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RESEARCH ARTICLE

Novel Blade Design and Performance Evaluation of a Single-Stage Savanious Horizontal Water Turbine

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Abstract
A type of micro-hydropower turbine known Savanious horizontal water turbine operates in freely flowing water of streams, canal, rivers etc. In a current study, blade shape and flow rates were used as the basis for an experimental assessment of a single- stage savanious horizontal water turbine. Numerical, experimental and statistical methods have used to examine the impact of blade shape and flow rates on performance metrics like rotational speed, torque and efficiency. The finding indicates that round curved blades performed better than semicircular and straight curved in terms of overall performance such as torque, rotational speed and efficiency. The performance comparison in term of efficiency amongst round curve blade, semicircular blade, and straight curve blade is carried out and found the maximum efficiency of 47.7%, 39.5%, and 36.5% at respectively at their corresponding speed of water 0.004 m³/s. However, the turbine's performance over optimum flow rates of 0.004 m³/s was found to be decreased due to the increase of water depth and higher water pressure. Moreover, output response was found to be significantly impact by all input parameters through ANOVA method.

Keyword: Savanious turbine; Blade shape; Numerical analysis; Torque; Rotational speed; Efficiency

Introduction

Among all renewable energy sources such as; solar, geothermal, hydropower, and wind, the most powerful and cost-effective is micro-hydropower (Sharif, Siddiqi et al. , Tipu, Arif et al. , Ekanayake 2002). A micro-turbines such as Kaplan turbines (10-70 m), Francis turbines (40-600 m) and Cross flow turbines (1.5-100 m) are a rich source of renewable energy but their heads are greater and need higher flow rates which depend upon the availability of larger water fall and rivers (Nasir 2013, Shoukat, Noon et al. 2021). To address these issues, a possible way is to design a savanious horizontal water turbine that should extract power from low flow rates beneath the water. Savanious horizontal water turbine (SHWT) is a small micro-hydropower in which the turbine lies under-water. It is a self-starting turbine and generates more power at low water speed (Wanchat, Suntivarakorn et al. 2013). A SHWT generates electrical energy from natural flowing water. It operates on a low volume of water and is installed inside the canal and river water (Banshwar, Sharma et al. 2017). The basic construction of a SHWT consists of two drums and having a rotor between them. A rotor consists of blades and a shaft attached to the blades. When the water directs the rotor, the water introduces rotational energy to the rotor. A generator is then used to convert the shaft rotational energy into electrical energy (Roth 1985, Iio, Katayama et al. 2011). A SHWT needed zero civil work, lower maintenance costs, and a minimum depth of water (Ullah, Siddiqi et al. , Williams 2003).

In the past, several authors worked on SHWT. (Khan, Islam et al. 2009) et al. used different Reynolds numbers for aspect ratios of α=1.82 and overlap ratio of β=0.207 to achieve the maximum efficiency. (Nakajima, Iio et al. 2008) worked on a conventional savonius water rotor with α=1.48, β=0.36, and Reynolds number of $1.1x\,10^3$ and found the maximum power by changing the distance between the bottom wall of the channel and rotor. (Huda, Selim et al. 1992) enhanced efficiency through reduction of drag force on the returning blade through deflector plate to minimize reversing torque on returning blade. (Abulnaga 1988) et al. compared the wind turbine and water rotor turbine and investigated that a savanious horizontal water turbine needs nine-times less water speed than that of air speed for wind turbines. (Blackwell, Feltz et al. 1977) absorbed that blade overlapping is the important parameter for SHWT. Blade overlap is dominantly associated with the turbine performance. (Fujisawa 1992, Fujisawa 1996) reported that overlapping of blades could significantly affect the performance of savanious horizontal water turbines. Savonius turbine with overlapping blades has lower performance compared to SHWT without overlapping blades. (Kamoji, Kedare et al. 2009) enhanced the average power of a SHWT by decreasing number of blades overlap to minimize negative torque on returning blades. (Nasef, El-Askary et al. 2013) has performed study and improved overall performance of SHWT with an overlap ratio of 0.15.

In the previous literature, limited work was performed on blade shape of SHWT. Therefore it is need to evaluate and maximize the performance of SHWT by designing a novel blade shape with varying water flow rates. The aim of this work is to investigate the influence of blade shape and flow rates on the performance evaluation of the SHWT.

Material and Method

Modeling of Savanious Horizontal Water Turbine

The blade are fabricated having thickness of 3 mm and blade radius of 45 mm in the form of a straight, semi-circular and round curve with an inside stiffener plate and without a stiffener plate. Then the fabricated turbine blade is attached to the turbine runner of diameter 30 mm. The diameter and length of turbine are 120 mm and 100 mm.

Numerical Analysis

Computational Domain and Boundary Condition

The challenging and time-consuming task for numerical analysis is the creation of the computational domain. In a current study, a 3D model of the savonius horizontal water turbine is generated in ANSYS Design Modeler. The cylindrical volume is generated in Z-axis that enclosure the savonius horizontal water turbine because the turbine can rotate in specified angular velocity. Furthermore, the interface is created between the flow field and the rotating zone to ensure flow field continuity. Fig 1 shows the complete computational domain of the system.

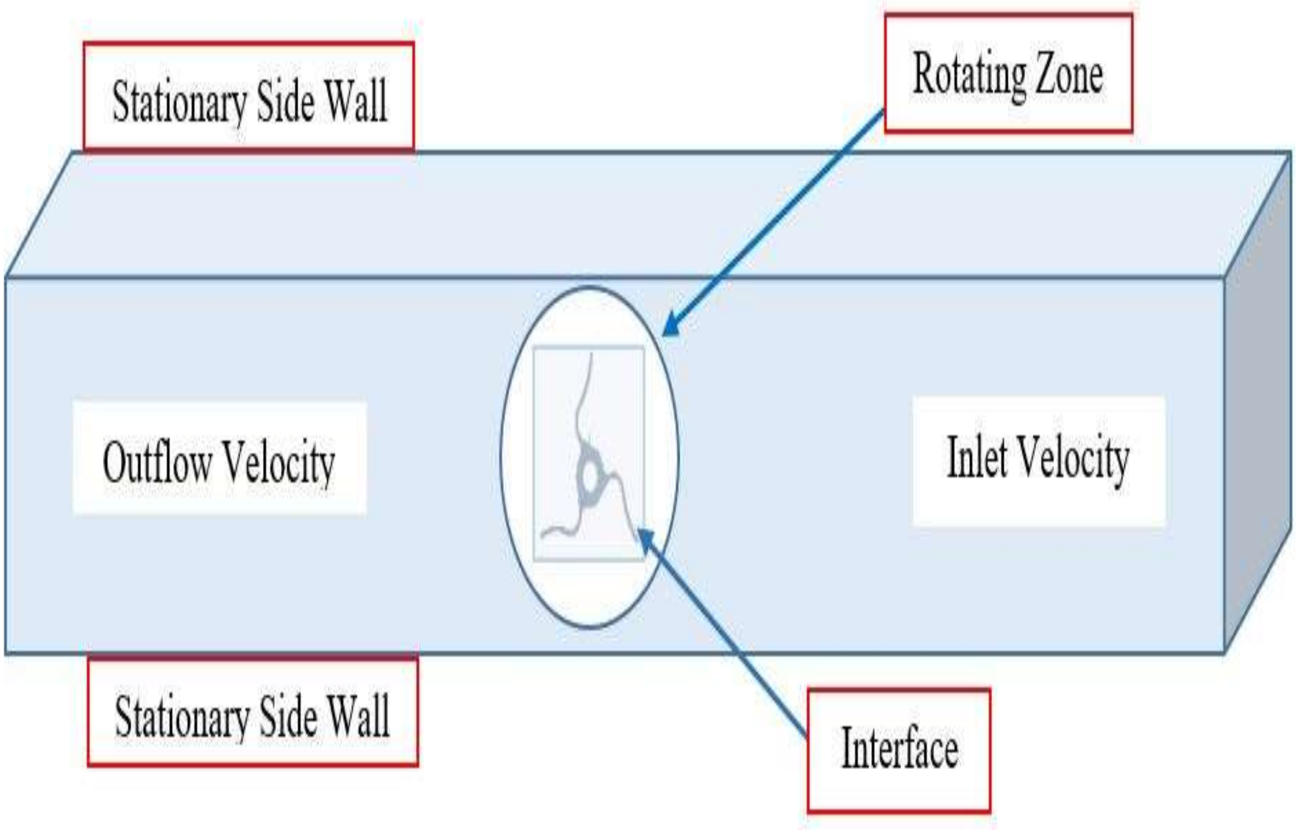

Figure-1: Computational Domain of the system

Simulation

Geometry of the turbine is imported into ANSYS Fluent and used as a flow solver with the help of finite volume discretization to solve the unsteady incompressible Navier Stokes equation. During initialization, stationary and rotating domains are required. The fluid domain is stationary domain and the geometry is the rotating domain. The rpm of the turbine depends upon the input parameter of the current study. The rpm of the rotating domain is set as 200 rpm and inlet velocity of water is taken 1 m/s. The inlet velocity of water is fixed to get the result of water pressure inserted on turbine blades. The time step size of 0.015 is selected and run the calculation. In a current numerical analysis the number of step is 100 and number of iteration is 10. The water pressure inserted on the blades of savanious horizontal turbine can set as a output parameter. Moreover, the shapes of the blades were selected the basis of water pressure inserted on the blades of SHWT. A total of 30 different conceptual designs were generated in which 20 best models were design in solid work. 10 out of 20 models were recommended for simulation. Three different types of blades shape such as round curved turbine, semicircular turbine and straight curved turbine were selected from the simulation. According to simulation shown in figure 2, the water pressure inserted on the round curved turbine is higher than semicircular turbine and straight curved turbine. A more water pressure is inserted on the maximum surface of round curved turbine. This is due to the shape of round curved blades which enhance to absorb maximum water pressure. Furthermore, a maximum water pressure enhances to generate maximum torque with higher rotational speed.

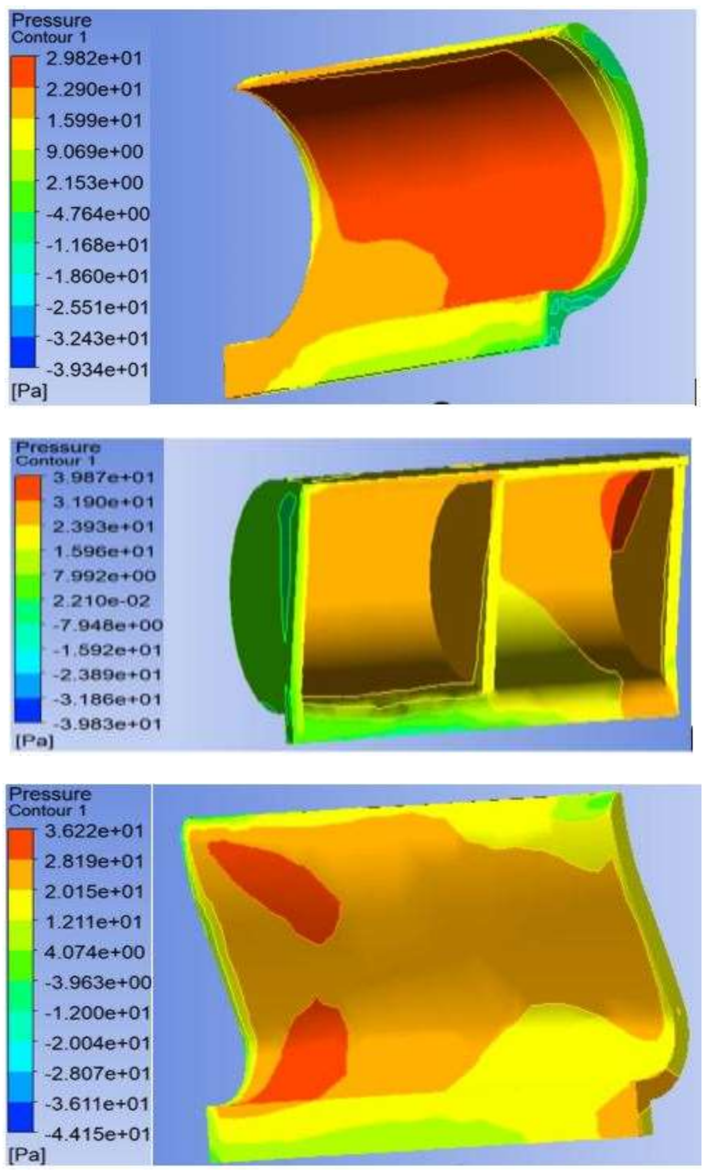

Figure 2: Simulation Result for three blade shapes

Design of Experiment and Analysis of Variance

Design of Experiment (DOE) is a statistical method used to identify process parameters that affect the output variable significantly (Habib, Sharif et al. 2021, Habib, Sharif et al. 2022). Moreover, it is used to study the behavior of two or more factors and identify the significant level (Hussain, Sharif et al.) . In a current study, Minitab 19 software was used to design a factorial approach to analyze each factor properly. The number of factors includes blade shape and flow rates, and each has three levels, as shown in table 1. Finally, Analysis of variance (ANOVA) was performed to investigate the effect of input parameters effects and their percentage contributions on the output response. ANOVA is a valuable statistical tool for determining the impact of input parameters on experimental findings in any process using an adequate design of experiments. It is a decision-making method for detecting the significance of process parameters and how they affect the response. In this work, input parameters were blade shape and flow rates whereas the output parameters were rotational speed, torque, and efficiency.

Experimental Set up

The experimental setup is placed in the titling fume of 350 mm x 150 mm. Water is supplied from a water storage tank with the help of a centrifugal pump through a 125 mm diameter pipe and then circulated back to the water storage tank after passing through a titling fume. The experimental setup for the SHWT consists of a structured house. The SHWT is placed in the structure house with the help of two bearings and a central shaft in between them. Using nylon thread, two digital spring balances with an accuracy of 0.02% are attached to the braking pulley mounted on the turbine central shaft to form a prony brake dynamometer for measuring torque. A digital tachometer has an accuracy of ±0.01% and an operating range of 1.0–20000 RPM (Lotron DT-2236B) to measure the rotational speed. Friction is another critical parameter that must be minimized because it affects the torque measurement. Moreover, the lubricant is used to reduce the friction of the bearing. The flow rates are measured with water flow meter having an accuracy of ±0.02%. The following equations are used to express these parameters (Golecha, Eldho et al. 2011, Elbatran, Ahmed et al. 2017, Patel, Bhat et al. 2017, Sharif, Siddiqi et al. 2020).

$$C_p = \frac{P_{out}}{P_{in}} \quad (1)$$

$$P_{in} = \tfrac{1}{2} \rho A V_3 \quad (2)$$

$$P_{out} = \frac{2\pi NT}{60} \quad (3)$$

$$T = 9.81 \times (W-S) \times (r_p + d_r) \quad (4)$$

$$C_q = \frac{T}{\frac{1}{2}\rho A V_{2R}} \quad (5)$$

Where T is the torque of the turbine, N is the rpm of the turbine, T and S are the tension in tight and slack sides, r_p is the pulley radius, and d_r is the string diameter.The experimental set-up and systematic of a single-stage SHWT is as shown in figs.3 and 4.

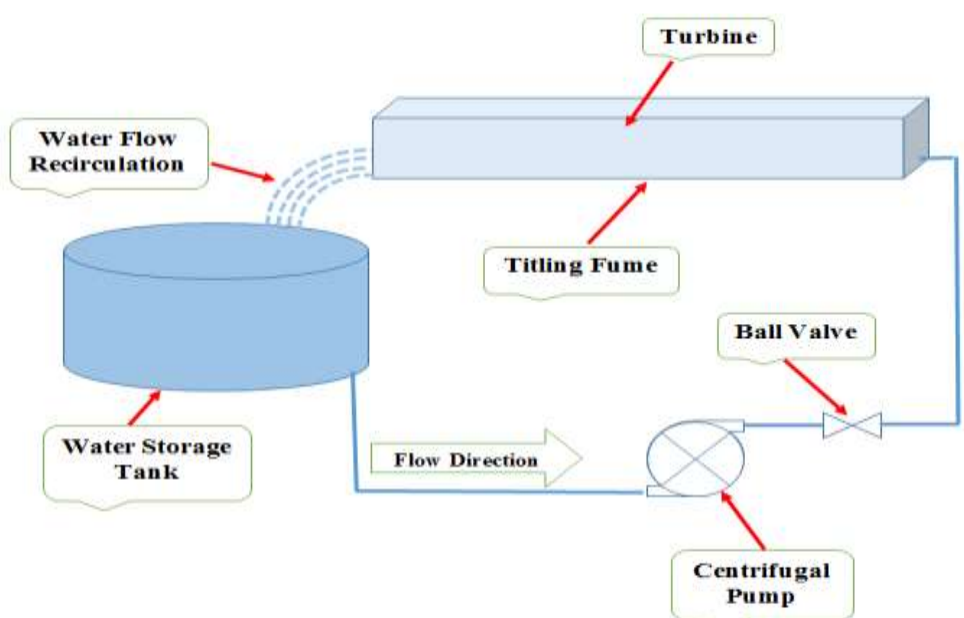

Figure 3: Schematic of experimental set up

Figure 4: Experimental Set Up of SHWT

Results and Discussion

Effect of Blade Shape and Flow rate on Rotational Speed

The SHWT is designed to run on a low-flow water stream and has a low-efficiency rating. As a result, improving the turbine's performance, either by augmentation techniques or changing the blade shape, is crucial. Changing the blade shape of wind turbines has been proven effective (Banerjee, Roy et al. 2014, Alom, Kolaparthi et al. 2016). However, minimal studies were performed on the effects of changing blade shape on SHWT. It is found that round curved blade shape has a higher rotational speed than the semi-circular blade profile and straight blade profile. The round curved blade shape turbine, semi-circular blade shape, and straight blade shape turbine rotate at 40 rpm and 76 rpm, 38 rpm, and 68 rpm, and 36 and 64 rpm, respectively, at no-load conditions. Moreover, the rotational speed has a more significant concern with flow rates (Banerjee, Roy et al. 2014) . The rotational speed increases as the water flow rate increases, decreasing at maximum flow rates. At three different levels of water flow rates, the maximum rotational speeds of three different profile-shaped turbines are achieved at 76 rpm, 68 rpm, and 64 rpm at flow rates of 0.003 m^3/s. The turbines rpm initially increases and then decreases at maximum water flow rates. As the flow of water increases in a water channel, the depth of water also increases. As a result, the static water pressure increases at the lower portion of the channel on the turbine, and the resultant rpm of the turbine decreases due to the increase in water static pressure. This causes the rpm of the SHWT to decrease. In table 1, both blade shape and flow rates significantly affect rotational speed. However, the P values in the table show that flow rates are more significant than blade shape. Moreover, figure 5 shows that a round curved blade has more significant rotational speed than a semi-circular and straight curved blade.

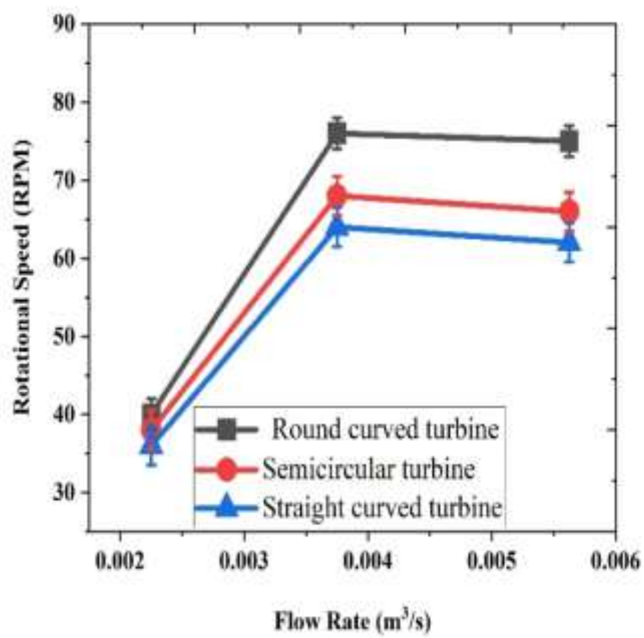

Figure 5: Flow rates vs. rpm

Table 1: ANOVA for RPM

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Blade shape	2	144.67	144.67	72.333	10.85	0.002
Flow rates	2	1864.67	1864.67	932.333	139.85	0.000
Error	4	26.67	26.67	6.667		
Total	8	2036.00	2036.00			

Effect of Blade Shape and Flow rate on Torque

As per the experimental result, it is observed that the round curved blade shape generates higher torque under the same flow condition as compared to the semicircular and straight blade shape turbines. The maximum torque obtained by round curved blades, semicircular blades, and straight blade shapes is 0.55 Nm, 0.66 Nm, and 0.65 Nm, 0.51 Nm, 0.61 Nm, and 0.60 Nm, and 0.48 Nm, 0.60 Nm, and 0.59 Nm, respectively at a water velocity of 0.1 m/s, 0.125 m/s, and 0.15 m/s. The torque generated first increases and then significantly decreases by increasing the water velocity and depth. The optimum water velocities where all three turbines generate higher torque are 0.125 m/s. Above and below, the optimum velocity torque generated decreases. Moreover, it is found that the rpm of the turbine decreases if mechanical load is applied to the braking shaft of turbine (Alom, Kolaparthi et al. 2016). The mechanical load increases as the net force on the brake shaft increases, which enhanced to rises brake torque. The torque generated first rises and then significantly reduces at maximum flow rates shown in figure 6. The depth of water in a flow channel of constant volume is directly proportional to the water flow rate. If the flow rates increase, the depth of water increases, as a result, the velocity of water at the bottom slows down, this causes higher static pressure of water inserted into the turbine, and the resultant torque of the turbine decreases. From ANOVA table 2, it is absorbed that both the blade's shape and flow rates have a highly significant impact on torque. However, the F values in the table show that flow rates are more significant compared to blade shape. Moreover, figure 6 shows at maximum torque as absorbed on a round curved blade having 0.003 m^3/s then to semi-circular and straight curved blades, respectively.

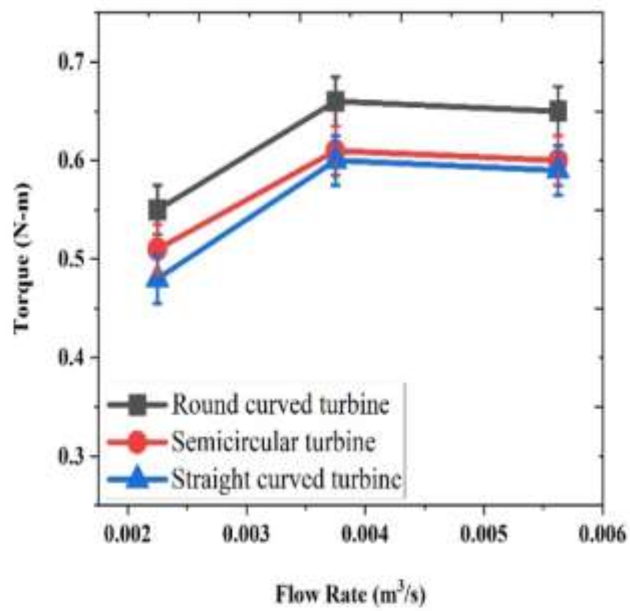

Figure 6: Flow rate vs. torque

Table 2: ANOVA for torque

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Blade shape	2	0.006467	0.006467	0.003233	97.00	0.000
Flow rates	2	0.022200	0.022200	0.011100	333.00	0.000
Error	4	0.000133	0.000133	0.000033		
Total	8	0.028800	0.028800			

Effect of Blade Shape and Flow rate on Efficiency

The turbine efficiency is a concern with blade shape (Mohamed, Janiga et al. 2011) . The turbine's efficiency initially increases and then decreases at maximum flow rates. The round curved shape turbine, semi-circular shape turbine, and straight shape turbine achieved higher efficiencies of 47.7%, 39.5%, and 36.5% at the same flow rate. The round curved blade has higher performance because of the roundness of the blades, which can contact more surface area of the water, and the water will deviate back. As a result, pushing the blade ahead, the concaveness of the blades can strike more surfaces with water. On the other hand, the convex side of the blade can reduced the negative torque on reversing blades. The turbine's rpm increases with the increase of flow rates (Fujisawa and Gotoh 1994). It is observed that the turbine's efficiency first increases and then decreases. The maximum efficiency obtained was 47.7%. However, at maximum flow rates, the efficiency obtained is 26.6%. As a result, the turbine's submergence in water is increased where the static pressure on the turbine inserted is more significant, and the rotational speed of the turbine is at its minimum due to the worse velocity of water at the bottom of the water channel over the turbine. It is absorbed from the ANOVA table 3 that both blades shape and flow rates have a highly significant impact on efficiency. However, the P values in the table show that flow rates are more significant compared to blade shape. Moreover, figure 7 shows that maximum efficiency was absorbed on round curved blades having 0.003 m³/s then to semi-circular and straight curved blades, respectively.

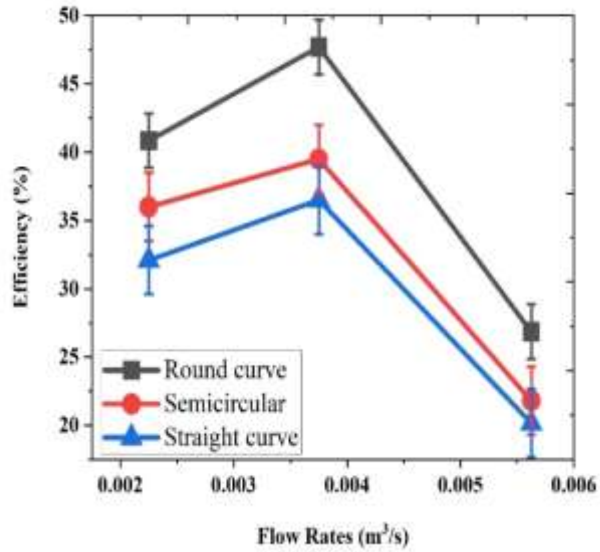

Figure 7: Flow rate vs. efficiency

Table-3: ANOVA for Efficiency

Source	DF	Adj SS	Adj SS	Adj MS	F-Value	P-Value
Blade shape	2	123.537	123.537	61.768	37.53	0.003
Flow rates	2	538.064	538.064	269.032	163.44	0.000
Error	4	6.584	6.584	1.646		
Total	8	668.185	668.185			

Conclusion

In the current research work, the parametric study of the Savonius horizontal water turbine is conducted based on blade shape and flow rates at various levels. CFD analysis was carried out to analyze the flow characteristics. The following conclusion is drawn from the current study.

The numerical analysis showed that higher pressure is inserted on a round curved blade than on a semicircular and straight curved blade shape. The round curved shape turbine shows higher efficiency of 47.7% than semi-circular shape turbine, and straight shape turbine having efficiencies of 39.5%, and 36.5% respectively. The performance of the above turbine is maximum at optimum flow rates. Increasing the flow rate in the channel, the rotational speed and torque of the turbine first increases and then decreases due to rises in static pressure inserted on the turbine as a result, minimizes the efficiency. The ANOVA method reported that both blade shape and flow rates have a high effect on the overall performance of the horizontal axis Savonius water turbine. However, flow rates are more significant than blade shape.

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