

Analysis of Savonius Rotor with Multiple Blades for Hydrokinetic Application



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Nomenclature

A	Frontal area (m^2)
A_s	The swept area of Savonius rotor (m^2)
C_D	Drag coefficient
C_p	Power coefficient of a Savonius turbine
D_f	Drag force
f	Frequency of the rotation (Hz)
U	Water speed (m/sec)
V	Velocity of the rotor tip (m/sec)
ρ	Water density (Kg/m^3)
ω_s	Angular velocity of Savonius rotor
λ	Tip speed ratio

1 Introduction

Use of Savonius rotor for hydrokinetic application is not new, but its uses for power generation with the application of water is new and recent research, only the hurdle is its lowest power coefficient. However, the drag mechanism of Savonius rotor is taken as advantageous in terms of water as a medium to rotate the same. Many research activities are going on to increase the power coefficient of this rotor, and Gorlov et al. [1] suggested that the maximum power coefficient with proper experiments can be thought of around 0.35. Khan et al. [2] tested the same experiments on single-stage, two-stage, and three-stage conventional Savonius turbine in a water channel.

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Nakajima et al. [3, 4] investigated the conventional Savonius turbine with a horizontal axis in a water channel. They concluded that the maximum coefficient of power is 0.25 at a Reynolds number of 1.1×10^5 . Golecha et al. [7] carried out an experimental investigation on the performance improvement of the modified Savonius rotor by providing a deflector plate on the returning blade side. Hence, there are many types of research worked and still working to make Savonius rotor better for hydrokinetic applications, such as Kamoji et al. [8], and can be seen in [5, 6, 9–22]. But they have not tested or had findings on the position of the rotor in the free-flowing river with different blades arrangements, which is prime important to extract electricity from free-flowing river or stream using this rotor or turbine.

In this paper, an experimental finding is an attempt for speed variation with the various positions at different blades. A rotor prototype is made with PVC pipe, and model is tested in the free-flowing river, and speed differences of various arrangements are observing and also validates with the theoretical results.

2 Savonius Rotor

Water is the best medium for power generations, which is a little predictable as compared with the wind. Extractions of electricity from free flow water or river demand turbine which works on drag mechanism not lift mechanisms, and among all wind turbines, Savonius rotor is the best suited for this work. Invented by Finnish engineer Sigurd Johannes Savonius in the year 1922, which was also called an ‘S’ type rotor because of its shape. This rotor has the lowest efficiency in the aerodynamic application the reason being characteristics, it works on drag force, and with sufficient wind velocity only it rotates, but with simply 2.5–5 m/s velocity of free-flowing water can rotate this turbine. The research of this paper is only to compare the different positions for Savonius for electricity production in rural areas for their socio-economics developments. Research and developments works are in full swing, and literature suggests that this rotor is gaining popularities [22, 23].

This rotor uses stagnation pressure on one side to facilitate rotation around the shaft, the blade turning redirects water around itself with its rounded shape. Because of the concave shape of the rotor, any tangential flow of water will produce a positive force on the rotor. But one should understand that this rotor cannot exceed the velocity of water, and it will operate at lower RPM range with huge torque which can give enough speed wit gearbox arrangements.

If C_p is the power coefficient of a Savonius, then the power (P) can be given from water as:

$$P = \frac{1}{2} C_p \rho A s V^3 \quad (1)$$

where

P is the output power (W), ρ is the water density in kg/m^3 , A_s is the swept area of the rotor in m^2 , and V is the velocity of water in m/s .

The tip peripheral velocity of the rotor,

$$U = \omega_s \times R_s \quad (2)$$

where

ω_s is the angular velocity of the rotor and R is the radius of the rotor.

2.1 Modifications of Savonius Rotor

Since the Savonius rotor is drag operated device, it has the lowest efficiency among all other wind turbines available, and the power coefficient (C_p) is marginally less than 0.5. All possible modifications are under test, as the use of multiple buckets, use of staged rotors in one axis and use of guided plates or vanes in the incoming lines, etc. Savonius rotor gives high drag force to overcome the rotor inertia, and the drag force can be seen as:

$$D_f = 0.5C_D \times \rho \times A \times V^2 \quad (3)$$

where

D_f = Drag force, C_D = Drag coefficient,

The drag force depends on the Reynolds number (Re). The power coefficient of Savonius rotor is very low as it operates on drag mechanism, rather than aerodynamics, researchers have shown that the power coefficient of Savonius rotor can be improved to 0.35, with various arrangements of guiding vanes, and with different rotor structures as shown in Fig. 1.

2.2 Aspect Ratio

Power generation using Savonius rotor also depends on aspect ratio, which is sometimes denoted by A_s or $A\alpha$ and defined as the ratio of active length or height (m) of the rotor to active diameter (m) of the rotor. The aspect ratio of the Savonius rotor should always be larger than unity,

$$A\alpha = \frac{H_s}{D_s} > 1$$

That means D_s should be less than H_s , shown in figure two different types of rotors with different aspect ratios (Fig. 2).

Fig. 1 Three different types of modified Savonius rotor

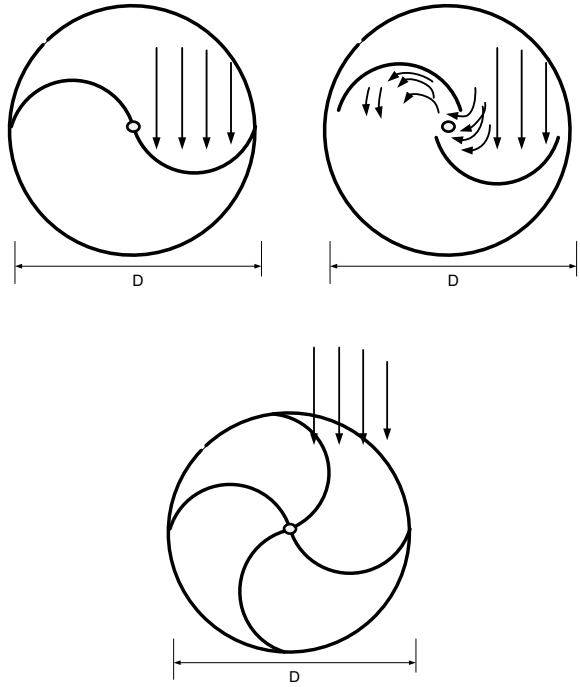
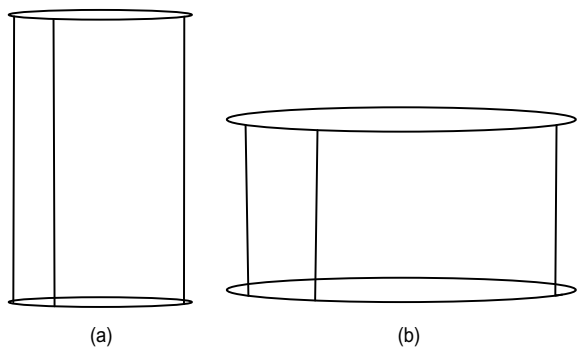


Fig. 2 Savonius rotor with **a** $H_s > D_s$ **b** $H_s < D_s$



2.3 Tip Speed Ratio (TSR)

The relation between the water speed and the rate of rotation of the rotor is characterized by a non-dimensional factor, known as tip speed ratio or lambda (λ).

$$\text{TSR: } \lambda = \frac{\text{speed of the rotor tip}}{\text{water speed}} = \frac{U}{V} = \frac{\omega r}{V} \tag{4}$$

where

U is the water speed (m/s)

V is the velocity of the rotor tip (m/s)

R is the rotor radius (m)

ω is the angular velocity (rad/s)

f is the frequency of the rotation (Hz).

2.4 Optimal Rotor Tip Speed Ratio

The optimal tip speed ratio for maximum power extraction is incidental by relating the time for the disturbed water to resettable, itself t_w to the time taken for the blade of rotational frequency ω to move into the position occupies by its predecessor t_s .

The time for the blade to move to its predecessor’s position for ‘ n ’ number of blades will be given as:

$$T_s = 2 \pi / n\omega(s)$$

If the length of the strongly disturbed water of the rotors’ then the time for the water to return to normal is given by:

$$t_w = s/U(s)$$

If $t_s > t_w$, then some water is unaffected, and if $t_s < t_w$, then some water is not allowed to flow through the rotor. The maximum power extraction occurs when two time periods are about to equal $t_s = t_w$

$$2 \pi / n\omega = s/U, \quad n\omega/U = 2 \pi / s$$

From which the optimal rotational frequency is;

$$\omega_{opt} = \frac{2\pi U}{ns} \tag{5}$$

3 Construction of Savonius Rotor

This study aims to design a device that generates energy using the Savonius rotor. To accomplish this, the following steps are made: First, the researchers will survey a location (river) to serve as the basis of the design and testing site of the hydroelectric generator using Savonius turbine as the rotor. The essential parts are the flow rate and width of the river, and these would determine whether or not electrical generation

would be possible to the location. After a location is chosen and gathered its data, the design and list of materials to be used for the system will be prepared. The next step will be the fabrication of a prototype; then after, the researchers will try to implement the prototype based on the data gathered from the qualified location. The last step will be the analysis and interpretation of data obtained for evaluation and recommendation.

4 Location of the Site

Pachin is a river in Arunachal Pradesh where the experiment is done. Because of the rainy season, the water of the river is dirty but we have an advantage of little higher density because of the dirtiness of water. Pachin River is at $27^{\circ} 5'0''$ N latitude and $93^{\circ} 42'0''$ E, longitude near Pachin Colony. The temperature of the river is recorded as 24°C during the observation. The depth of the river is calculated as 0.7 m, and the average speed of the river is calculated as 1.06874 m/s. The material used for the rotor is PVC whose details are given in Table 1.

The blade is made up of PVC pipe, which is strong and rigid. It is resistance to a variety of acids and bases, but it may damage by some solvent and chlorinated hydrocarbons. PVC can be used in the maximum temperature of 140°F (60°C) can be used for water, gas, and drainage system. For study purpose PVC material is used but in the actual turbine can be constructed with water-resistant materials. Use of PVC material for study can also advocate that it have little elasticity, which helps in gaining more efficiency, as water striking the concave side of rotor blade will elongate the blade to increase its torque. All rotor parts can be produced cheaply by a simple manufacturing process. The shaft is made up using wooden for a prototype for easy assembling into frame also it makes the whole process fast, and there will be no any effect on the actual performance of rotor, also to the fact that metal shaft may rust and corrosion may take place. On the shaft, required slots are made and blades are fixed with the nail. The main reason to choose wood for the shaft is it is rigid in mature and light in weight. The manufacturing process can be done very easily on the wood so according to the requirement of dimension, we can easily get that dimension. The shaft is adjusted in the bearing which is fixed in the two legs of the support using the iron key.

We need not require heavy support as it is difficult to handle; therefore, support is also made up of wood which is rigid in nature and light in weight, and according to the requirement, we can easily do manufacturing process on the wood. As the system

Table 1 Parameter of rotor used

Nominal pipe size (inches)	Outside diameter (inches)	Minimum wall thickness (inches)	Inside diameter (inches)	Weight (kg/m)
6	6.625	0.280	6.065	5.25

is used in the water, there is the possibility of corrosion in the metallic structure which will decrease the life of the structure, so the support is made by using wooden material which can easily be manufacture according to the requirement. Within the support to the hole is made for the ball bearing which will be fixed in the two legs of the support.

Dimension of the support.

Height of the support = 30 inch = 1.062 m.

Width of the support = 13 inch = 0.4602 m.

The complete assembly is shown in Fig. 3.

For smooth rotational outputs, a ball bearing is used, and it works excellent, the purpose of using the ball bearing is to reduce the rotational friction and support radial and axial loads, by using at least two races to contain the balls and transmit the loads through the balls. In most applications, one race is stationary and the other is attached to the rotating assembly because balls are rolling, and they have a much lower coefficient of friction than if two surfaces were sliding against each other. The wooden frame is fixed with the stationary race of bearing, and shaft is fixed on the movable race of bearing for smooth and frictionless rotation when the force applied.

The ball bearing is fixed into the two legs of the support as shown in Fig. 4d, and the rotating shaft is adjusted into the bearing during the experiment with the help of key.

Fig. 3 Rotor holding frame

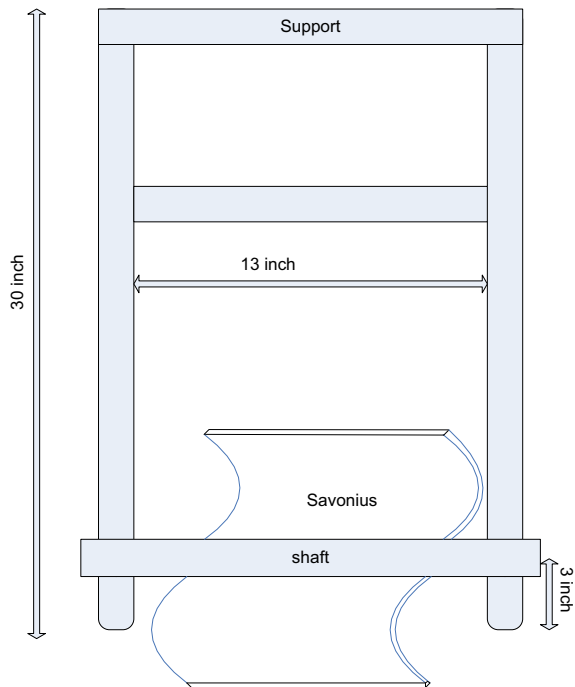
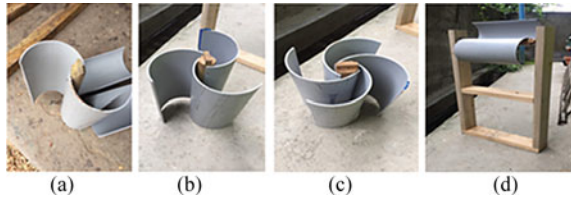


Fig. 4 a Two blades, b three blades, c four blades and d complete set



The internal diameter of the bearing = 2.5 cm.

The external diameter of the bearing = 3.5 cm.

The design is made up of both wood and plastic. The blades are made with PVC pipe, shaft, bottom support, and the upper support are made up of wood. This design was synthesized from numerous past Savonius wind turbine application. The plastic material is classified as both super lightweight and has great elasticity. This is useful for it follows or bends to the direction of water flow rather than resist it. The wooden part is both harder than plastic and lighter than galvanized steel which is great for the supports.

5 Result and Discussion

During the experiment, the revolution of the different set up (two-blade system, three-blade system and four-blade system) is observed at different positioning of the axis (horizontal and vertical axis) of rotation at partially submerged and fully submerged condition. During the experiment, the speed of water is observed, the temperature of the water is observed, the depth of the river is observed, and the density of the water is observed. The speed of the running water is measured by using the simple method of measuring the speed of the running water; i.e., a sponge ball is used to flow over the running water and measure the distance cover by the sponge ball and calculate the time taken to cover that distance, and the speed is so calculated by dividing the distance by time taken to cover that distance. The average speed of the water is found to be 1.0678 m/s as shown in Table 2.

$$\text{Average speed} = \frac{10.6874}{10} = 1.06874 \text{ m/s}$$

The average speed of the water is 1.06874 m/s. (Though surface velocity).

The prototype was tested in the river with different blades, and the rotational speed has been observed as given in Table 3.

Table 2 Observation table for calculating the speed of running water of Pachin River

S. No	Distance (m)	Time (s)	Speed (m/s)
1	10	9.2	1.0869
2	10	9.3	1.0752
3	10	8.9	1.1235
4	10	9.3	1.0752
5	10	10.5	0.9523
6	10	9.9	1.0101
7	10	9	1.1111
8	10	9	1.1111
9	10	9.7	1.0309
10	10	9	1.1111

Table 3 Observation table for rotational speed with different blades combinations

Inclination of blades	Position of a blade in the water	Rotational speed (rpm) (two blades)	Rotational speed (rpm) (three blades)	Rotational speed (rpm) (four blades)
Horizontal axis	Partially submerged	63	58	38
Horizontal axis	Fully submerged	68	53	49
Vertical axis	Partially submerged	52	50	39
Vertical axis	Fully submerged	56	52	46

6 Calculation

The theoretical calculation for optimal rotor tip speed ratio for two blades is shown below:

Angular velocity of the two-blade system

$$\omega = 2\pi f = \frac{2\pi N}{60} = \frac{2 \times 3.14 \times 68}{60} = 7.117 \text{ rad/s}$$

Velocity of rotor, $V = \omega r = 7.117 \times 0.3998/2 = 1.4227 \text{ m/sec}$

$$\lambda_1 = \frac{\text{speed of the rotor tip}}{\text{water speed}} = \frac{V}{U} = \frac{\omega r}{U} = \frac{1.4227}{1.06874} = 1.331$$

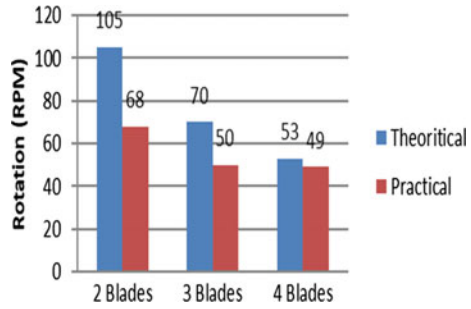
ω_{opt} for two-blade,

Speed of water $U = 1.068 \text{ m/s}$,

Number of blade $n = 2$,

Length of blade $s = 12 \text{ inch} = 12 \times 0.0254 = 0.3048 \text{ m}$.

Fig. 5 Comparison between the theoretical and practical rotational speed



Now,

$$\omega_{opt} = \frac{2\pi U}{ns}$$

$$\omega_{opt} = \frac{2 \times 3.14 \times 1.068}{2 \times 0.3048} = 11.0023.89 \text{ rad/s}$$

$$\omega_{opt} = \frac{2\pi N}{60} = 11.0023.89 \text{ rad/s}$$

$$N = 105.118 \text{ rpm}$$

And the speed of the other two arrangements is also been calculated in the same fashion and presented in Fig. 5.

It is observed from the above result that two-blade systems are best as compared to the three and four-blade system. But during the observation, it is found that two-blade systems are more unbalanced than the three-blade system and four-blade system, because of the turbulence of the water during the striking of water on the blade. Theoretically, if the number of the blade increases, the rotational speed of the rotor decreases. It is also observed during the investigation that in the fully submerged condition, the rotational speed of the rotor is more than the partially submerged condition.

7 Conclusion

This paper details the possibility of extraction of hydropower from free-running rivers, by run-off-river. A Savonius rotor, which is commonly used as a wind turbine, is a unique fluid mechanical device, which works on drag force rather than lift force. Among all known wind turbines, it has a low power coefficient. Experiments have shown that the Savonius rotor can be effectively used to generate power using hydrodynamics rather than aerodynamic. Generation of electricity using flowing

river water is a good option as it does not require the construction of dams or water storage system. The generating scheme uses the kinetic energy of the natural flow of river water requiring zero head rotors. It is also being shown that for remote areas, this scheme of the generation of electricity may give added helps to the inhabitants. The possibility of distribution of power to remote location produced by generation plant established with simple locally available materials is more vital than any other technologies. Local manufacturer, local entrepreneurs, and employments generation will be its main advantages; it will, not only boost socioeconomic development, but will also transformation of their lifestyles.

The appropriate tip speed ratio for power generation is advocated, keeping the factual conditions of the velocity of water in hilly areas, hilly areas like state of Arunachal Pradesh, which comes under seismic zone Vth, construction of the large dam is always been a big question mark. Hydro-potential of this beautiful state is widely known, especially the surface flowing rivers. Mini- and micro-hydropower plants using the Savonius rotor will be encouraging one.

From the above studies, two blades Savonius rotor was found to be unique and more efficient in harvesting hydrokinetic energy as compared to the three blades and four blades Savonius rotor, with proper gear system power can be extracted from the free-flowing river. It was also found during the observation that the balancing of the two blades Savonius rotor is least because of high turbulence of water; but for the four blades Savonius, the turbine is rotated smoother than the three blades and two blades Savonius rotor. Theoretically, also it was found that as the number of blades increases, the revolution of the turbine decreases. The major differences in theoretical and practical reading for two blades are because in two blades system, there is huge jerking effect as the subsequent blades are at a far distance. So the experiment is validating the theoretical concept.

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