because it is dependable and predictable, tidal energy offers Bangladesh a feasible alternative to fossil fuels. The purpose of horizontal tidal current turbines is to harness the kinetic energy of tidal currents and transform it into electrical power, much like underwater wind turbines [17]. Using CFD analysis, fluid flow around turbine blades is simulated, performance metrics are assessed, and design parameters are optimized to extract the most energy possible. Bangladesh may achieve greater energy resilience and environmental sustainability by utilizing its tidal energy potential and reducing its reliance on fossil fuels by integrating CFD analysis with horizontal tidal current turbines [18].

Even with the availability of sophisticated CFD tools and the theoretical benefits of HATCTs, their use in Bangladesh is still restricted. Although the Passur River and other estuarine areas of the nation have a considerable potential for tidal flow, they lack localized performance data and design optimization that is suited to local hydrodynamic conditions. Previous research frequently ignores the distinctive features of Bangladesh's tidal zones in favor of generic models or offshore facilities.

Additionally, this study fills the gap by using CFD analysis to assess a benchmarked HATCT's performance in the Passur River under site-specific circumstances. The study's objectives are to measure the turbine's thrust, torque, and power output as well as evaluate its viability for producing renewable energy locally. The study aims to enable the scalable implementation of tidal energy plants in Bangladesh and inform future design strategies by combining simulation results with regional tidal characteristics.

2. Methodology

2.1 Airfoil Selection and Blade Design Parameters

A NACA airfoil (taken from web), commonly used in tidal turbine blade design, as shown in Fig. 1 both symmetrical and asymmetrical airfoils are employed in the tidal turbine industry to produce. In the tidal turbine design, symmetrical airfoils are most common because of their high cavitation qualities and ability to vary the angle of attack across the complete rotation of the turbine blades [19].

The NACA 63-415 model in Fig. 2 from Benchmarking Project was used to simulate HATCTs. [20]The hydrodynamics of the hydrofoil is examined, especially on the trailing edge treatment: a) Sharp trailing edge b) Thickened trailing edge c) Truncated trailing edge. As the seawater velocity rises with the rising angle of attack of the airfoil top surface, more drag forces are generated during HATCT's whole rotation, in addition to lift variations. As a result, creating a blade with a curved caudal fin design reduces vibration and produces greater lift and power coefficients at both lower and higher tidal current velocities [21].

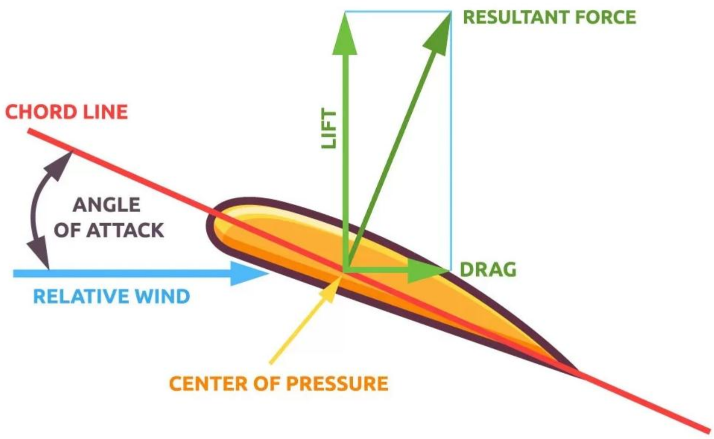


Fig. 1. Airfoil characteristics

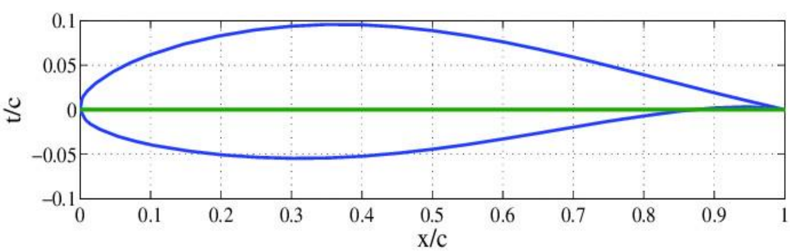


Fig. 2. NACA 63-415

In the hydrodynamics of hydrofoil of NACA 63-415, Below Fig. 3 shows the Drag Coefficient against the angle of attack, Fig. 4 shows the Lift Coefficient against the angle of attack and Fig. 5 shows the

Lift to Drag coefficient ratio against the angle of attack. All the Fig. 3, Fig. 4 and Fig. 5 have been taken from the Benchmarking Project by Supergen.

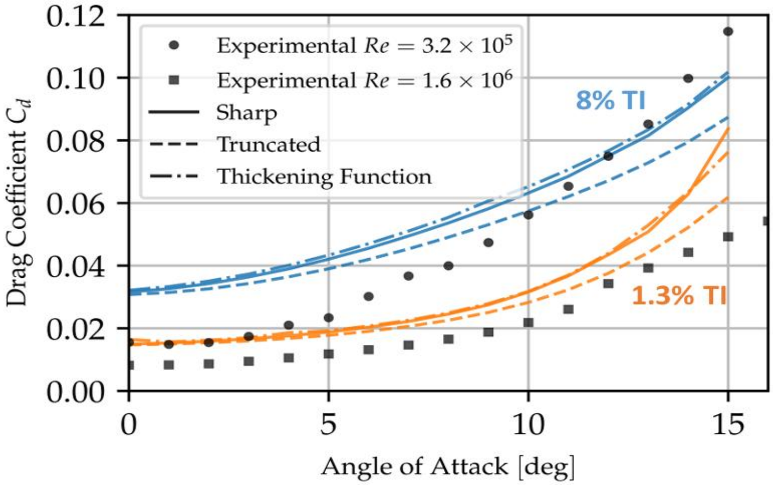


Fig. 3. Drag coefficient against the angle of attack

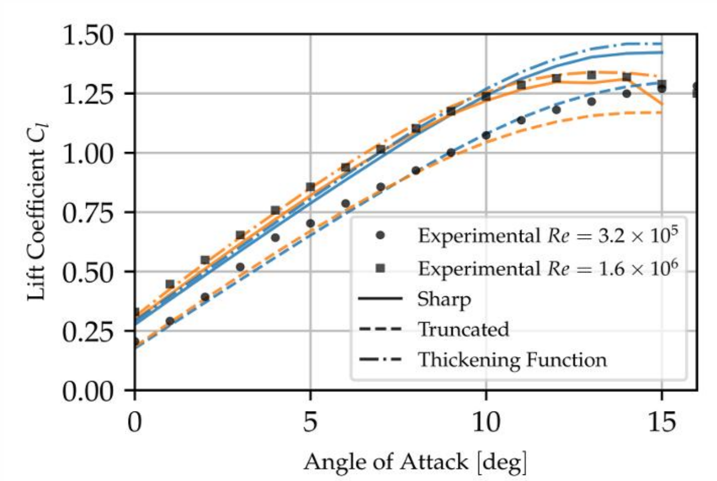


Fig. 4. Lift Coefficient against the angle of attack

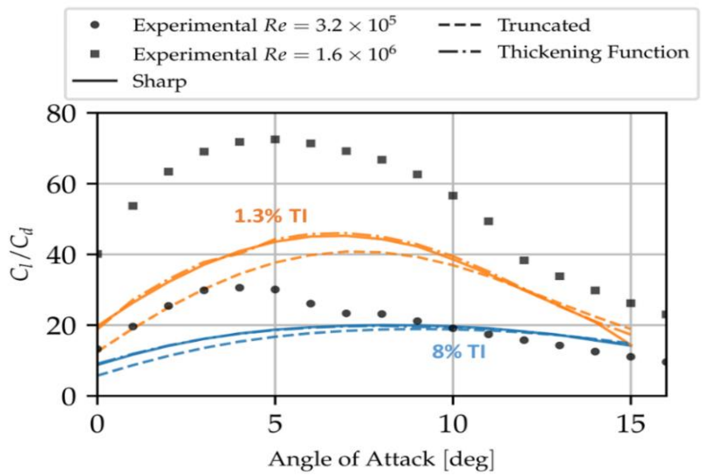


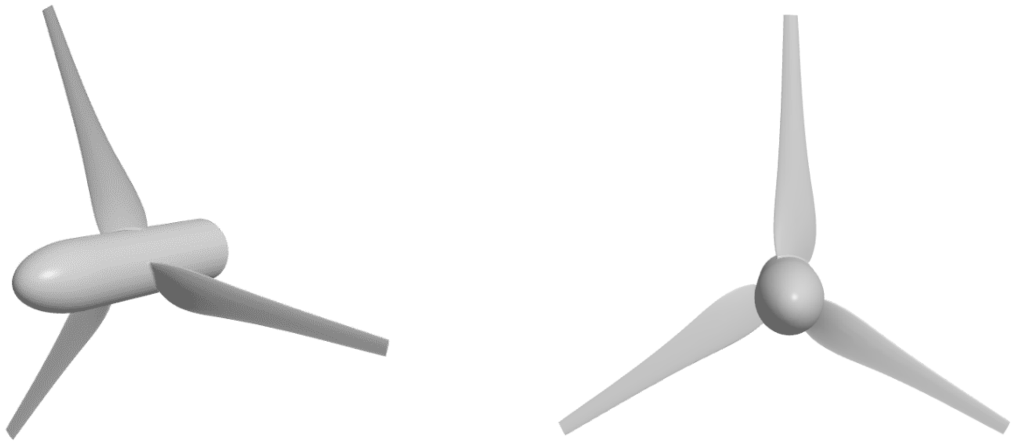
Fig. 5. Lift to drag coefficient ratio against the angle of attack

Here, Table 1 shows the parameters of the taken blades. These parameters were obtained from the Tidal Benchmarking Projects by Supergen

Table 1. Blades parameter

Parameter	Value
Rotor Diameter	1.6 m
Blade Diameter	0.7 m
Nacelle Diameter	0.2 m
Blade Number	3
Turbulent Length Scale	0.037 m
Turbulence Intensity	3.1%
Twist Angle	35 degrees

Here, Fig. 6 (a) and (b) show the 3D design of the tidal turbine, where the Blade view can be seen. And this design has been taken from the Benchmarking Project.



(a) (b)

Fig. 6. 3D Blade view

3. CFD Simulation Setup

The flow hydrodynamics were solved using Simcenter STAR-CCM+ 2210.0001 (17.06.008-R8) by using the finite-volume approach to solve the Reynolds Averaging Navier-Stokes (RANS) equations. As mentioned in the previous sections NACA 63-415 (Fig. 2) was employed on the designed blades. This paper consists of the dimensional force, thrust, and power which is produced by K-Omega turbulence and Reynold's Averaged Navier Stokes method by STAR-CCM+, at the turbine level thus putting forward a comparative analysis.

3.1 Meshing, Boundary Conditions and K-Omega Turbulence Model

3.1.1 Meshing

In Computational Fluid Dynamics (CFD) simulations, meshing is an essential component that forms the basis for the accuracy and dependability of the whole computational process. To create a computer grid, meshing essentially entails splitting the geometric domain of a simulated fluid flow into discrete pieces or cells. This grid approximates fluid dynamics within each cell by serving as a numerical representation of the physical region. Meshing is important since it directly affects the computing efficiency and fidelity of the simulation. Capturing the finer aspects of fluid flow phenomena, like boundary layer effects, vortices, and turbulence, requires a well-structured mesh. Finer meshes provide a more accurate representation of the underlying physics, and their resolution directly impacts the quality of the numerical solution. Therefore, before beginning the primary analysis, a mesh independence test was conducted [22].

3.1.2 Boundary Conditions

For simulations, Three-Dimensional, Liquid, Constant Density, Implicit Unsteady, Segregated Flow, Turbulent, K-Omega Turbulence, Reynolds-Averaged Navier-Stokes, Elliptic Bending models are used [23]. The velocity of initial condition in the positive x-axis for simulation-1 the velocity & the rotation rate was taken from the Benchmarking paper which are 0.9207 m/s and 81 rpm. Again, for simulation no. 2, 3 and 4 the velocity was taken 0.945 m/s, and the rotation rate was taken at 81 rpm in the positive x-axis in the perspective of the Passur River. The velocity is taken from a reference paper that shows the velocity of the Passur River of Bangladesh in the monsoon [24]. Fig. 7 demonstrates the velocity distribution from where the velocity has been taken for the simulation regarding Passur River.

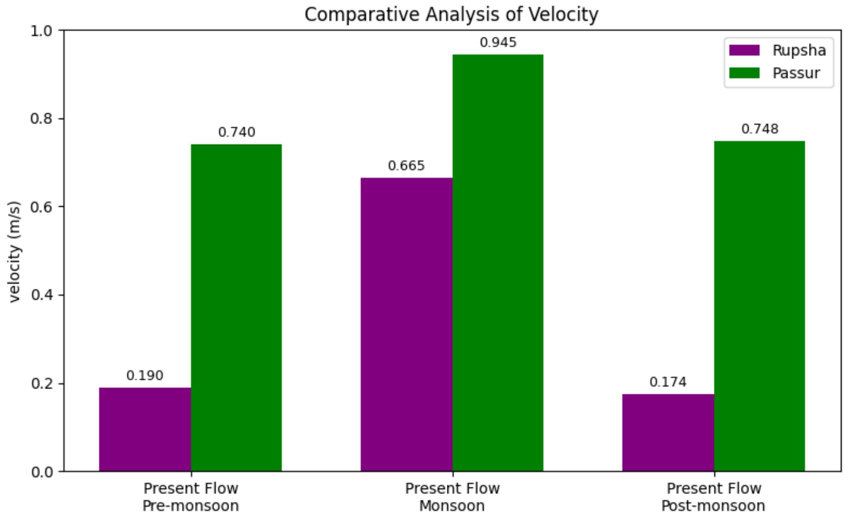


Fig. 7. Velocity analysis between rupsha and passur river

3.1.3 K-Omega Turbulence Model

In computational fluid dynamics (CFD), the k–omega (k–ω) turbulence model is a widely used method for estimating turbulent flow and also, is a common two-equation turbulence model, that is used as an approximation for the Reynolds-averaged Navier–Stokes equations (RANS equations). The model attempts to predict turbulence by two partial differential equations for two variables, k and ω, with the first variable being the turbulence kinetic energy (k), which represents the energy contained in the turbulent motion. While the second (ω) is the specific rate of dissipation (of the turbulence kinetic energy k into internal thermal energy). This model helps estimated the effects of turbulence in fluid flow by simplifying the complex Reynolds-averaged Navier–Stokes (RANS) equations [25]. The eddy viscosity ν_T, as needed in the RANS equations, is given by: $\nu_t = k/\omega$, while the evolution of k and ω is modelled as Eq (1) and (2):

$$\frac{\delta(\rho k)}{\delta t} + \frac{\delta(\rho u_j k)}{\delta x_j} = \rho P - \beta^* \rho\omega k + \frac{\delta}{\delta x_j}\left[\left(\mu + \rho_k \frac{\rho k}{\omega}\right)\frac{\delta k}{\delta x_j}\right] \tag{1}$$

$$\frac{\delta(\rho\omega)}{\delta t} + \frac{\delta(\rho u_j \omega)}{\delta x_j} = \frac{\alpha\omega}{k}\rho P - \beta\rho\omega^2 + \frac{\delta}{\delta x_j}\left[\left(\mu + \rho_\omega \frac{\rho k}{\omega}\right)\frac{\delta\omega}{\delta x_j}\right] + \frac{\rho\sigma_d}{\omega}\frac{\delta_k}{\delta_{xj}}\frac{\delta_\omega}{\delta_{xj}} \tag{2}$$

Where; k is the turbulence kinetic energy, - ω is the specific rate of dissipation, ν is the kinematic viscosity, νt is the eddy viscosity (νt = k/ω), σk, σω, α, and β are empirical model constants, ρk is the production term.

4. Validation with Benchmarking Case Study

At first, using the values of Turbulent Benchmarking Grid Case-10 from Benchmarking project by Supergen, the initial simulation was done to find the result of their project. Where the RPM was taken 81 and the velocity was taken 0.9207 m/s from it.

Table 2. Rectangular region domains (Inlet, outlet, and height extension)

Axis	Corner-1	Corner-2
x	-1.5 m	4 m
y	-1.5 m	1.5 m
z	-1.5 m	1.5 m

Table 3. Cylindrical region domains

Axis	Start Coordinate	End Coordinate	Cylinder Radius
x	0.5 m	-0.5 m	
y	0 m	0 m	1 m
z	0 m	0 m	

Here, Table 2 and Table 3 show the values of the cylindrical region and the rectangular region for the mesh set up as well as for the boundary set up around the turbine. The coordinate system is categorical as x in the stream-wise, y in the vertical and z in the span wise directions, respectively.

After meshing, the cell number for Benchmarking Project was found almost 2.5 Million, where the faces were almost 7.15 Million and the vertices were 2.5 Million. The simulation has been done where the solution time was 31.41 seconds, and the Iteration was more than 17,000 by taking the velocity as 0.9207 m/s and torque as 81 rpm from the Benchmarking Paper.

Table 4. Simulation results for benchmarking project

Simulation No.	V (m/s)	RPM	Thrust (N)	Torque (N-m)	Power (W)	Tidal Time (h)	Electricity (kW-h)
1	0.9207	81	1045	58.604	497.098	6	2.982

Here, Table 4 shows the result after the simulation is done. From the simulation the Torque has been found 58.604 N-m, and the thrust has been found 1045 N. The power has been found 457.098 W after the calculation. So, the electricity found from the simulation by multiplying with the Tidal time is 2.982 kW-h or almost 3 kW-h.

4.1 Simulation Using Passur River Condition

The similar methods have been taken for completing the simulations by taking the Passur River data of Bangladesh. The coordinate system is defined as x in the stream-wise, y in the vertical and z in the span wise directions, respectively.

Table 5. Rectangular region domains (Inlet, outlet, and height extension)

Axis	Corner-1	Corner-2
x	-1.5 m	9 m
y	-2 m	2 m
z	-2 m	2 m

A total of three meshes have been done as well as three simulations by using the data taken from Passur River, Bangladesh. For every mesh, Table 5 and Table 6 show the values of the cylindrical region and the rectangular region, which was taken similarly. Here, the cylindrical region as

Cylindrical rotating domain will contain the turbine and the rectangular region as Water tunnel will contain the sea water.

Table 6. Cylindrical region domains

Axis	Start Coordinate	End Coordinate	Cylinder Radius
x	0.4 m	-0.4 m	
y	0 m	0 m	1 m
z	0 m	0 m	

Three meshes have been done by changing their cell numbers. Among three meshes mesh-1, which cell number is 3537595, mesh-2 where its cell number has been decided by multiplying by √2 with mesh-1 cell number, and mesh-3 where its cell number has been decided by dividing by √2 with mesh-1 cell number. So, these all is done for the mesh independence test to find out that if the results from simulation-2, simulation-3, and simulation-4 vary much or not, by using the velocity and rpm values of Passur River of Bangladesh.

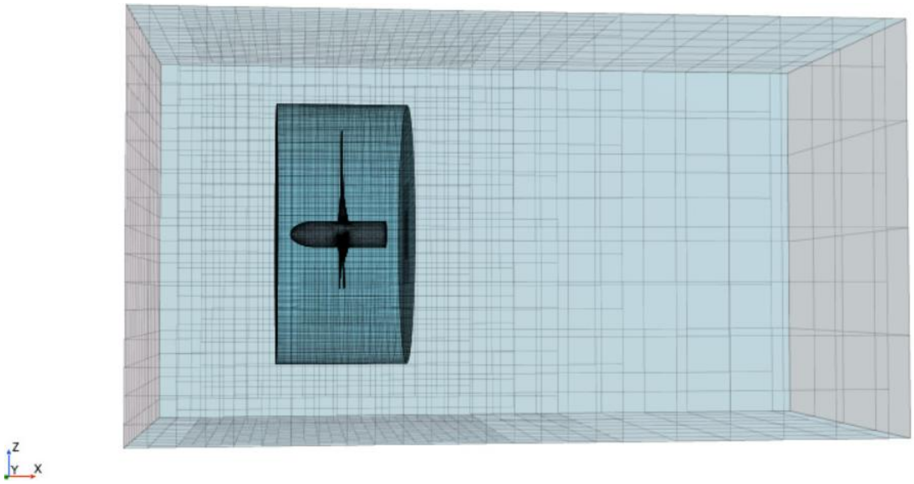


Fig. 8. Inlet, outlet, and height extension

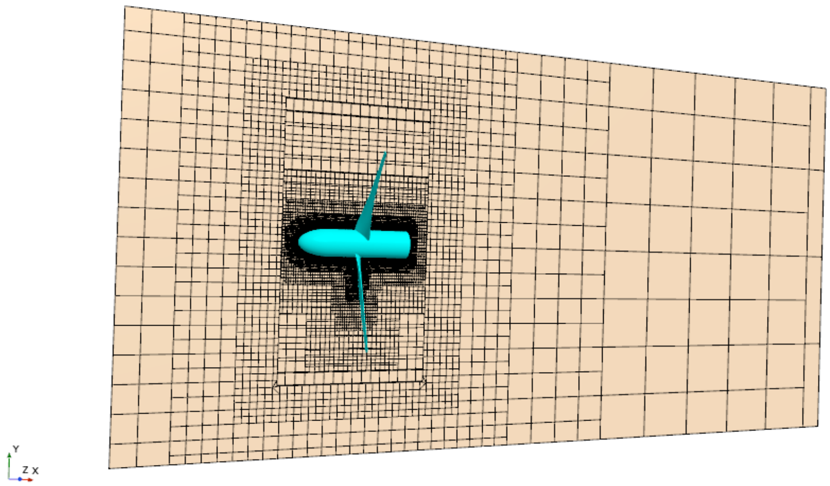


Fig. 9. Mesh scene

Here, Table 7 shows that for Mesh-1 the cell number was found almost 3.5 Million, for Mesh-2 cell number was found almost 5.5 Million and for Mesh-3 cell number was found almost 2.3 Million. Fig. 8 and Fig. 9 represent the meshed Inlet, Outlet, Height extension and mesh scene view after meshing.

Table 7. Meshing values

	Mesh-1	Mesh-2	Mesh-3
Cells	3537595	5540313	2363576
Faces	10463931	16399651	7024652
Vertices	3602374	5543425	2465137

5. Results and Discussion

The CFD analysis with a Horizontal Axis Tidal Current Turbine of 1.6m blade (HATCT) was carried out for three different types of meshes as well as three different simulations. The turbine from a benchmarking project and then numerical solvers to simulate the flow around the tidal blade with STARCCM+ to obtain effective power. Power, thrust force, and torque were calculated for each simulation, by keeping this intention water velocity, and rpm were assumed as Passur River which is near the Khulna area. This study was simulation-based, without physical modeling; therefore, actual results may differ when using a practical model.

The design has been taken from a benchmarking project by Supergen, which is mainly a practical model of their turbine. With our research and design a practical model can be made to justify the design and know the accuracy of the design. Further research can be made if this project can be implemented in Bangladesh. The simulation results indicate that

- Thrust and Torque have been found. The power has been calculated through Eq (3):

$$P = RPM \times \left(\frac{3.1416 \times 2}{60}\right) \times Torque \tag{3}$$

- Then the value of electricity has been found by multiplying with the tide time which is taken 6 hours initially. Here, Eq (4):

$$E = Power(Watt) \times Time\ (Tidal) \tag{4}$$

Table 8. Results from three different simulation

Simulation No.	V (m/s)	RPM	Thrust (N)	Torque (N-m)	Power (W)	Tidal Time (h)	Electricity (kW-h)
2	0.945	81	1067.9	59.0965	501.275	6	3.00765
3			1021.3	57.9407	491.496		2.948976
4			1064.5	58.9734	501.483		3.008718

Here, Table 8 shows the results for Thrust, Torque, and Power after three different simulations have been done and all are nearly identical. Therefore, based on these results, the final power value was taken from the lowest-resolution mesh (mesh-3) which refers the simulation 4 and the power found from that is 3 kW-h. Where simulation-4 has been run for 20.025 seconds. Fig.10 & Fig. 11 represent the Scalar View and Power Monitor of Simulation-4 whereas Fig. 12 & Fig. 13 show the Thrust Monitor and Torque Monitor view in the same simulation.

As a result, the simulation results showed that the power output, torque, and thrust values had been quite consistent across the three mesh sizes (Table 8). The simulation setup's numerical stability and mesh independence are confirmed by this consistency. Mesh-3, which had the fewest cells, nevertheless generated a similar amount of electricity (3.008 kWh), confirming computational efficiency without compromising precision. This conclusion is consistent with the results of several research that highlighted the importance of localized mesh refinement over global cell count in attaining computational efficiency.

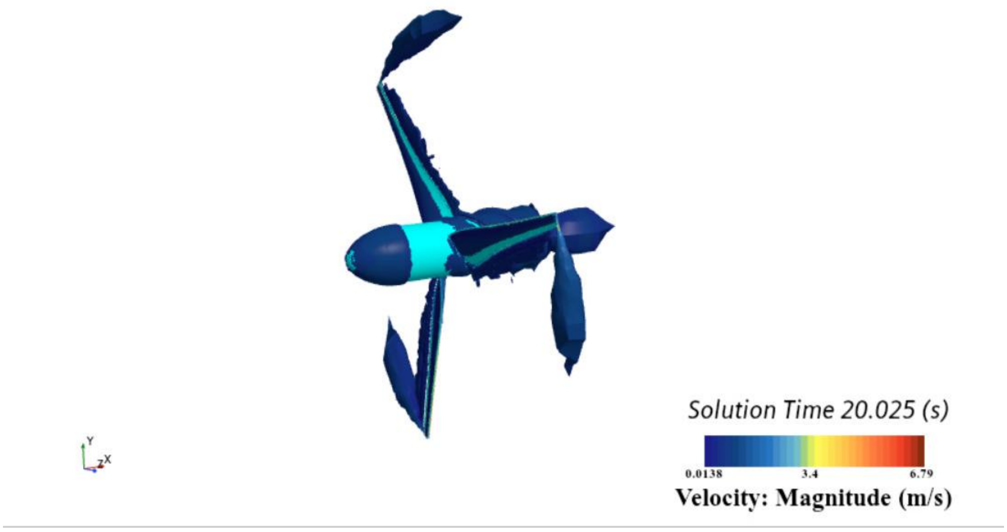


Fig. 10. Scalar view

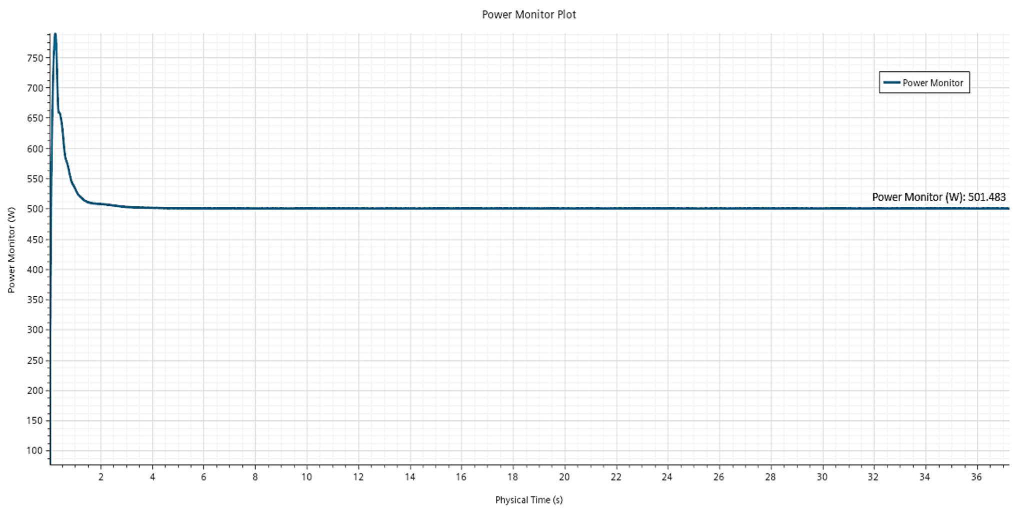


Fig. 11. Power monitor

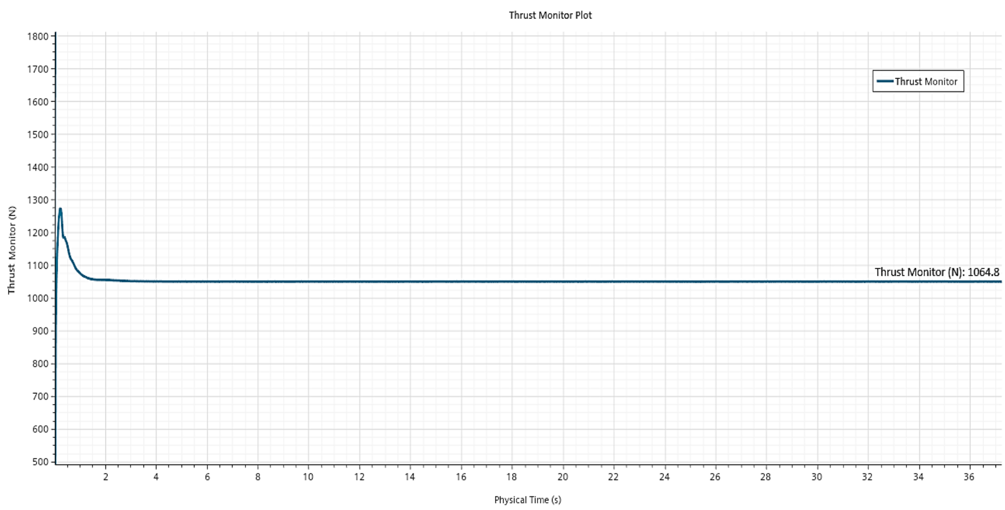


Fig. 12. Thrust monitor

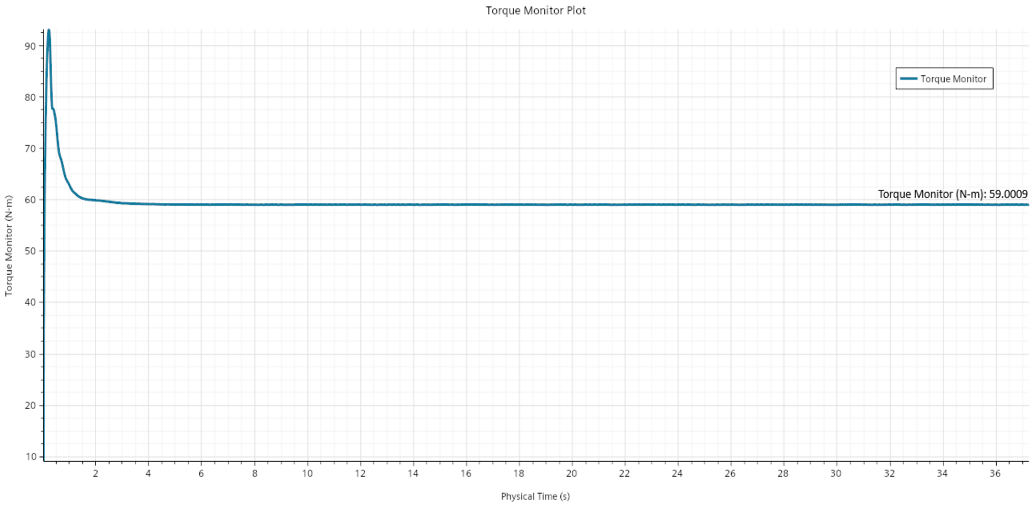


Fig. 13. Scalar view

Additionally, comparable research has shown that designs with curved trailing edges act better in situations with fluctuating flow. The high thrust and torque stability across a range of flow speeds is the outcome of the design optimizations that our CFD model included. As noted in earlier maritime CFD research and recently validated in tidal array conditions, the results also support the validated use of the k–ω turbulence model. Our scalar velocity profiles illustrated how well this turbulence model simulated intricate boundary-layer interactions (Fig. 10).

This study provides competitive performance parameters when juxtaposed with real-world tidal setups and turbines, especially in estuary environments like the Passur River. The practicality of small-scale, decentralized renewable energy projects in Bangladesh has been shown by the estimated electricity generation of approximately 3 kWh per turbine every single tidal cycle. This could make a substantial contribution towards the regional energy grid if developed with multiple turbine units.

The low performance variation across simulations, despite variations in mesh resolution, is yet another noteworthy result. This supports the findings that geometric symmetry and suitable airfoil selection have an important influence on simulation efficiency and stability. Furthermore, our findings are consistent with site-specific tidal flow measurements in the Rupsha-Passur system as reported in several studies, giving assurance that the simulated environmental inputs accurately represent field conditions.

In terms of comparative output, the final thrust (1064.5 N), torque (58.97 N-m), and power (501.48 W) values are within the expected range based on the benchmarking turbine case by Supergen, validating both our numerical setup and boundary selection. And from the above all results, we can see that the measuring value of Electricity for Passur River is almost same with the simulation result of Bench marking projects Electricity value, which justifies the result.

6. Conclusion

The Computational Fluid Dynamics (CFD) analysis conducted on the Horizontal Axis Tidal Current Turbine (HATCT) has provided valuable insights into the turbine's hydrodynamic performance and behavior of the turbine under varying operational conditions. Through high fidelity (CFD) simulations have enabled a comprehensive evaluation of the turbine's hydrodynamic characteristics, finding the key performance indicator- thrust, torque, and power. By simulating the interaction between the turbine blades and tidal currents. These findings are crucial for engineers and designers to enhance the reliability and longevity of the Horizontal Axis Tidal Current Turbine, contributing to the sustainable harnessing of tidal energy.

Using a validated turbine design from a benchmarking project and applying site-specific flow conditions from the Passur River near Khulna, Bangladesh, the simulations consistently produced similar results across different mesh configurations. Where for every simulation the cell number of every mesh was different to see the variation of the power, thrust, and torque values. Therefore, the Passur River can create power as well as electricity with the tidal turbine and the energy output per tidal cycle was found to be approximately 3 kWh. As it is done by one tidal turbine, the generation of electricity is not much to give it in the grid system but it provides a promising baseline for larger, distributed turbine networks.

Practically speaking, a network of these turbines might provide off-grid coastal communities with energy, lessen reliance on fossil fuel-based power generation, and improve energy resilience in areas that are already at risk. Furthermore, tidal turbine systems are ideal for a progressive integration into Bangladesh's energy system because of their modular & flexible design, which permits staggered adoption. Tidal turbines produce a low visual impact and emit no greenhouse emissions while in operation, making them an environmentally friendly option that aligns with global climate targets. Furthermore, its predictable generation profile based on tidal cycles may be combined with intermittent sources like solar and wind, helping to create a more stable and diverse renewable energy portfolio.

This study not only demonstrate technical feasibility of HATCT deployment in Bangladesh's tidal zones but also emphasizes the broader socio-economic and environmental benefits. By advancing CFD-based design and optimization strategies, this research lays a foundation for future efforts aimed at developing site-specific tidal energy projects that are efficient, environmentally responsible, and economically viable. That is why the CFD analysis has been instrumental in providing a detailed and data-driven assessment of the Horizontal Axis Tidal Current Turbine, accordingly offering valuable insights for further research, design refinement, and the eventual deployment of efficient and robust tidal energy systems. This study contributes to the ongoing efforts to harness clean and renewable energy sources, paving the way for the sustainable development of tidal power technology.

Acknowledgement

The authors declare that they have no financial or personal relationships that could have influenced, or been perceived to influence, the research presented in this paper.

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