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Article

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Comparative investigations for performance and self-starting characteristics of hybrid and single Darrieus hydrokinetic turbine

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Abstract

Hydrokinetic turbine technology is an emerging field to produce clean energy from the riverine systems. Lot of hydrokinetic potential sites are available to provide the energy to the people living in those areas. Under the present work, two different hydrokinetic turbine rotors (hybrid and single Darrieus) are evaluated in term of performance and flow across the rotor. The flow velocity of water is considered as 1.0m/s and the model for both type of rotors are designed and modeled along with an open channel. Based on the investigations, it has been found that hybrid rotor is more efficient for hydrokinetic turbine and yields about 9.9% higher power coefficient (C_p) than single Darrieus rotor. The average torque coefficient (C_T) for hybrid rotor has also been found 15.9% higher than single Darrieus rotor with less fluctuations in torque. The results obtained from the numerical investigations are validated with experimentation results. Flow contours across the turbine rotor were plotted and smooth flow was observed with low-pressure range for hybrid rotor while the single Darrieus rotor experience a flow re-circulation zone with high-pressure range.

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Keywords: Hydrokinetic; Power coefficient; Flow velocity; Darrieus; Starting capability

1. Introduction

In the quest for non-conventional energy resources, hydrokinetic energy available in small water streams, canals, man-made channel may be the suitable alternative source of energy. The technology used to harness these potential site are commonly known as hydrokinetic turbine. Hydrokinetic turbine are similar in design and working concept to wind technology and usually categorized in two viz. Axial flow hydrokinetic turbines and cross flow hydrokinetic turbine. Cross flow hydrokinetic turbine are usually recommended for riverine systems having low depth applications. The efficiency of cross flow turbine usually decided by the rotor used. Darrieus rotor has been

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Nomenclature

C_P	Coefficient of Power (C_P)
C_T	Coefficient of Torque (C_T)
λ	Tip Speed ratio (TSR)
θ	Attachment angle

suggested by various investigators for its superior efficiency. However, Darrieus rotor suffers the problem of self-starting phenomena. It is therefore various feasible solution are available to maintain the self-starting of hydrokinetic turbine rotor without reducing the performance [1].

The concept of combined/hybrid rotor with Savonius and Darrieus rotor was introduced for cross flow hydrokinetic turbine which has the characteristics of both type of rotors [2]. Various experimental and numerical investigations have been carried out to improve the design of both single Darrieus and hybrid cross flow rotor. In this way, 20 different airfoils from various series were investigated for Darrieus rotor and found that S-1046 airfoil of S-series yields the maximum performance as 0.4061 which is about 26.83% higher than the conventional NACA airfoils [3]. Patel et al. [4] investigated experimentally the Darrieus hydrokinetic turbine at different solidity and also found the optimum placement for hydro farm application. The study concluded that the NACA0018 airfoil has the maximum performance as 0.16 and 0.13 at 0.382 and 0.398 solidity for a three and four bladed rotor respectively.

In case of hybrid rotor the relative placement of individual rotor significantly influence the outcome of hydrokinetic turbine. Attachment angle and radius ratio for a hybrid rotor (two Savonius blade and two Darrieus blade) hydrokinetic turbine govern the placement and it is reported that radius ratio as 0.2 and 30° and 60° attachment angle are optimum parameters having maximum performance as 0.34 [5]. Kyojuka [6] experimentally tested a Darrieus–Savonius rotor based hybrid rotor and concluded that the axis of the two rotors should not be co-axial. Darrieus and hybrid rotor was compared in term of power coefficient and 30% reduction in power coefficient was observed for hybrid turbine rotors. Hybrid hydrokinetic turbine was evaluated in field with two semi-elliptical shaped Savonius rotor blades along with three NACA0015 Darrieus blades and it has been found to have maximum performance with 0.36 radius ratio along with 60° attachment angle [7].

Under the present investigations, a comparative analysis of the performance (self-starting and power coefficient) and flow field across the hybrid rotor are investigated numerically and compared with the single Darrieus rotor. Further, the results of the study was validated with the experimental results. Three dimensional (3D) simulations were performed in the CFX solver module of ANSYS.

2. Numerical methodology

2.1. 3D modeling and grid generation

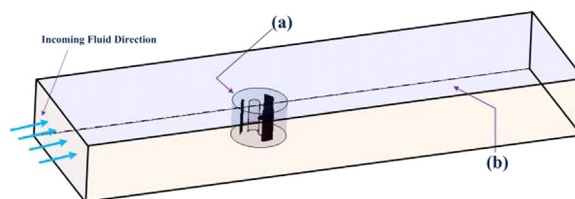


Fig. 1. 3D modeling (a) Rotating domain; (b) Stationary domain.

The computational domain of the study was modeled with the channel dimension having the cross-section of 0.7 m (width) \times 0.3 m (water height) and 4.0 m in length. The rotor having the diameter of 0.175 m and height of 0.160 m was modeled in the channel with 13.3% blockage. Three S-1046 airfoils are used for Darrieus rotor along with two semi-circular shape blade for Savonius rotor [3]. Based on earlier studies, 0.3 radius ratio and 90° attachment angle is adopted for present hybrid rotor. A rotating domain (enclosure) with 1.1 times the turbine diameter is created across the turbine blades. The rotor channel 3D model is the resemblance of the hydrokinetic

turbine in channel and is shown in Fig. 1. The complete 3D model is discretized with un-structured mesh and the grid convergence exercise is carried out to obtain the grid independence results. The mesh with less than 0.15% numerical uncertainty in results (power coefficient) was chosen for numerical analysis having the mesh elements of 14.65 million. To visualize flow field at turbine walls, 20 inflation layers are provided with a growth rate of 1.01. Mesh of the flow domain is presented in Fig. 2.

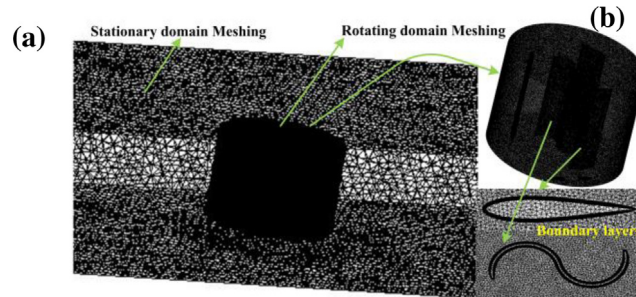


Fig. 2. Meshing of (a) Rotating domain; (b) Stationary domain.

2.2. Boundary conditions and turbulence modeling

3D computational domain was required to adopt the suitable boundary conditions based on the actual operating conditions provided in the CFX solver which are given in Table 1. A Moving Mesh/sliding mesh motion (SMM) approach is used to simulate the rotating behavior of the turbine rotor. In order to solve the Unsteady Reynolds Averaged Navier Stokes (URANS) equations, RNG $k-\epsilon$ turbulence model along with wall function (scalable) is utilized to simulate the flow over the rotating flow field across the turbine and to model the circulated flow vortices and eddies [8]. Further, transient simulations corresponding to 10° rotation at each time step are carried out and a convergence criteria of 1×10^{-6} was set for the residuals. The rotor was allowed to rotate 6 revolutions with 216 time steps.

Table 1. Boundary conditions for present numerical simulation.

Location	Boundary condition	Boundary type
Inlet	Velocity inlet	Dirichlet (flow velocity = 1.0 m/s)
Outlet	Pressure outlet	Dirichlet (Atmosphere pressure)
Upper surface	Wall	Moving wall (with flow velocity)
Side wall	Wall	No-slip
Turbine rotor	Wall	No-slip (Desired RPM)
Contact surface of domain	Interface	Symmetry

3. Experimental setup

To carry out the experimental validation of numerical results for both turbine rotors, model of each rotor was fabricated with the dimensions adopted under numerical analysis. The turbine model was developed in the 3D printing facility available in Tinkering Lab IIT Roorkee with PLA as the printing material. The model is attached with the mechanical dynamometer through a supporting structure to measure the torque. Both hybrid and the single Darrieus rotor were tested at the hydrokinetic turbine test rig available at Department of Hydro and Renewable Energy, IIT Roorkee. Water flow in Channel is maintained by two parallel connected axial flow pumps having the flow capacity of $0.15 \text{ m}^3/\text{s}$ each. The flow velocity in channel is controlled by the regulated valve and a lift to control the channel slope. The slope and the flow of the water are adjusted in such a way that the rotor is always submerged in the water. Tests are carried out with the constant flow velocity of 1.0 m/s (measured through current meter and water velocity logger). The RPM of the turbine is measured by a digital tachometer and the performance of the turbine is evaluated at different RPM by varying the load on the turbine rotor. The model with supported structure was properly lubricated before each set of experiment and the observation is repeated twice to minimize the recording error. The complete experimental facility along with model schematic can be visualized from Fig. 3.

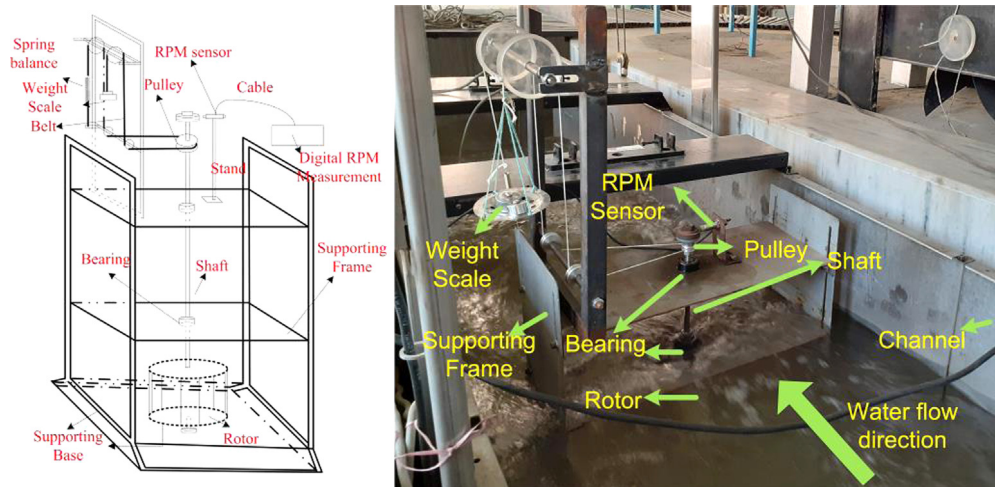


Fig. 3. Experimental facility schematic and laboratory view.

4. Results and discussions

4.1. Visualization of flow across hybrid and single Darrieus rotor

The flow contour across both (hybrid and Darrieus) turbine are plotted corresponding to maximum performance conditions i.e. at 0.8 value of TSR as presented in Fig. 2. Low pressure zone is witnessed in back sideways of airfoil and the intensity of the wake is more in single Darrieus rotor which generate the water re-circulation and can be visualized by velocity streamline in single Darrieus contours (Fig. 4(b)). A smooth flow is observed in the rotating domain of hybrid rotor (Fig. 4(a)). It is confirmed from the velocity contours of both the rotors that water approach the turbine blade with the given input velocity condition (1.0 m/s) therefore almost no variation in velocity is experienced in the upstream side of rotor. The flow contours obtained under present investigation have also been compared with the contours of earlier investigations and these follow the similar trends [5].

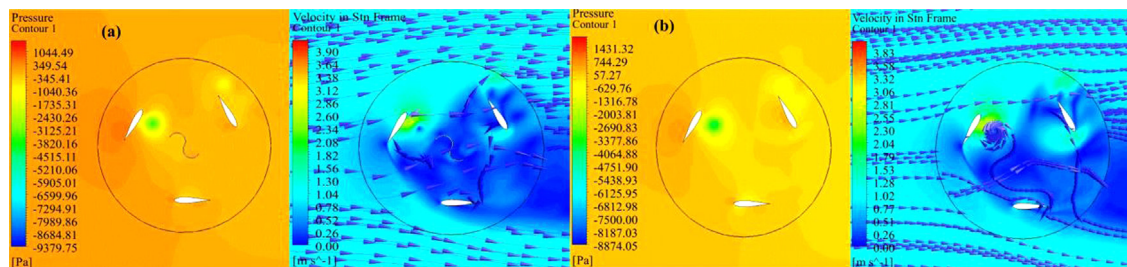


Fig. 4. Flow contours of pressure and velocity for (a) Hybrid rotor; (b) Single Darrieus rotor.

4.2. Performance and self-starting characteristics

The performance of both (hybrid and single Darrieus) hydrokinetic turbine are assessed in term of coefficient of power (CP) and torque coefficient (CT). Flow velocity as 1.0 m/s is considered with different rotation and hence the TSR (0.2, 0.5, 0.8, and 1.1). The performance curves (C_p vs. TSR and C_T vs. θ) have been plotted to analyze the performance of different rotor. Hybrid rotor with Savonius as the inner rotor yields its maximum coefficient of power (CP) as 0.08 at 0.82 value of TSR while single Darrieus rotor is about 9.9% less efficient than hybrid rotor and yield its maximum performance as 0.0728 at 0.84 TSR value. It has been observed that experimental results validate the numerical results as shown in Fig. 5(a). The average torque generated by hybrid and single Darrieus rotor is 0.13 N m and 0.11 N m. Further, the presence of Savonius rotor in hybrid rotor equally distribute the force

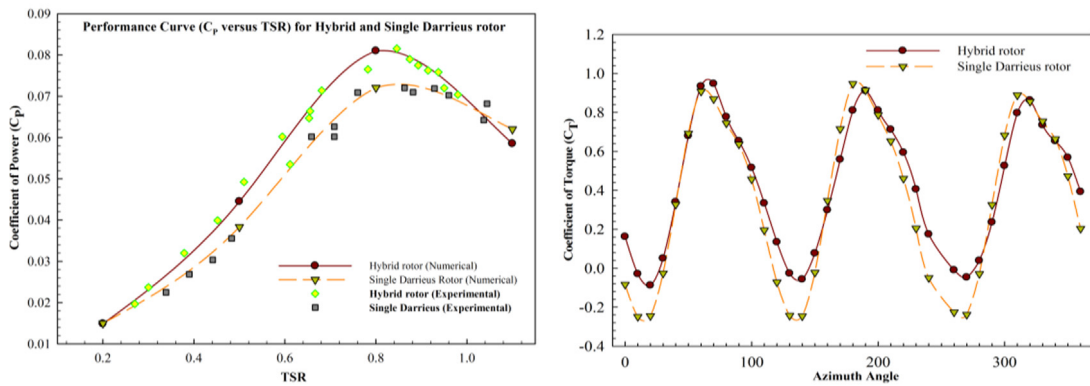


Fig. 5. Performance curves (a) Power coefficient (C_p) vs. TSR (λ); (b) Torque Coefficient (C_T) vs. Azimuth angle (θ).

(resultant of lift and drag) at each azimuth positions on turbine blades and lower the fluctuation in generated torque. The lift/drag ratio for Darrieus rotor is high in comparison to hybrid rotor, therefore, it experiences more negative peaks in torque coefficient at several azimuth positions i.e. 10° , 130° , and 270° as shown in Fig. 5(b).

5. Conclusions

In this work, the comparative evaluation of the hybrid and Darrieus hydrokinetic turbine rotor has been performed at constant water flow velocity of 1.0 m/s under different operating conditions. Based on the investigation, hybrid rotor is found to be suitable for hydrokinetic turbine which shows the maximum coefficient of power (C_p) as 0.08 at 0.81 value of TSR. The results of the numerical investigation are validated with experimentation and are found under similar range. Maximum error of 1.25% was observed in the maximum power coefficient (C_p) for hybrid rotor hydrokinetic turbine. Therefore, good agreement between experimental and numerical results are achieved. Further, in case of hybrid rotor, the fluctuation in torque coefficient (C_T) is also found to be lower with an average torque of 0.13 N m. The flow across the turbine vicinity confirmed that hybrid rotor experiences smooth flow and lower pressure range. Lower fluctuation in torque coefficient and low-pressure range for hybrid rotor may reduce the stress over the turbine body. The present study may be helpful to select the rotor for a given hydrokinetic potential site with better performance and self-starting capability.

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