Experimental and Numerical Analysis of Fish Friendly Water Turbine For Small Scale Power Generation

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Abstract: - In a modern world, tremendous advancement in electronic technology played important role in the 21st century. However, many remote areas of the world are still not introduced with electric power. Some barriers are their while setting up of power grids. Off-grid energy generation is the one solution for this problem face by remote areas. The majority of the off-grid energy solutions are required to develop this remote area, but those are costly and not environment-friendly. This turbine is characterized as horizontal axis hydrokinetic turbine perpendicular to flow of water in the open channel. This research paper examines on 'floating water turbine', its advantage and effective alternative to fossil fuel based on producing power generation in remote areas. To understand the development of turbine design and actual working in water application, an experimental result was computed with the Computational Fluid Dynamics (CFD) analysis by considering same input flow velocity. The performance of turbine is measured by a computational fluid dynamics analysis along with an experimental work in the Hydro machinery lab. The turbine is rotated by water flow with a flow velocity within a range of 0.58 m/sec to 1.65 m/sec in an open channel viz. rivers, streams, and canals. The research paper also discusses the methodologies chosen while designing the turbine and computing result were based on various parameter viz. Maximum power, torque, RPM, Tip Speed Ratio (TSR) and coefficient of power.

Key-Words: - Horizontal axis hydrokinetic turbine, CFD, Maximum Power, TSR and Coefficient of Power.

1 Introduction

In the 21st century, over 1.1 billion people are unknown about getting access to electricity. Majority of these people are located in remote areas, where conventional power grid generation is not possible. Some off-grid energy solutions are required for providing electricity to remote areas [1]. Even though such solutions were provided, then most of these technologies require high capital investment and also complex to install. Major off-grid power required diesel or other fossil fuel to generate energy source. Fossil fuel for power generation is costly and complex for a process. The transportation of fuel is required, from readily available sites to the remote locations for power generation [2].

Hydrokinetic turbine is used to generate power technology and it extracts the hydrokinetic energy from the incident flow of water, it will get from low velocity and head. The report summited by the department of energy (USA) in the year 1980 that, in low-pressure rivers and low head condition turbine will be operated i.e. head of the equivalent or less than 0.2 m [3]. Hydrokinetic turbines are launched by the company in the year 2002. The company named Marine Current Turbines Pvt. Ltd. installed the world's first hydrokinetic turbine alongshore ocean current location and these turbines generated the 310 kW rated power in that location [4]. The hydrokinetic turbines are categories by four ways viz. based on the direction of the incident water flow and an axis of their rotation viz. cross-flow turbines, vertical axis turbines, inclined axis turbines and horizontal axis turbines. The horizontal axis hydrokinetic turbines are installed in the river, canal, and stream as energy converters [5].

It is required to place a hydrokinetic water turbine on a floating body across a water stream. However, hydrokinetic turbines are still in a development period and still, the turbine is not been totally commercialized in the market [6]. Horizontal axis hydrokinetic turbines are more suitable than the vertical axis hydrokinetic turbine, it consists of some efficient features.

Since horizontal axis turbine have less torque fluctuation, easier self-starting, larger speed operation and higher efficiency [7]. The very important component of a turbine system is a conversion of hydrokinetic energy of the water current into mechanical energy with help of turbine blades [8]. It contains the shaft and three blades in turbine system. In a hydrokinetic turbine, blades are assembled by bolts to the shaft. As mechanism is

Nomenclature

d	Shaft diameter (m)
D	Turbine diameter (m)
H	Turbine blade height (m)
H_C	Channel height (m)
$R1$	Blades radius (m)
R	Turbine radius (m)
Re	Reynolds number
T	Torque generated in the shaft (N-m)
U	Flow velocity (m/s)
Z	Number of blades
A	Surface area of the turbine - H*D (m^2)
C	Chord length of the blade (m)
C_P	Coefficient of power
P_{max}	Maximum power of fluid flow (W)
P_{rot}	Power extracted by turbine shaft (W)
RPM	Rotational speed of the turbine
TSR	Tip speed ratio
FFWT	Fish Friendly Water Turbine
CFD	Computational Fluid Dynamics

simple, so maintenance made locally and the components are readily available. Floating water turbines require minimum maintenance and operate continuously irrespective of time [9].

Even though the power output of a single unit is minor, by setting up of multiple units output can be increased. The adequate electricity generated for basic uses like water pumping, lighting, refrigeration of medicines in camps, etc. [10]. The performance of the shaft depends on the tip speed ratio, number of blades, blades pitch, chord length, type of airfoil, distribution along the blade span, the coefficient of power and twist [11]. This paper focus on the procedure is utilized, step by step is explained and involved in experimental and CFD analysis of a horizontal axis turbine perpendicular to flow of water. These turbines are required to develop electrical power at offshores in a remote area in developing nations [12].

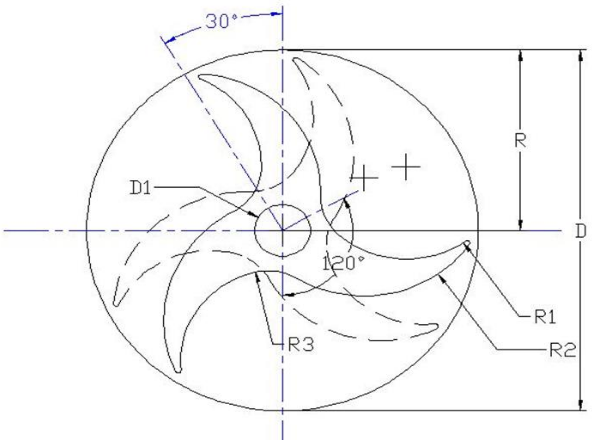

Fig.1 Schematic Diagram of Fish Friendly Water Turbine

2 Experimentation

As it is discussed about the hydrokinetic turbine, the proposed design of FFWT also consist of three blade turbine and it also considered for the experiment as shown in fig. 1. The material used to fabricate the turbine blade is PVC sheets. The PVC sheets having the thickness of 5 mm and turbine blade is constructed by cutting the aero-foil profile on the sheets. Then cut profiles of turbine blade were joined by the material known as Araldite, one by one joining of profiles and also given the curved angle of 30^0. In this way, the FFWT blade is constructed as shown in fig. 3. The cross-section of the turbine is measured with a chord length of 0.14 m. Turbine blade width and surface area of a single blade are 0.3 m and 0.72 m^2 respectively.

Experiments are carried out for different flow velocity in an open channel in Fluid mechanics Lab. The open channels have 3.6 m length with an effective width and height of 0.46 m and 0.54 m respectively. The flow discharge through the open channel is approx. obtained as 42 l/s and the constant depth of water in the open channel is 0.4 m. However, discharge changing gate in the outlet is required to change the depth of water and it can be increased or decreases according to the need by changing the discharge [1].

Water is circulated from tank to the open channel with the help of single centrifugal pumps and it is installed by Kirloskar Brothers Ltd. Consist the rated power of 10 hp. An additional pump of 12.5 hp is kept in working in the system, which is required to increase the flow velocity in the channel by changing the discharge. In the present, the study is required to know the performance of the fish-friendly water turbine in the actual sense so it can be installed to each and every individual person [1].

The incident flow of water with a flow velocity (U) carries the kinetic energy within the flow that can be expressed as

2.1 Experimental Calculation of Turbine

The incident flow with a flow velocity carries the energy of the flow

$$P_{max} = \frac{1}{2}\rho A U^3 \tag{1}$$

The torque generated can be expressed as

$$T = \frac{1}{2}\rho A R U^3 \tag{2}$$

The Power extracted by Water Turbine from flow

$$P_{rot} = T\omega \tag{3}$$

One of the Primitive factor, which relate the velocity of the flow velocity and the velocity of the tip of the blade i.e. Tip Speed Ratio (TSR)

$$TSR = \frac{0.5\omega D}{U} \tag{4}$$

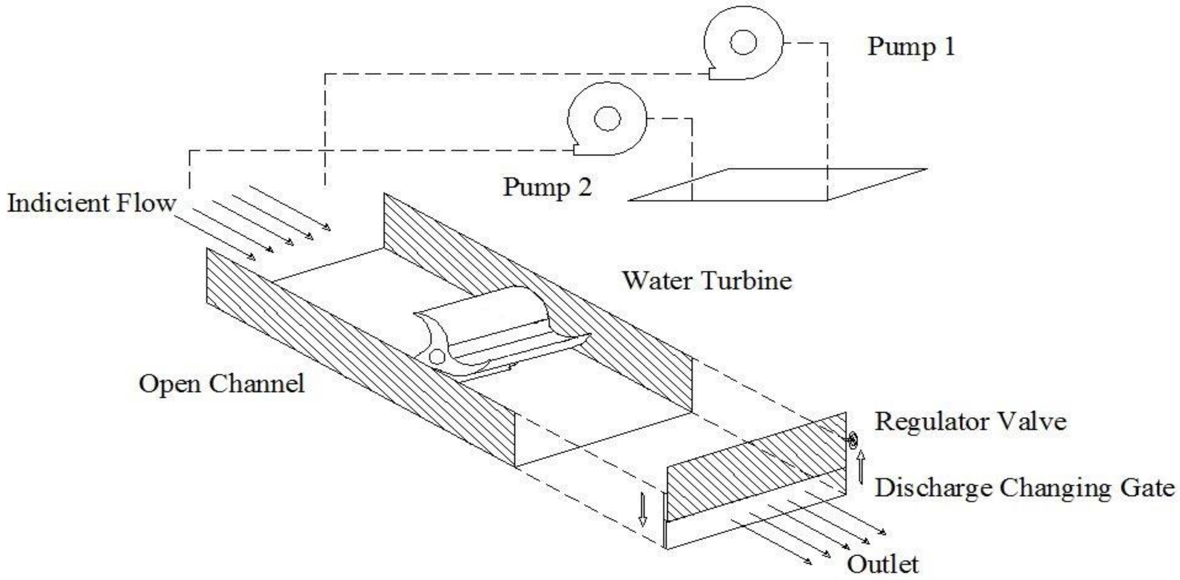

Fig. 2 Schematic of Experimentation of Fish Friendly water turbine

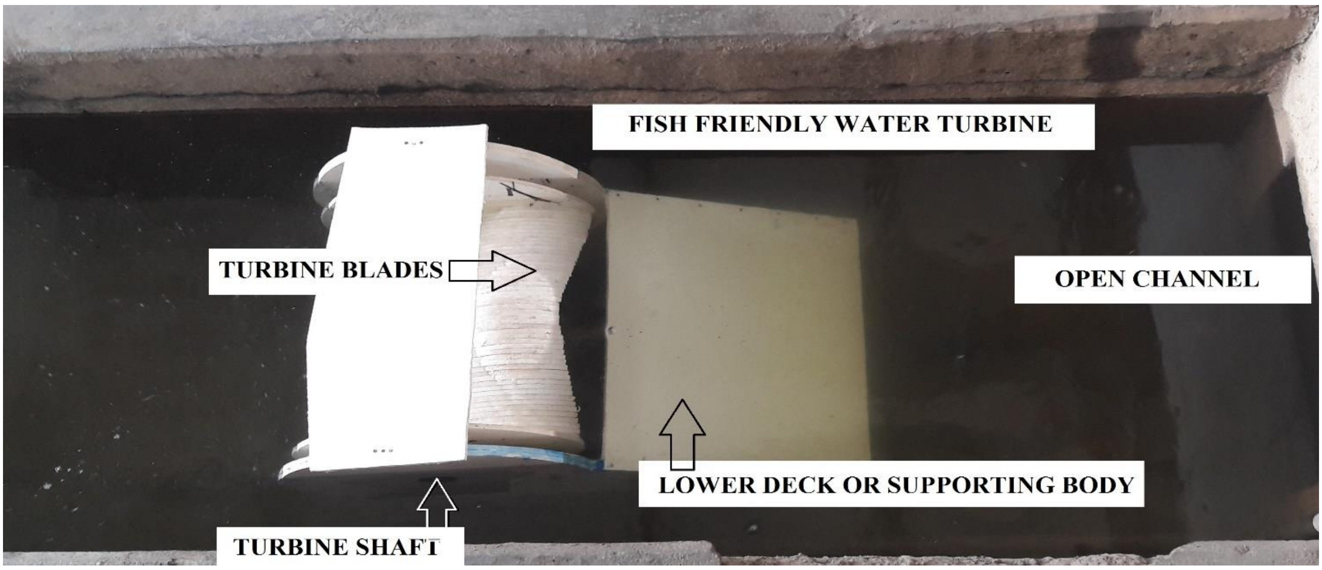

Fig. 3 Merged water turbine in the open channel

The coefficient of power determine the fraction of power that is extracted by the turbine,

$$C_p = \frac{P_{rot}}{P_{max}} \quad (5)$$

The results for the 1.16 m/s flow velocity are discussed. The coefficient of power and tip speed ratio is 0.569 and 0.911 respectively. Similarly for flow velocity 0.58 m/s and 1.65 m/s same experimental procedure is applied.

3 CFD Analysis

In CFD Analysis domain is considered an open channel is 1.82 m length with a proportional width and height of 2 m and 0.8 m respectively. Turbine profile is located in inner domain of diameter 0.24 m. CFD Analysis is carried out in Fluid Fluent Ansys 18.2. As it is a problem of fluent and dynamic, so sliding meshing is done to get RPM of turbine from free flow velocity of 1 m/s. The problem is frame motion type. The Final step is to get a result and compare with Experimental values.

Geometry consists of three-part i.e. flow domain, inner domain, and turbine. Two walls represent inlet and outlet for water should flow passing through the turbine. Now dimension of turbine consist blade angle of 120^0, the chord length of 0.14 m and thickness of the blade is 1.5 mm. Outer circle represent the boundary between flow domain and inner domain, it has diameter 350 mm. A rectangle is main flow domain represents the part of a river to initiate the flow of water. It has a dimension of length 1000 mm and 600 mm.

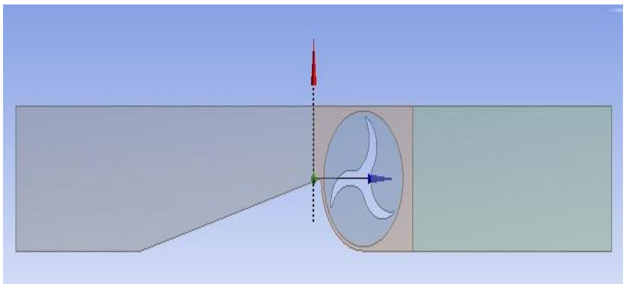

Fig. 4 Geometry of 2D Fish Friendly Floating water turbine

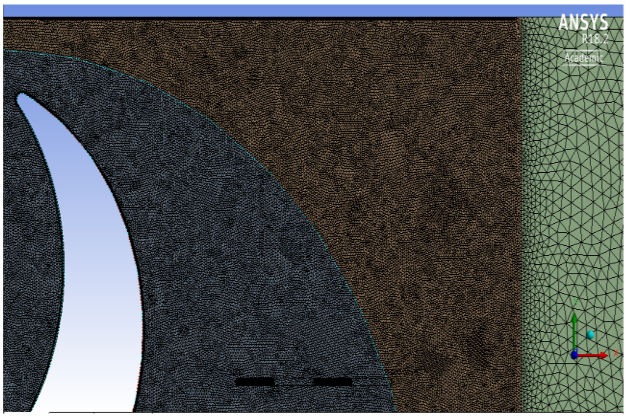

Fig. 5 Meshing of Fish Friendly Floating water turbine

Mesh consists of three parts similar to geometry. Flow domain and the inner domain has Maximum Face size of mesh 0.002 m. The method used for meshing is triangular for flow domain and inner domain only. High-resolution meshing is done. Facing mesh is applied on green zone and fine mesh is applied to the blue and red zone to get the result more accurate.

Turbine represents the boundary in the geometry. Boundary meshing method is applied on turbine known as Inflation method. The maximum layer is given while meshing is 5 layers. Inflation method is used when there is a chance of frame motion i.e. the dynamics motion is given to any part of a body. So, while moving the mesh changes to point to point. And inflation layer helps out to moves smoothly and give an accurate solution to the problem.

The setup contains six steps to be followed to solve the problem in given condition. Transient simulation is used because it is a dynamic simulation. Transient modeling is a way of looking at a process with the primary criterion of time, observing the pattern of change in the subject being studied over time. As in study water is flowing, so it has gravity effect in a downward direction. Gravitation Acceleration value is assigned in Y-axis i.e. -9.81 m/s^2.For this type of problem viscous-laminar model is used. In viscous model further option are selected i.e. k-epsilon (2 equation) and near a wall, treatment is considered as scalable wall function.

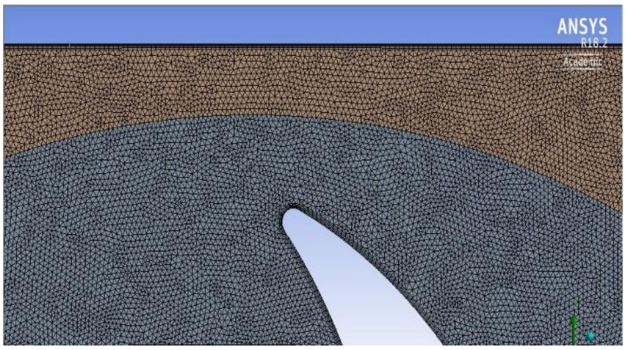

Fig. 6 Inflation Layer on turbine blade boundary

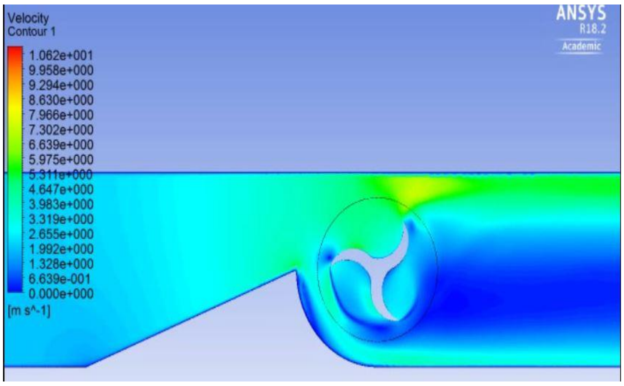

Fig. 7 The solution of Fish Friendly Floating water turbine

K-epsilon is used to analyze the mean flow characteristics for turbulent flow condition because the velocity of flow is low and flow is rough. Scalable wall function is used when the problem has mesh refined below Y+30.

In material, flow domain and inner domain it contains water as material. Water (H2O liquid) is available is the Fluent database. At normal temperature, a density of water is 998.2 kg/m^3 and viscosity is 0.001003 kg/m-s. Material assign to a turbine is PVC composite material, it has density 1480 kg/m3.In cell zone condition check the flow domain and inner domain contain operating condition as a similar i.e. density of water value is assigned to flow domain and inner domain. In boundary condition, inlet section velocity magnitude value is given as 1.16 m/s. Dynamic Mesh is the important parameter in the setup. In dynamic mesh lead to three option i.e. smoothing, layering and re-meshing. In smoothing diffusion is selected and boundary distance is kept. Then in layering split factor is kept at 0.2 and collapse factor is 0.15. In re-meshing local cell is selected and maximum length scale, minimum length scale and maximum cell skewness (0.5) are copied from mesh scale info.

In the Dynamic mesh, a main important parameter is defining six degrees of freedom. Going in settings in six DOF, select one DOF rotation, assign the moment of inertia and specific the center of rotation.

The M.I of a turbine is calculated in software i.e. Rhino software. So, in this problem, M.I is 0.0024Kg-m2. Another process is applied for six DOF by compiling User Defined Function Program. Now creating, inner domain, domain, and turbine in dynamic mesh zones. Inner domain and turbine have a rigid body. Flow domain in deforming a body. In smoothing and re-meshing zone, a parameter is selected and maximum length scale, minimum length scale, and maximum cell skewness are copied from zone scale info.

Now, the whole setup is prepared and to save this setup case file is saved. Whenever the setup is open values are auto-saved because case file is reloaded. In this way, the setup is made for Water turbine for suitable flow condition. In solution, hybrid initialization is done and calculates the problem. Two thousand iterations are giving to for initial calculation. The scaled residual graph is converged i.e. it represents solution is correct. In the 3D model width of a turbine is taken as 0.4 m and width of flow domain is taken as 0.6 m. Result observed for fish-friendly water turbine for the flow velocity i.e. 1.16 m/sec. Similarly, for the flow velocity 0.58 m/sec and 1.65 m/sec are carried out by changing the value in a setup in CFD analysis (18.2).

The Coefficient of power and TSR are extracted by the turbine is 0.813 and 1.343 respectively. Similarly, by calculating for a flow velocity of range 0.58 m/s and 1.65 m/s result are observed and values of Coefficient of power and TSR.

4 Result and Discussion

The result given by CFD and Experimental analysis are shown in the form of a graph to interpret them and to get the basic terms about the parameter. Some parameters are considered to know the performance of study done in fish-friendly floating water turbine viz. RPM, maximum Power, torque, and rotational power, the coefficient of power and tip speed ratio.

For different flow velocity in CFD and Experimental analysis, RPM is shown in fig.8. The RPM values in CFD analysis are greater than the Experimental for different velocity. As it is seen that, the nature of graph of both the line is similar in RPM values and if the trend is considered then it is a straight line. While experimentation due to some constraint in experiment setup the RPM values is less than the CFD analysis for different flow velocity as shown in a graph.

The increase in Flow velocity there is an increase in torque is shown in fig.9. This due increase in the pressure force of water while flow. But the nature of graph shows that the value of torque is an increase in straight line. The fig.10 shows the increase in velocity there is an increase in Maximum Power. Maximum power is directly proportional to the cube of flow velocity by dimensional analysis. But the nature of graph shows that the value of torque is increased in a cubical curve.

The fig.11 shows the variation of Maximum power to the rotational power of the hydrokinetic turbine. Maximum power is extracted from the flow of water and rotational power is measured from the shaft of a turbine by calculating and measuring RPM. As it is seen that the nature of graph of both the line is similar and if the trend is considered then it is straight lines. While experimentation due to some constraint in experiment setup maximum power values is less than the CFD analysis for different flow velocity as shown in a graph.

The variation in the experimental and CFD analysis in the TSR for different flow velocity is shown in fig.12. It is seen that there is fall in the experimental values for flow velocity 1.16 m/sec and 1.65 m/sec respectively. This fall is due to some constraint in the experimental setup or it while measuring the RPM values for different flow velocity. Similarly, there is the variation in the experimental and CFD analysis in the Coefficient of power for different flow velocity as shown in fig.13. The experimental results are less than the CFD result due to some constraint in the experimental setup. Similarly, there is fall in the experimental values for a flow velocity of values 1.16 m/sec and 1.65 m/sec.

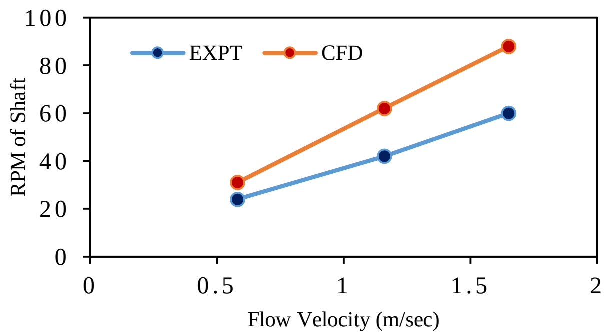

Fig. 8 Comparing the Experimental and CFD result of turbine shaft RPM to the flow velocity of water

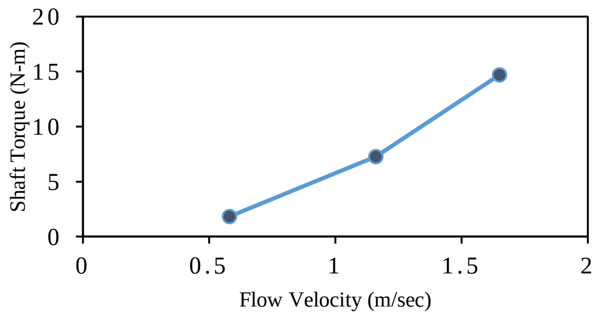

Fig. 9 Experimental result of torque of turbine shaft to flow velocity of water

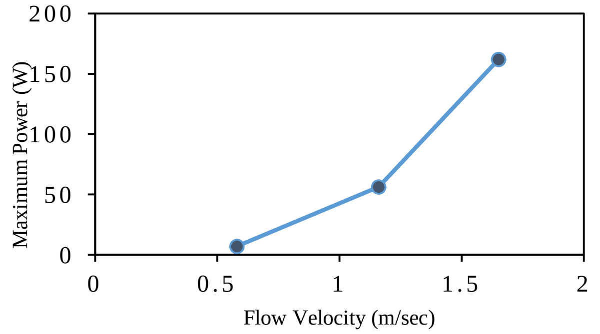

Fig. 10 Experimental result of Maximum Power incident by the flow to flow velocity of water

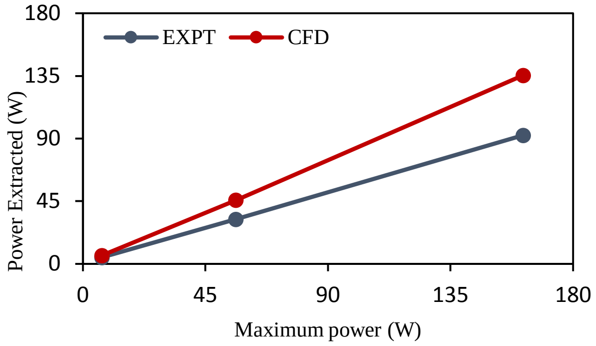

Fig. 11 Comparing the Experimental and CFD result of Power extracted from water flow to Maximum Power incident by the flow

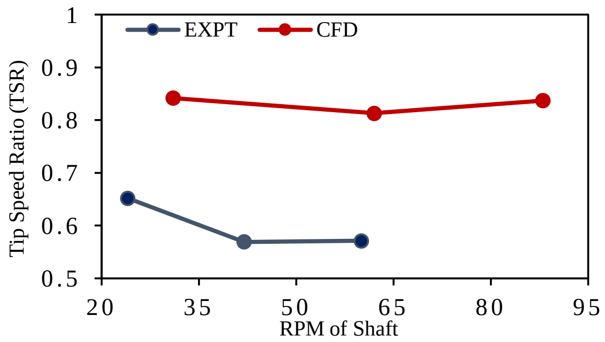

Fig. 12 Comparing the Experimental and CFD result of Tip Speed Ratio of turbine blade to the RPM of turbine shaft

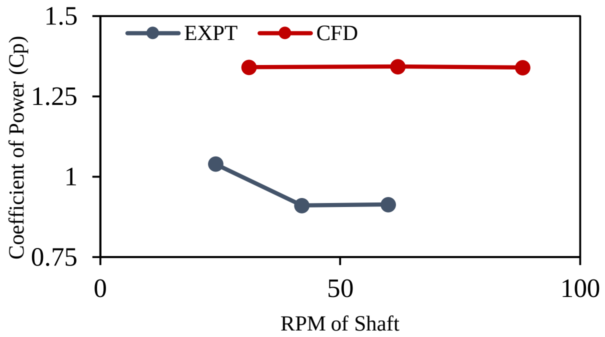

Fig. 13 Comparing the Experimental and CFD result of the Coefficient of Power of turbine blade to the RPM of turbine shaft

5 Conclusion

Floating water turbines are a renewable source of energy having a minimum impact on the environment. The initial setup cost is less as these turbines do not require dams to operate in a free flow environment of water. The maintenance required for the hydrokinetic turbines are less and can be repaired locally. The analysis has given the result about the improved design of the floating, which leads to a higher efficiency. Based on an experimental study, it is recommended that there is a need for further studies on the following aspects.

- The torque and power of the hydrokinetic turbine increases with increase in flow velocity of the water, which is maximum for velocity of 1.65 m/s as per the experimentation and CFD analysis.

- There is an optimum value of tip speed ratio (TSR) of 0.82 at which the maximum coefficient of power (Cp) of 1.34 is observed in the CFD analysis.

- The power extracted by the turbine is inconsistent in all layers of water. The higher velocity gradient on the top most layer results into highest extraction of power than the other layers.

- The Maximum power generated turbine for flow velocity 1.65 m/sec is 92.36 W. It indicates that this power can be used for individual house hold appliances.

The study of a hydrokinetic turbine has given the evidence of the tremendous potential to generate power. More smooth and stable operation is performed by a hydrokinetic turbine with good service life may be expected. The most emerging technologies in the 21st century are a hydrokinetic turbine, by proper mathematical modeling and some modification in the turbine increase its performance to the superior level.

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