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Computation and Experimental Analysis of Helical Bach-Type Savonius Wind Turbine for Water Pumping Application

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Abstract:
Access to clean, accessible, affordable and renewable energy resources and their sustainable application has been a major concern in the 21 st century due to environmental and socio-economic consequences from the conventional use of fossil fuels. Wind energy has been seen as one of the potential options for meeting the need of energy target set under the UN SDG goals and promoting energy and water security. This study deals with a comprehensive study on the performance evaluation and analysis of a helical Bach-type Savonius wind turbine design for the water pumping applications. The results obtained from the computational and experimental analyses were examined for determining the performance parameters such as power coefficient (Cp), torque coefficient (Ct), and tip speed ratio (TSR) at different wind speeds. The findings demonstrated that a TSR has direct relationship power coefficient and inverse relationship torque coefficient. With the helical Bach-type turbine model of 0.7 m rotor height and surface area of $0.7\ \mathrm{m}^2$ two bladed helical rotor was found to generate 2.306 W of energy with the Cp of 0.114 at $4\ \mathrm{m/s}$ wind speed. The cutoff speed of the turbine was found to be $1\ \mathrm{m/s}$. These results signify that the rotor can operate even at a very low wind speed opening the avenues for tapping its potential of applications for pumping water in the sustainable manner thus helping to address the water and energy security in the modern energy deprived countries.

Keywords: Computational modeling, Helical Bach-type turbine, Power coefficient, Tip Speed Ratio, Wind energy

1. Introduction

Adopting a low-carbon development path is crucial for developing countries to achieve sustainable development, and renewable energy plays a pivotal role in mitigating the challenges and fulfilling clean and accessible energy demands in the long run. Among the available renewable energy resources, wind energy is one of the promising options[1]. In 2022, 77.6 GW of new wind energy power plants were installed with the total generation capacity reaching around 906 GW in the world. [1]. There are mainly two types of wind turbines i.e. horizontal axis wind turbines and vertical axis wind turbines. Among the existing vertical axis wind turbines, the Helical Savonius wind turbine has been a popular choice [2]. Savonius rotors are said to be of high productivity and low technicality due to which this can be used for water pumping [3].The main principle of the Savonius Turbine is that "when the wind blows, the concave part of the turbine catches the wind flow, resulting in the rotation of the blade around its central vertical shaft" [4]. Bach-type Helical Savonius Turbine is the modified form of the conventional form of Savonius wind turbine. It has a curved blade that forms a helix around a rotor axis and forms a scoop that captures the wind from any direction and allows the rotor and shaft to rotate.An experimental investigation on single stage modified Savonius rotors found out that the Savonius rotor of 0.7 aspect ratio is found to be better performing in comparison to other rotors [5]. It is found that rotors with 124 degrees has the highest coefficient of power compared to other rotors with different blade arc angle [5]. Based on the experiments it is concluded that rotors with overlap ratio of zero will results the better performance [5]. Another study concluded that helical batch rotor with twist angle of 90 degrees to be better performing during the optimization of helical Savonius rotor [6]. A comprehensive wind tunnel testing study on the Savonius turbine of Bach type to get the optimal configuration shows that the power coefficient of 0.32 was found at the optimal tip speed ratio(TSR) of 0.79[7].

1.1 Wind energy for irrigation

There has been several studied for the harvesting of wind energy for irrigation purpose. With the increase in the price of fossil fuel and as the entire world is in the path of low carbon energy transition, wind energy has been seen as the potential alternative source. Since the long time there has been several studies of feasibility of wind energy for the irrigation and water pumping. Either from horizontal or vertical wind turbine, there has been several attempt on the study of wind energy water pump. The prototype of wind turbine in Indonesia for the purpose of irrigation was designed and manufactured which consisted of the vertical axis wind turbine of 8 blades with each wheel of $2\text{ m} * 1.5\text{ m}$ to pump the 20,347 liter /min water with a pump efficiency of 89.7% with the piston type water pump of 2 m head [8]. In Nigeria, a research team has developed the horizontal axis wind turbine powered water pump prototype with a rotor diameter of 2.14 m and total surface area of 3.733 m^2 which was able to pump water in the range of 3.4liter/min to 6.44liter/min for irrigation purpose [9]. On a similar study in Pakistan, the researcher team has performed the design and analysis of a horizontal axis wind turbine and recommended the windmill tower of $35 - 50$ft rotor diameter to pump the water from 50ft depth [10]. Another study of wind energy potential for agricultural water pumping in Thailand has found the feasibility of wind energy harvesting even at the low speed of 2 m/s [11]. A team in Nigeria has pumped the 15.5liter/min with a wind speed of 3.49 m/s using the Savonius turbine of 1.45 m diameter and 2.35 m length turbine of 3.41 m^2 total surface area [12]. Similarly optimization of vertical axis water pumping was also attempted at the lab of Massachusetts Institute Of Technology [13].

1.2 Cost of Wind powered water pumping system.

A research on economic analysis done at the North Central Anatolia, Turkey has concluded that medium scale water pumping system by wind energy conversion system is more reasonable that that powered by DG system [14]. A research done in the Nigeria has concluded that the turbines within the cut-in speed from 2.0 m/s2.5 m/s and operating range of 8 m/s to 10 m/s is economically viable for power generation and water pumping system [15]. Research done in Nigeria has revealed that the wind turbine operating within the cutout speed of 2.7 m/s was sufficient to provide water requirements to tackle water poverty in Nigerian communities [16]. In the research, at Ethopia the cost of pumping water at three sites Siyadberand Wayu, Adami Tulu and East Enderta sites, was found to be 0.08, 0.05 and $0.036\$/m^3$ respectively by the wind powered pump, meanwhile if it was done by Diesel. Generator it would have cost 0.12, 0.07 and $0.044\$/m^3$, respectively for the particular sites [17]. Previous studies were focused on the power generation from the various design of wind turbine technologies however there are limited studies on the design of the wind turbine for water pumping applications.

This study tries to fill the research gap in the field of wind turbine design and testing for water-pumping applications. Its main objectives are to design, fabrication and testing of a Helical Bach-Type Savonius Wind Turbine model for pumping applications in the low-wind speed conditions, computational analysis of the model and interpretation of the results and recommendations for further research and policy interventions.

2. Materials and Methods

This study uses systematic approaches for the design, and testing of the Helical Bach-Type Savonius Wind Turbine model. It consisted of a detailed review of rotar design and application, selection of the optimal design parameters, design and performance analysys using experimental and numerical models and followed by the interpretation of the results as shown in figure 1. Detail is explained in subsequent sections.

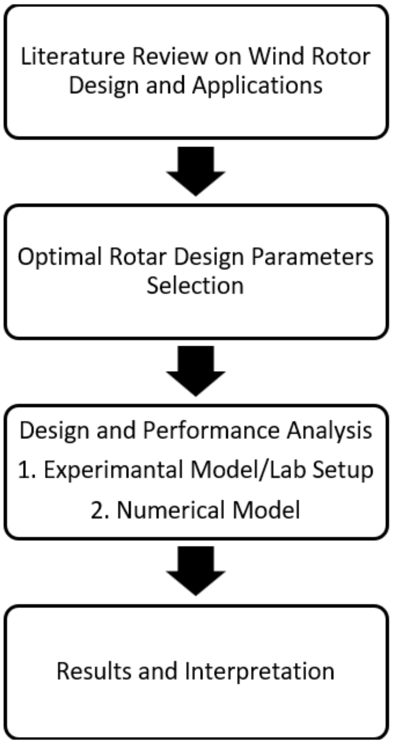

Figure 1: Methodological Framework

2.1 Experimental model

Based on the different literature review parameters such as blade overlap ratio, blade gap size ratio, twist angle, and blade arch angle for the initial model of a helical Bach model was selected, and with the reference of these parameters 3D CAD model was designed and the helical groove was 3D printed while the rotors of the Bach turbine was fabricated using the locally available material such as sheet metal and iron bars. The detailed dimensions of the experimental model are given in table 1.

Table 1: Detailed dimensions of the turbine model

Aspect Ratio	0.7[5]
Overlap ratio	0[7]
Blade gap size	0[5], [7]
Twist angle	90°[6]
Blade arc angle	124°[5]
Number of Blades	2
Height(H)	0.7 m
Diameter(D)	1 m

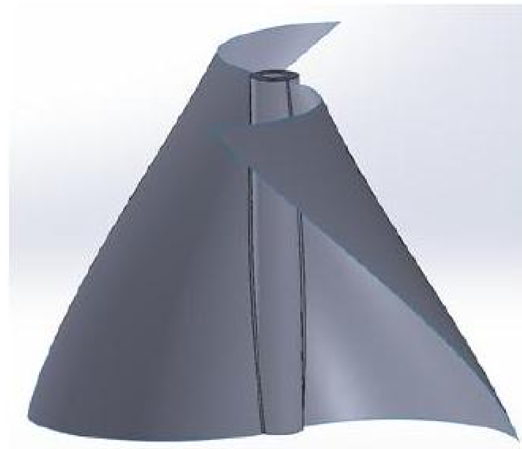

Figure 2: 3D view of the Helical Bach Savonius Turbine

2.2 Testing Process

For the process, axial fan was strategically positioned at the 1.5 m distance from the experimental model. The fan had a CFM value of 5400 at a pressure of 75 Pa which has a diameter of 0.6 m . The wind velocity for the setup can be obtained ranging from 1 m/s to 4 m/s. The anemometer was used for the measurement of air velocity which has an accuracy of 0.03 . The rotational speed was measured using a tachometer having an accuracy of 0.05 . Testing process is shown in figure 3.

Figure 3: Setup for the testing process

2.3 Torque Measurement

A setup of spring balance and dead weight was used for the measurement of the dynamic torque of the turbine. The setup of a rope brake dynamometer was employed. It was done by wrapping the rope around the Nylon pulley attached to the shaft of the turbine. One end of the rope was attached to the spring balance and another to the dead weight or counterweight. When the turbine started to rotate, there was no load. As the shaft of the turbine rotates the pulley attached to the Nylon pulley also rotates and the force exerted on the rope causes the spring balance to move or the counterweight to change. Then, the turbine's rotation speed was consequently reduced by braking the shaft by adding each load of 50 g . Consequently, the loads on the digital spring balance and the counterweight were recorded. The process of adding of counter was done until the turbine stopped rotating. The process was followed multiple times, Hence, the dataset was recorded repeatedly to determine the torque of the turbine. The torque Meter was not readily available at the time so; it was not used which was a limitation of this experiment and a rope brake dynamometer was used for the measurement of the torque.

2.4 Mathematical formulation

The power coefficient C_p and the torque coefficient C_t were determined through the following equations:

$$C_{\mathrm{p}} = \frac{P_{\text{rotor}}}{P_{\max}} \tag{1}$$

$$C_{\mathrm{t}} = \frac{C_{\mathrm{p}}}{\lambda} \tag{2}$$

The mechanical power was calculated using the measured value of the mechanical torque and the corresponding rotational speed of the turbine. It was calculated by:

$$P_{\text{rotor}} = T\omega \tag{3}$$

where w is the angular velocity of the rotor, where T is the torque measured.

To calculate Torque T using the measured value of dead weight and the electronic balance load

$$T = F\left(r_{\text{shaft}} + r_{\text{nylon}}\right) \tag{4}$$

where r_{shaft} is the shaft radius; r_{nylon} is the nylon string radius and F is the force exerted on the rotor axis and calculated by

$$F = (M - m)g \tag{5}$$

where M is the mass of dead weight; m is the electronic balance load reading and g is the gravitational acceleration.

3. Numerical model

3.1 Governing equation

The commercial software ANSYS-FLUENT has been used to solve the continuity equation, momentum equations, and turbulent kinetic energy (k) equations in order to evaluate turbulent flows in the rotor of the Helical Savonius rotor. A standard k-w turbulence model was used with a logarithmetic surface function. The equations in the form of Cartesian system for the conservation of mass and momentum for the compressible and incompressible flow positions in the numerical analysis can be written as:
The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{6}$$

The momentum equations is:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial t} = F_i - \frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_i} - \frac{2}{3}\delta_i j\frac{\partial u_i}{\partial x_i}\right)\right] \tag{7}$$

k-turbulence model

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho k u_i}{\partial x_i} = \frac{\partial \rho}{\partial x_i}\left[\mu\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \rho}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_m \tag{8}$$

3.2 Meshing

The mesh was made fine with the number of elements of 2859436 following the sensitivity test as shown in table 2 (232% increase in number of elements results only 0.58% change in C_p). The mesh independence test shows that this mesh size was sufficient to resolve the average rotor torque. Both global and local meshing controls are utilized to guarantee the accuracy and dependability of the final mesh. Faced sizing involves specifying a target element size for individual faces or surfaces of the geometry. This allows for more control over the mesh in regions where high levels of detail are required. Inflation was also applied along the boundary of the turbine which created a high density of cells near the boundary layer than on the other regions of the other regions of the domain that helped to capture the simulation near the boundary layer more accurately (figure 4).

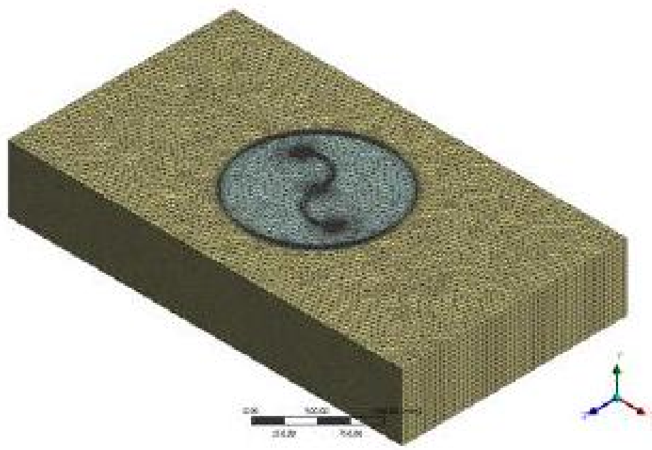

Figure 4: Meshing

3.3 Boundary conditions

In this simulation, the "Velocity inlet" up to 4.0 m/s at the input of the control domain was imposed. On the exit surface, the "pressure outlet" condition was imposed following [18]. A "Stationary Wall" condition was applied for the side walls. A rotary mesh area is applied to the blade onto the surface utilizing a non-slippery wall with a zero angular side speed (figure 5). The solver used was pressure based and time was transient as it gives the instantaneous values in each time for each quantity. Dynamic meshing was performed using 6 degrees of freedom.

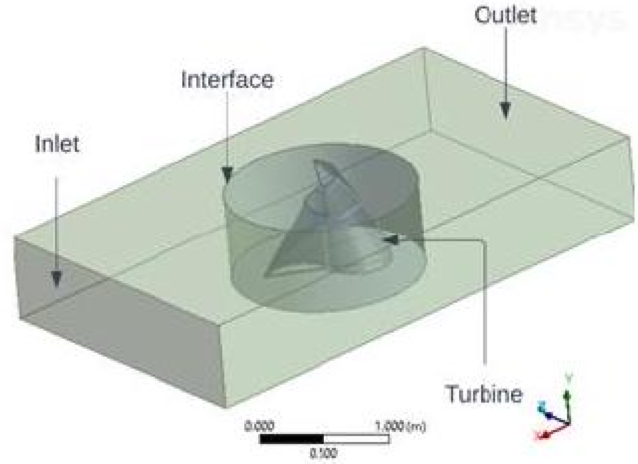

Figure 5: Boundary conditions

3.4 Grid Independence Test

During the study different simulations were run by producing mesh of various size and dimensions. At each simulation power produced by rotor were measured. With difference in the size of mesh performance of rotor were evaluated and particular mesh size were selected. The simulation from larger mesh size to fine mesh were run until the convergence was obtained. Finally, when there was no significant change in the value of the power coefficient 2859436 numbers of mesh size were selected, which is the basis of the simulation of this study.

Table 2: Grid Independence Test

Test No.	Velocity (m/s)	No. of elements	(C_p)
1	4	359969	0.158
2	4	736131	0.165
3	4	858991	0.172
4	4	2859436	0.173

4. Results and Discussion

4.1 Variation of Performance of Turbine at various wind speeds

These data are the evident that when the wind speed increases, the rotational speed of the wind turbine shows a corresponding increase. This relationship is observable because at higher wind speeds, more force acts on the turbine, so it rotates faster.The torque and power coefficients exhibit a dependence on wind speed.

At low wind speeds the turbine exhibits low torques and power, while these coefficients show an increase with increasing wind speed.It is also evident that the power coefficient remains relatively low at specific wind speeds. Similarly, the torque coefficient tends to decrease as the wind speed increases. This suggests that the turbine may reach a saturation point at higher wind speeds, where further increases in wind speed do not lead to a proportional increase in torque generation.

Table 3: Variation of Performance of Turbine with wind speed

Wind Spd(m/s)	RPM	Torque(N-m)	(Cp)	C_t
1.1	15.6	0.077	0.207	0.279
1.53	19.9	0.154	0.198	0.29
1.9	23.1	0.259	0.201	0.317
2.45	32	0.336	0.169	0.247
3.01	39.5	0.356	0.119	0.174
3.6	44.6	0.422	0.093	0.144
3.8	46.9	0.427	0.085	0.131
4	48.2	0.649	0.114	0.179

4.4 Torque of turbine at different rpm

4.2 Effects of varying tip speed ratio in torque coefficient of the helical rotor

According to the figure 6, the torque coefficient decreases as the tip speed ratio increases. The reason *f* or this is that as the tip speed ratio increases, the RPM increases, which leads to an increase in drag forces within the turbine. Furthermore, higher TSR values result in more turbulent blades, which further reduces torque generation.

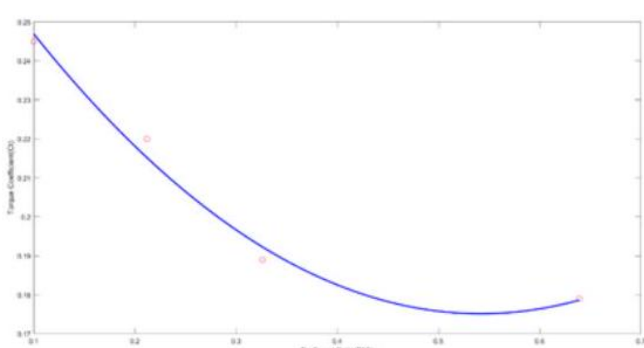

Figure 6: Variation of Torque Coefficient with Tip Speed Ratio(TSR)

4.3 Effects of varying tip speed ratio in power coefficient of the helical rotor

When TSR is lower, the helical Savonius turbine produces relatively low torque and power while experiencing low levels of flow separation. In addition to increasing drag and torque, the flow over the blade becomes more turbulent as the TSR increases. By increasing torque, the turbine is able to produce more power, leading to an increase in Cp. So, upto the TSR = 0.7 the value of Cp increases with the increase in TSR which can be seen in figure 7 .

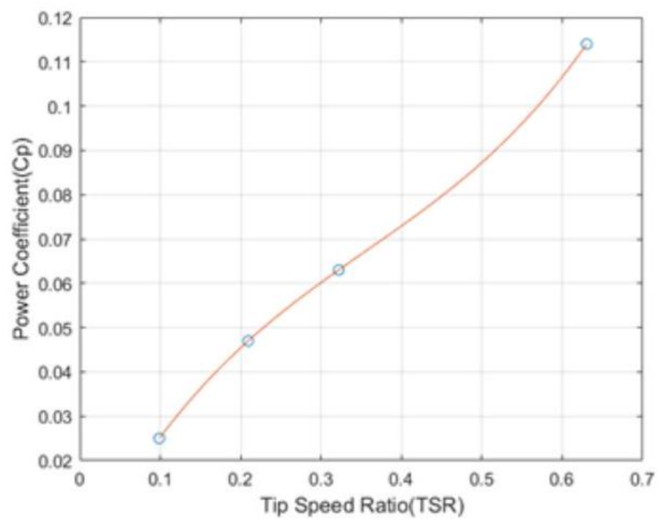

Figure 7: Variation of Power Coefficient with Tip Speed Ratio(TSR)

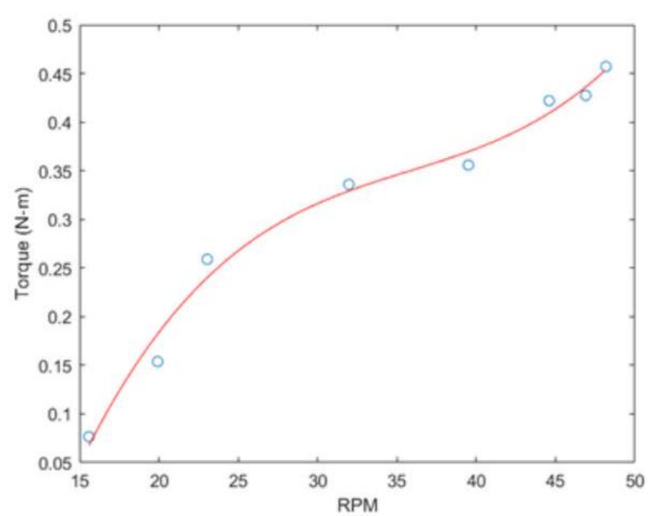

Figure 8: Variation of Torque with rotational speed.

The torque of the turbine increases with the increase in the rotational speed of the turbine. As, seen in figure 8 with the rise in the wind speed, the RPM also rises and eventually the torque of the turbine too increases.

4.5 Comparison of Power coefficient vs TSR from CFD and experimental analysis

The analysis of the experimental results and computational fluid dynamics (CFD) simu- lations indicate that the power coefficient (Cp) increases with an increase in the tip speed ratio (TSR) for the tested wind turbine as shown in figure 9. This trend is consistent with different literature and confirms the expected performance of the wind turbine. However, it should be noted that the test was limited by the bearing friction at the wind speed of 4 m/s, preventing the observation of the complete nature of the curve.

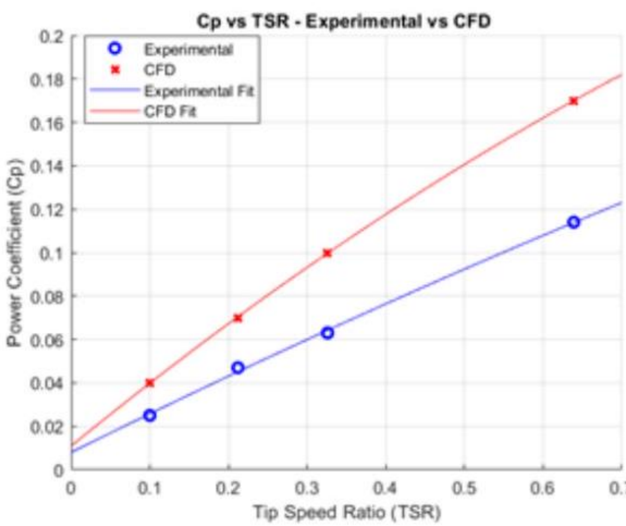

Figure 9: Comparision of variation of Power coefficient vs Tip Speed ration CFD and experimentally.

4.6 Comparison of Torque coefficient vs TSR from CFD and Experimental analysis

Based on the analysis of the experimental data and CFD simulation, it was observed that the value of torque coefficient (Ct) decreases with an increase in the tip speed ratio (TSR) for the tested Helical Savonius Bach type wind turbine. At lower TSR values, the incoming wind flow strikes the blades at a higher angle of attack, resulting in a greater amount of wind energy being transferred to the rotor and converted into mechanical energy. As the TSR increases, the angle of attack decreases, causing a reduction in the amount of wind energy transferred to the rotor. This reduction in the amount of energy results in a decrease in the value of Ct which can be observed in figure 10.The friction, fabrication limitation and difference in the flow pattern of the air than that of CFD might have created the deviation between the CFD and experimental observation. The torque in the pump powered by the Savonius Turbine is of fluctuating type. The starting torque for the system is a little higher than the operating torque. The torque coefficient of the turbine becomes higher at low wind speed and its corresponding rotational speed. The requirement for the piston pump is higher torque which suggests the need for a low-tip speed ratio.

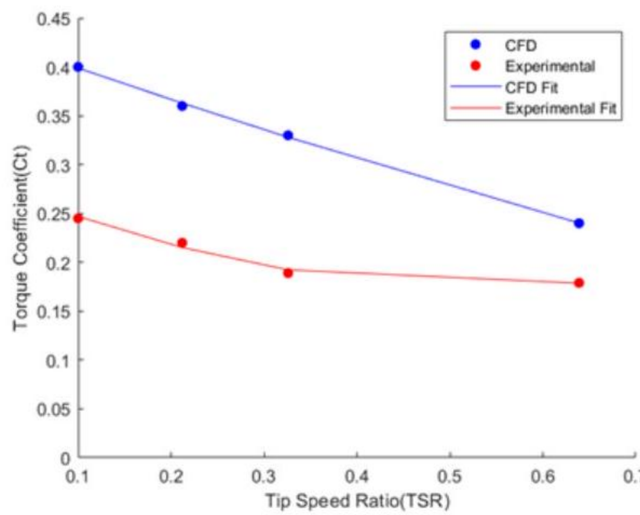

Figure 10: Variation of Torque coefficient vs Tip Speed ration CFD and experimentally.

5. Conclusions and Recommendations

5.1 Conclusions

This study has evaluated the performance and efficiency of a helical Bach-type Savonius wind turbine through experimental and computational analysis and it explores the possibility of using the technology for irrigation purposes. The model turbine was designed with specific dimensions and parameters, and its performance was tested at various wind speeds and tip speed ratios.
The results obtained from both the experimental and computational analyses provided valuable insights into

the turbine's performance. The turbine exhibited higher power and torque coefficients at higher wind speeds and optimal tip speed ratios. The experimental and computational data were in good agreement, indicating the reliability of the computational model. Overall, the helical Bach-type Savonius wind turbine demonstrated promising performance characteristics, with the ability to harness wind energy and generate power efficiently. The turbine's design, incorporating a helical blade shape, allowed for capturing wind from any direction, making it suitable for small-scale power generation applications as well as harnessing the wind energy for water pumping at low wind speeds. This research suggests the scope of fabricating a bigger size of the turbine to harvest wind energy at low wind speed, which can be used in the field of water pumping for drinking water and irrigation purposes.

5.2 Recommendations

Further research and policy recommendations are made as follows:

i) simulation and experimental studies on the performance of the integrated wind turbine and water pumping system.

ii) detailed wind mapping of the potential sites in the country for determining the potential intervention of the technology under study.

iii) implications of the technology on the economic, environmental, and social aspects of the country

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