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Design of a Ducted Cross Flow Turbine for Fiji

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Abstract. Marine current energy is clean and reliable energy source. It can be alternative energy source to produce electricity if tapped with a suitable marine current energy converter. Pacific Island countries (PIC) like Fiji can reduce the amount of Fossil fuel used. However for most energy converters designed perform well at marine current velocities above 2m/s and it needs to be installed at depths of 20 – 40m also installation and the maintenance cost of such devise will be quite high if it needs to be installed in Fiji. Therefore a ducted cross flow turbine was designed, which can give desired output at minimum installation and maintenance cost. A dusted cross flow turbine has been design taking into account for its operating condition. The turbine was modelled and analyzed in commercial; Computational Fluid dynamic (CFD) code ANSYS-CFX. The code was first validated and with experiment results and finally performance analysis of full scale turbine was carried out. The designed turbine can have maximum efficiency of 56% producing rated power of 21kW; it produces 0.77kW at cut in speed of 0.65m/s.

Introduction

Many pacific Island countries (PIC) including Fiji burn a lot of fuel to produce electricity [1]. Due to increase in fossil fuel cost and electricity demand, many PIC's including Fiji are now looking for alternative energy sources for electricity production. Renewable energy technologies are one of the alternative energy sources. Due to limited renewable energy sources available at different location, number of renewable energy sources and technology could be used to keep the electricity grid energized. Marine current energy is one of the promising Renewable energy resources and it can be utilized to meet the electricity demand. Many marine current channels are around Fiji and have good energy potential.

Many marine current energy converters are designed to tap the kinetic energy from the marine current flow. The most commonly used one is horizontal axis marine current turbine (HAMCT), having efficiency between 45 – 48 % [2 -5]. Installing HAMCT in Fiji will be costly both in terms of installation and maintenance. As well as HAMCT is governed by lift therefore, its performance is significantly reduced due to blade fouling [6]. Another major issue with lift governed turbines is, they encounter cavitation very easily, due to pressure being reduced on the blade surface. Cavitation causes blade failures and significantly reduces the turbine performance. Taking into account for above issues, a totally new turbine was designed, called "ducted cross flow turbine". Many cross flow turbines are developed and tested [7-9] for hydro power generation application, here water is delivered from a height, for this case cross flow turbine efficiency normally exceeds 60% [10-11]. However, for open channel flows such as marine current channels, the efficiency of isolated turbine will be less than 59.2% according to Betz criteria. A cross flow designed and numerically analyzed by Kim et al [12], they achieved maximum theoretical efficiency of 51%. The efficiency of isolated cross flow turbines can be further improved by placing a duct around the turbine. Duct can improve the turbine efficiency by 70%, as presented in refs. [13, 14]. Kirke [15] performed studies on a Darrieus hydrokinetic turbine without diffuser and obtained C_P ranging from 0.1-0.25; placing a diffuser increased the C_P to 0.3-0.45.

Present work involves design of ducted cross flow turbine for Fiji; it should have minimized installation and maintenance cost, hence achieving desired output. The turbine was designed, modeled and tested using Ansys-CFX. As well as a model turbine was fabricated and tested experimentally to validate the CFD results. The ducted cross turbine can achieve maximum efficiency of 56% and can produce rated power of 20kW, and it produces 0.77 kW of power at cut in speed of 0.65m/s.

Turbine Design

The turbine size and operating parameters were determined, based on the marine current study done at one of the location in Fiji, the location is named as Gun-barrel passage, and the passage is at coral cost, Sigatoka. This passage has combination of both tidal current and rip current, and the current speed exceeds 2.5 m/s in days of good wave. During 3 month of measurement the average current velocity was 0.85 m/s [1]. The depth of the passage varies from 10m - 20m along the channel and also the width varies from 5–8m. Marine current flow at this location is very turbulent.

For such condition a turbine needs be designed which can give maximum output with changing operating condition. A ducted cross flow turbine will be most appropriate for this condition, giving the best output and reducing the installation and maintenance cost. Fig. 1 shows the schematic of the ducted cross flow turbine. It consists of 4 main parts 1. Nozzle, accelerates flow velocity and guides the flow to the blades, 2. Diffuser, reduces the pressure at the back of the turbines, hence enhancing the turbine performance; 3. Cross flow turbine, converts kinetic energy from the current flow to mechanical energy (shaft power) and 3. Generator coverts shaft power to electrical energy. Ducted cross turbine, is made of very simple components therefore can be easily manufactured without using advanced manufacturing assembly line, therefore, it has lower maintenance cost, compared for HAMCT. Also blade fouling will have minimum effect on turbine performance; the generator is can be mounted over the water for easy and regular maintenance.

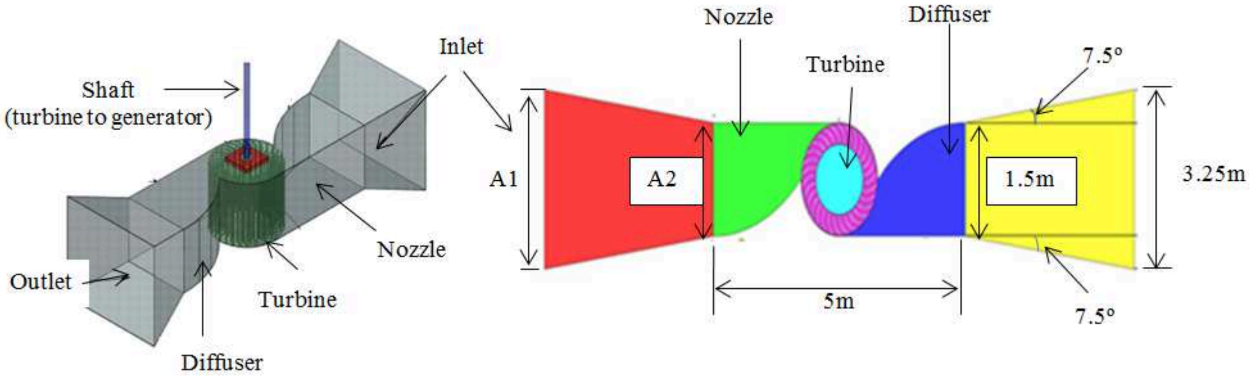

Fig. 1: Schematic of ducted cross flow tubine.

The inlet of the turbine is taken to be 3.35 m x 3.35 m, this allows to have blockage of 25% and does not disturb the flow. The outlet and inlet area ratio (A1/A2) were optimized maximize the turbine efficiency at various operating condition; the optimum area ratio came to 4.7. The diverging and converging angles of outlet and inlets were also optimized for the best performance and optimum angle came to 15º. The length of the Nozzle and diffuser selected to have smooth flow through the duct. Other geometrical details are shown in Fig. 1. The diameter of the turbine was selected to be 1.5 m, this is optimum diameter, and altogether 30 curved blades are used in the cross flow turbine.

Experiment and Numerical Validation

A scaled down model of 1:10 of the turbine was fabricated and experimentally tested. First the duct was fabricated using the Perspex, and then the turbine blades were fabricated using 3 mm thick aluminum sheet. The fabricated model was then tested in a natural water channel of 0.8 m x 0.8 m wide and 3 m long. The torque was measured for 5 different revolutions per minutes (RPM). The results were used to validate the CFD results. For CFD, a 3-D ducted cross flow turbine was modeled using UniGraphics NX 4 package, the dimension were same as experimental model. The 3-D model was then imported and meshed using ANSYS-CFX. The sets of equations solved by ANSYS CFX are the unsteady Navier-Stokes equations in their conservation forms. SST turbulence model was used and the simulation type was transient to capture the rotor fluid interaction more accurately. The time discertization of the equations was achieved with the implicit second order Backward Euler scheme.

The domains and boundary conditions were defined for each of the components; all the domains were stationary except for the turbine which was free to rotate and rotational speed was defined. The inlet velocity was assigned for free stream velocity between 0.65 m/s a to 3.25 m/s. The inlet velocity drops by 20% compared to free stream velocity, this was determined using experimentation. The exit was specified with outlet boundary condition with relative pressure set to 0 Pa. The outside walls of the turbine were modeled as solid wall and non-slip boundary condition was applied. Lastly, appropriate interface regions were created. For interface, the mesh connection method was automatic. High resolution advection scheme was chosen with high resolution turbulence numerics. For convergence control, maximum coefficient loop was set to 10. The torque was calculated at each time-step at given RPM, and once the torque converged, the simulation was interupted and results were computed. Great care was taken while generating the grid. As a check on the accuracy, the results obtained numerically were compared with the experimental data and if the results were way off, then the grid was refined and simulations were caried out once again.

Fig. 2 shows velocity vector of flow across the final model of the turbine computed using CFD at free stream velocity of 1.95m/s. The velocity vector shows smooth flow taking place across the turbine. The results show increase in velocity just after the turbine, this significantly reduces the pressure, hence enhancing the turbine performance.

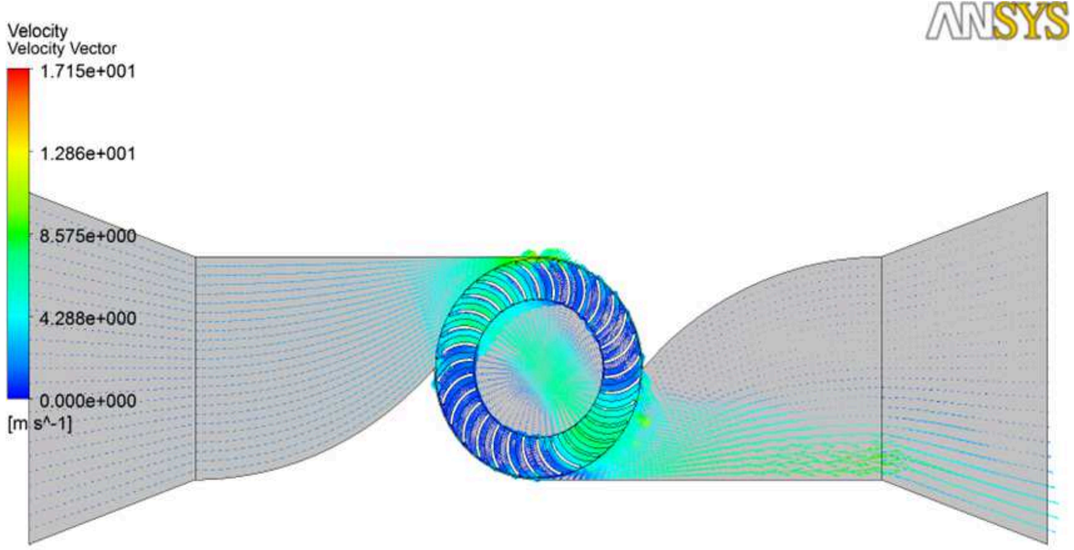

Fig. 2: Velocity vector acros the turbine

Finally the experimental and final CFD results were compared. Fig. 3 shows the results optained by experimentation and CFD results for 1:10 scaled down model. The experiment was carried out at 5 different tip speed ratio (TSR), and CFD analysis was also caried out for same 5 TSR, at free stream velocity of 1.04m/s. The results shows very good agreement between the experiment and CFD results. The CFD results is underpredicted by aproximatly 6%, which means actual performance of the turbine will be 6% higher compared to CFD achived. This promises that CFD analysis can be used to analyse the performance of the full model.

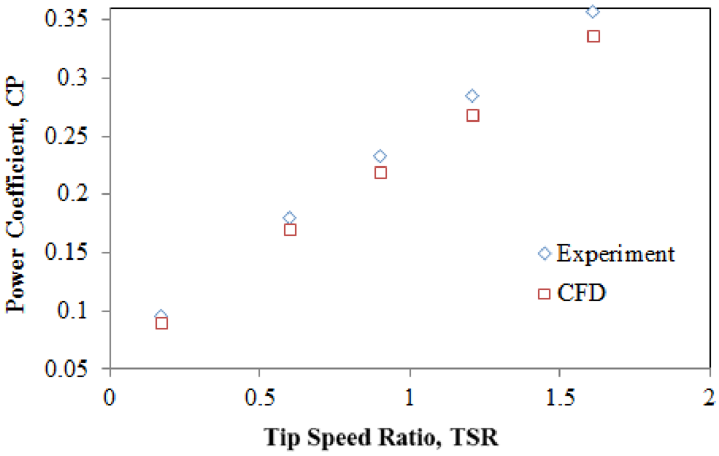

Fig. 3: Power coefficient obtained by experimentation and CFD

Performance Analysis of Full Model

The performance of the full model was analyzed using Ansys-CFX, the analysis was done for free stream velocities of 0.65m/s, 1.95m/s and 3.25m/s. For these free stream velocities torque was measured at the blade at different TSR, and the power out and power coefficient was calculated, using the output results and equation 1 and 2.

$$P = T \times \omega \tag{1}$$

$$C_P = P / (0.5 \times \rho \times A \times U_o^2) \tag{2}$$

Where, P is power output (W), T is Torque (N), ω is angular speed (rad/S), C_P is Coefficient of power, ρ is the density of sea water, A is the cross sectional area the turbine (m^2), and U_o is the free stream velocity (m/s). The performance of the turbine at difference TSR is shown in Fig. 4. The turbine gives maximum efficiency of 54% at TSR of 3.2, for free stream velocity of 0.65m/s and 1.95m/s, the maximum efficiency slightly increases to 56% for free stream velocity of 3.25m/s. The maximum power output at rated speed is 20kW and for cut in speed is 0.77kW.

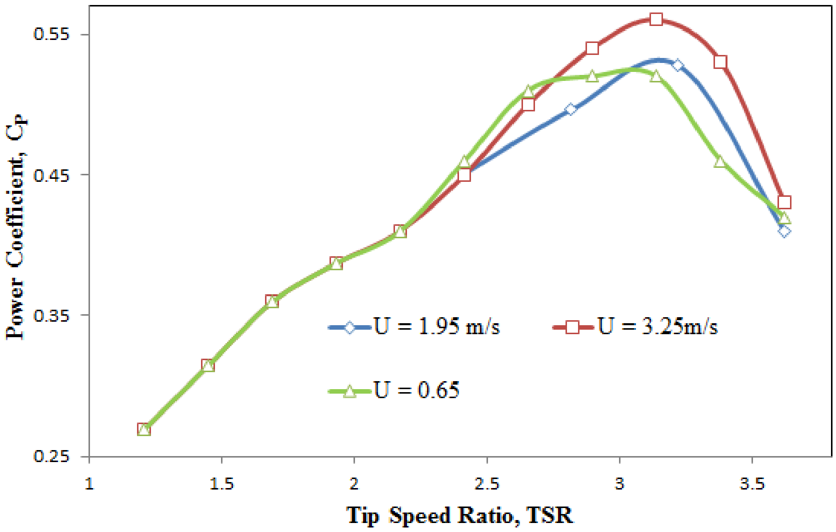

Fig. 4: Turbine performance at free stream velocity between 0.65m/s to 3.25m/s

Conclusion

A ducted cross flow turbine was successfully designed and performance analysis was carried out. The CFD results were validated with experimental the result, which shows very good agreement. Such turbine will very suitable for Fiji and for PIC's. This turbine will have lower manufacturing, installation and maintenance cost compared to HAMCT and hence giving the designed output. Other advantages includes, the chances of cavitation is reduces for this type of turbines and it can be installed at channels with lower depth. The designed turbine has maximum efficiency of 56%, and can produce rated power of 20kW, and can produce 0.77Kw of power at cut-in speed of 0.65m/s.

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