Computational Fluid Dynamics-based Simulation and Design of a Horizontal Tidal Turbine System

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Abstract. Tidal phenomena, the rhythmic rise and fall of sea waters due to gravitational forces among celestial bodies like the Sun, Earth, and moon, offer a dependable source of renewable energy. Tidal energy, with its predictability and high energy density, is an attractive sustainable option. Tapping into this energy requires a specialized device, the tidal turbine, where the rotor plays a vital role. The rotor converts the kinetic energy of incoming tides into useful mechanical energy, evaluated through thrust, torque, and power efficiency. This study focuses on designing a horizontal tidal turbine using a three-dimensional Computational Fluid Dynamics (CFD) model with ANSYS Fluent software. Input parameters are based on real-world measurements of the average current velocity of 1 m/s obtained using Acoustic Doppler Current Profiler (ADCP). The paper serves two purposes: validating the applied design approach and analysing crucial design factors. By confirming design compatibility and assessing factor properties, the research contributes to optimizing tidal turbine efficiency and its feasibility as a sustainable energy source.

1 Introduction

In line with the worldwide trend, Malaysia's demand for renewable energy sources is rising. This pattern is the result of growing concern over the negative effects of fossil fuel and coal-based energy generation on the environment [1]. The hydroelectric plant, which is primarily responsible for producing electricity, dominates Malaysia's energy landscape. However, the country has untapped natural resources, like solar and wind potential, that might be harnessed before being converted into electrical energy [2]. The energy mix is also highlighted by the reliance on conventional fossil fuels like coal and natural gas.

The substantial environmental effects of this heavy reliance on non-renewable resources include the release of greenhouse gases that worsen climate change and have a negative impact on human health. In order to address these problems, there is an increasing push to fully utilize renewable energy sources. This campaign highlights the need to reduce reliance on conventional fuels, which is especially important for isolated areas that are not connected to the grid [3].

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The quick switch from dirty, emission-free renewable energy sources to carbon-intensive fossil fuels represents a practical and essential answer in tackling this urgent issue. Numerous renewable resources, including thermal energy, solar photovoltaic energy, biomass, wind, tidal energy, hydropower, and geothermal energy, are available in the face of rising global energy demands [1]. Due to its predictability, robustness, and minimum environmental impact, tidal energy in particular shows promise [4]. This is made possible by the low rotating speed of tidal turbines.

The key to using tidal movements for energy extraction is to transform the predictable vertical water motions that create tidal currents into kinetic energy. Different tidal turbine topologies, such as horizontal axis tidal current turbines (HATCT) and vertical axis tidal turbines (VATCT), can be used to capture this energy and use it to create electricity. Notably, Penang Port's favorable tidal characteristics make it an ideal location for the use of tidal energy, with the electricity produced able to reduce the requirement for hydroelectric power grid supply [5].

Tidal turbines and wind turbines both use fluid flow to extract energy as a fundamental operating concept [6]. The turbine blade is a crucial element in this situation because it converts tidal currents into rotational forces. Although tidal currents move more slowly than wind, their higher energy density makes up for this difference, allowing tidal stream devices to produce energy similar to that of wind turbines. Low risk subaquatic flow velocities ensure operational continuity. Tidal turbines must be built robustly in order to handle stronger water-induced stresses, nevertheless [7]. The horizontal axis tidal current power turbine adaption uses the fluid-to-saltwater conversion paradigm and the conceptual design is in line with wind turbine principles [2].

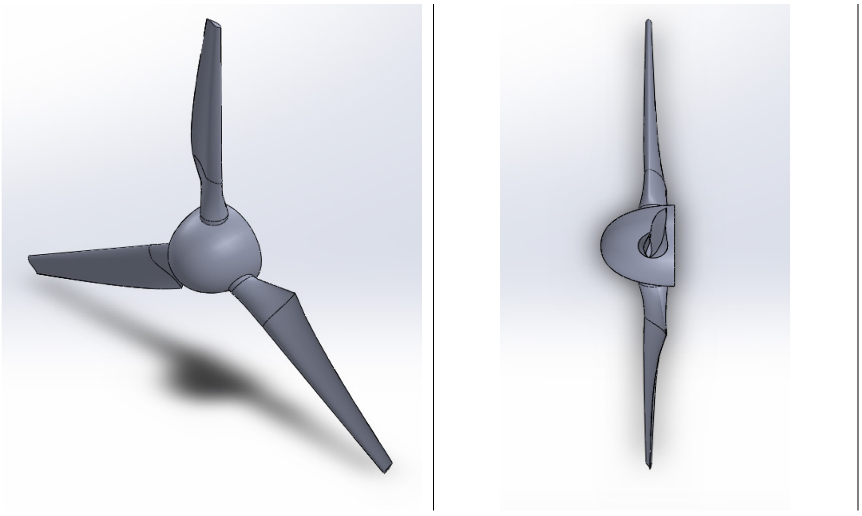
Ansys Fluent software is used in this study to simulate the fluid dynamics inside a tidal turbine using computational fluid dynamics (CFD). Because of this improvement in computer power, CFD is now a useful analytical technique [8]. When a tidal turbine interacts with tidal streams that are influenced by tidal fluctuations, the CFD model calculates torque and power generation. Virtual simulations of tidal turbines using computer-aided design software (SOLIDWORKS) eliminate the need for real prototypes, saving money and staff time before full-scale implementation. Empirical information acquired from the underwater conditions at Penang Port is used to validate the simulations.

2 Methodology

2.1 Turbine blade design

The determination of optimal power generation within the specified aquatic locale entails the careful selection of a current velocity, factoring in tidal amplitude alongside supplementary data detailing tidal current direction and speed, including potential wind-induced fluctuations [9]. This endeavour is undertaken with the intention of evaluating and corroborating the turbine's operational performance, aligning it with the prognostications derived from Computational Fluid Dynamics (CFD) analysis.

In this context, the design parameters are methodically chosen. Specifically, a design current velocity of 1.0 m/s is designated, and a tidal turbine of 0.5 m diameter is employed. Illustratively depicted in Figure 1, both an ISO view and a top view unveil the turbine model's configuration, originating from meticulous calculations involving chord distribution and angle distribution.



(a) Tidal turbine model [ISO view] (b)Tidal turbine model [Top view]

Fig. 1. Figure quality (a) Tidal turbine model [ISO view (b) Tidal turbine model [Top view]

2.1.1 Power estimation calculation

Through the application of the turbine blade specifications outlined in the provided Table 1, coupled with the utilization of the power output equation denoted as Eq (1), a calculated projection of the rated power output is ascertained to be 1610.1 watts.

By implementing the turbine blade parameters as presented in the preceding Table 1, and employing the power output Equation (1) indicated below, the computation yields an appraisal of the rated power output amounting to 1610.1 watts.

$$P = 0.5\rho A V^3 \quad (1)$$

The design of the turbine Tip Speed Ratio is, 5 with a rated angular speed is 7.54 rad/s.

Table 1. Tidal turbine blade design parameters.

Design parameters	Values
Rated power (W), P_{rated}	1610.1
Estimated power coefficient, C_P	0.4
Estimated power train efficiency, n	0.9
Current velocity (m/s), V	1.0
Sea water density (kg/ m^3 ρ	1025
Turbine diameter (m), D	2.0
Blade number, N	3
Angular speed (RPM), ω	47.75

2.1.2 Chord length distribution

The determination of the chord length for an airfoil conventionally follows a formula attributed to Schmitz, expressed as Equation (2), wherein C represents the chord length, N denotes the count of blade sections, λ signifies the Tip Speed Ratio, R designates the rotor blade's complete radius (1m), and r signifies the blade radius of the airfoil.

$$C = \frac{16\pi r}{C_L N} \sin^2\left(\frac{1}{3} tan^{-1}\left(\frac{R}{\lambda r}\right)\right) \quad (1)$$

2.1.3 Distribution of twist angle of the airfoil

The twist angle b is chosen in accordance with Eq (3) so that the sectional airfoil of a blade has the ideal life force coefficient.

$$\beta = \frac{2}{3} tan^{-1}\left(\frac{R}{\lambda r}\right) - \alpha \quad (2)$$

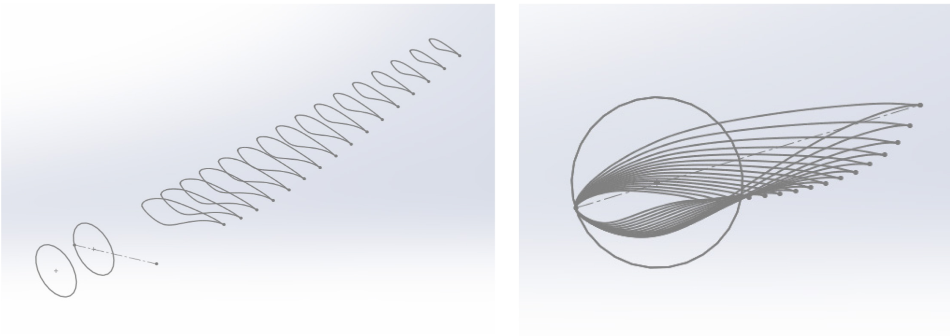
Where the β is the twist angle of the airfoil and α is the angle of attack of an airfoil.

2.2 Tidal turbine blade design

In accordance with the parameters specified in Table 1 of the design, the resultant values detailed in Table 2 were computed. Employing SOLIDWORKS, a software application specialized in three-dimensional modelling, the requisite point coordinates essential for the representation of a comprehensive 3D model were derived. The ensuing framework was then visualized, as depicted in Figures 2 and 3 presented subsequently, utilizing the design information extracted from Table 2.

Table 2 Tidal turbine blade airfoil chord length distribution and twist angle distribution.

r (mm)	Chord length (mm)	Twist angle (degree)
12.5	-	
25	6	-
37.5	6	-
50	Transition	Transition
62.5	12.62	16.682
75	12.07	13.929
87.5	11.52	11.462
100	10.98	9.783
112.5	10.44	8.432
125	9.90	7.324
137.5	9.36	6.404
150	8.81	5.631
162.5	8.27	4.974
175	7.73	4.415
187.5	7.19	3.942
200	6.64	3.784
212.5	6.10	3.55
225	5.56	3.247
237.5	5.02	3.092
250	4.48	3.062



(a) (b)

Fig. 2. Figure quality (a) Blade design chord distribution [ISO view], (b) Blade design chord distribution [Front view].

3 Results

3.1 Calculation of condition

In Figure 3, the external domain, encompassing the outer region, is designated as the bounding boundary for fluid flow. This flow proceeds through an inlet positioned in the negative z-direction. Additionally, an internal domain is established wherein the turbine rotor is in rotational motion, governed by pertinent boundary conditions. The external domain fulfills the role of an enclosing structure, featuring apertures at both termini that are configured in the form of a rectangular contour. This configuration is characterized by dimensions encompassing a width and height of 5 meters, conjoined with a length of 25 meters.

The fluid's velocity condition at the inlet within the external domain interfaces with the interior domain occupied by the rotating turbine. This interaction manifests a velocity of 1.0 meters per second, constituting the standard default velocity attributed to the stream current.

The change in fluid flowing through the turbine was then computed using ANSYS Fluent and the wall condition on the surface of the turbine boundary.

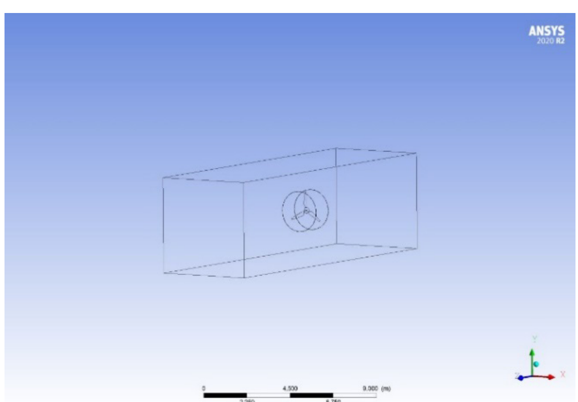


Fig. 3. An enclosure of outer domain part with inner rotating part.

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3.2 CFD analysis result

When operating at a rotational speed of 47.75 revolutions per minute (rpm), with a Tip Speed Ratio of 5, the generated torque reaches a value of 144.49 Nm. The tidal current turbine's performance curve is built with reference to a current velocity of 1.0 m/s. Notably, the output coefficient is 0.45, which is a little higher than the predicted Cp value of 0.40.

Figures 4 show the pressure contours for the anterior (a) and posterior (b) faces of the turbine blade visually. Additionally, the frontal (c) and posterior (d) aspects capture the radial velocity contours that affect the airfoil, while the frontal (e) and posterior (f) aspects clarify the turbulence kinetic contours.

This illustration perfectly captures the thorough flow analysis carried out using computational fluid dynamics (CFD) simulation. Figure 5 provides a thorough representation of the fluid dynamics and streamlines inside the turbine, made possible by the aforementioned CFD research.

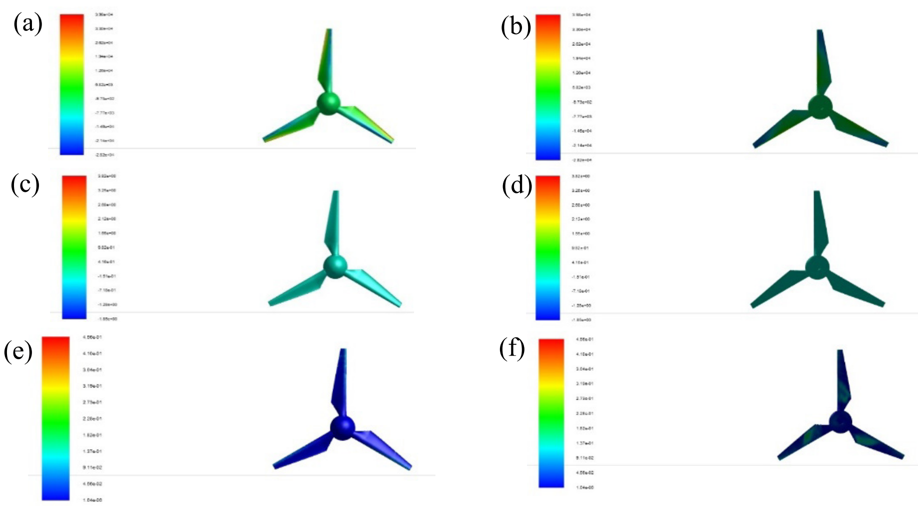

Fig. 4. Contour of the blade post-solution.

Due to the asymmetric geometry of the airfoil's cross-section section, the lift-type type turbine presented in this research utilizes lift generated by fluid differences in pressure.

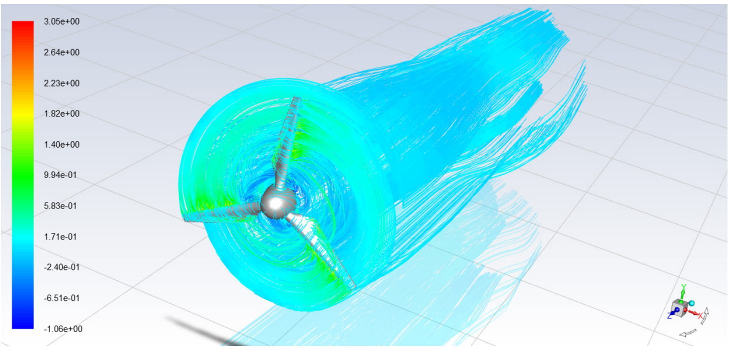

Fig. 5. Pathline of the current stream hitting the turbine rotor.

Table 3. Table of overall results.

Result of power obtained	Values
Current velocity (m/s)	1
Estimated power	1610.06
Calculated power	722.45
Cp	0.45

4 Conclusions

The ensuing outcomes have been derived subsequent to conducting a comprehensive three-dimensional flow analysis utilizing computational fluid dynamics (CFD), and concurrently integrating established turbine design principles for the creation of a tidal current power turbine, as meticulously delineated in Table 3.

In alignment with the outlined design methodologies, a horizontal axis tidal current power turbine with a diameter of 2 meters was meticulously conceived, while judiciously considering factors such as tip loss grounded in turbine design theory, inclusive of blade element theory. To execute this conception, the application of SOLIDWORKS, a proficient 3D computer-aided modelling software, was invoked for the purpose of simulation.

A subsequent examination of the three-dimensional flow characteristics of the model through the utilization of ANSYS Fluent culminated in the generation of an output curve and torque profile. The resultant power coefficient for a Tip Speed Ratio of 5 was found to approximate 0.45, concurrent with an applied current flow of 1.0 m/s. This configuration yielded a maximum torque value of approximately 144.49 Nm, ultimately affording a power generation of 722.45 watts.

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