Performance Enhancement of Savonius Hydrokinetic Turbine with a Unique Vane Shape: An Experimental Investigation

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Nomenclatures

D Diameter of the rotor
V Free stream velocity
P_T Mechanical power output from turbine shaft
H Height of the rotor vanes
T Torque available on rotor shaft
ω Angular velocity of the turbine rotor
ρ Density of the flowing fluid

1   Introduction

There is a need to explore more efficient renewable energy sources and energy conversion technology, which is the need of the globe. Compared to another renewable energy sources, the tremendous growth rate is observed in the field of solar, wind and hydrokinetic energy conversion technology. Wind turbines produce the electrical energy from the kinetic energy of the wind source. Similarly, hydrokinetic turbines utilize kinetic energy of water flow in the river streams, tidal currents or other man-made water channels for mechanical power production. Due to high density of the water compared to the air, the power output which can be extracted from the hydrokinetic turbine is quite more compared to wind turbine from same size of the turbine unit. In spite of this, the hydrokinetic turbine is not explored much compared to the wind turbine. There are two main types of hydrokinetic turbines are explored widely, which are (1) Darrieus turbine and (2) Savonius turbine.

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Darrieus turbine is working on the principle of lift force generated due to the motion of the hydro foiled vane in submerged in the water flow. The coefficient of power of the Darrieus turbine is quite high compared to Savonius turbine; however, its starting capacity is quite poor. The Experimental investigations on Darrieus straight blade turbine for tidal current application and parametric optimization for hydro farm arrangement are studied by Patel et al. [1] With experimental investigation, they obtained optimum number of vanes, types of vanes and solidity and its best operating speed. They also explored the stream wise and span wise distance required between two Darrieus turbines if it is used as a hydro farm arrangement. Patel et al. [2] proposed an innovative technique to enhance the performance of the Darrieus turbine using blocking of the specific flow region passing from the turbine region.

On other hand, Savonius turbine is working on the principle of drag force while flow passing from the concave vanes. The power coefficient of the Savonius turbine is quite less compared to the Darrieus turbine, but its starting characteristics is quite good. A typical Savonius turbine unit is shown in Fig. 1. Patel et al. [3] experimentally investigated the best relative height of the vane, i.e. aspect Ratio and best relative gap size, i.e. overlap ratio to get the best performance from the Savonius turbine. The performance of the semicircular vane Savonius turbine can be predicted with the impulse momentum principle. The simple mathematical formulation is explored by Patel et al. [4] which can be widely used to obtain optimum design parameters of the turbine for particularly site condition and also can be useful to predict the optimum performance parameter for specific design of the Savonius turbine. They provided the ready reference code sheet for the calculation also. In the present investigation, the same code sheet is used to validate the presented experimental methodology and
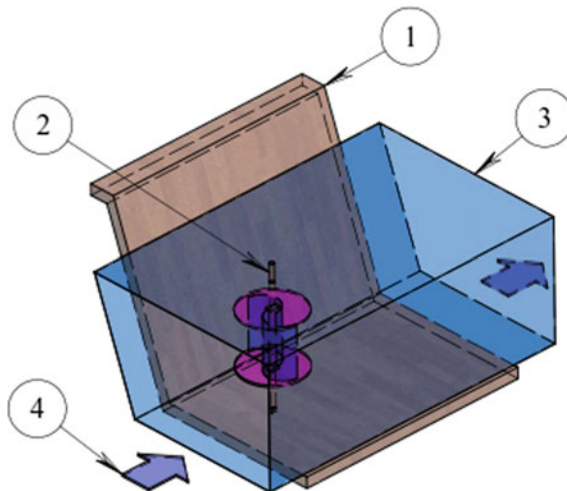
(1) Water channel (2) turbine (3) water domain (4) direction of water flow

Fig. 1 Typical Savonius rotor in fluid flow in open channel

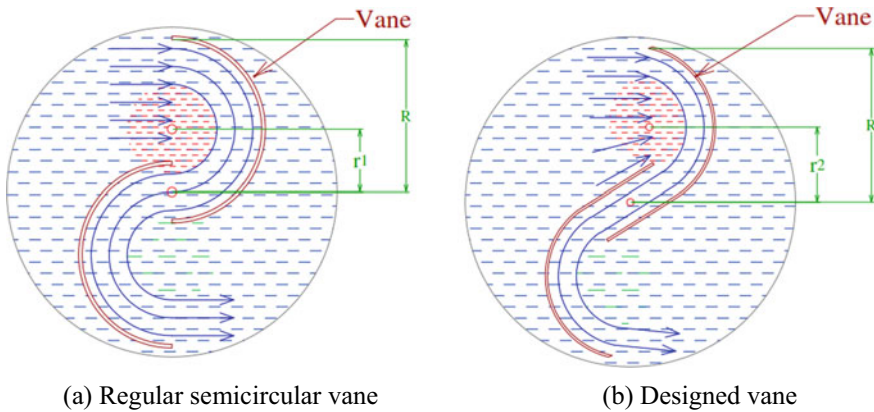(a) Regular semicircular vane   (b) Designed vane

Fig. 2 Conceptual representation of designed vane shape

calculation steps. If the Savonius turbine experimented in very narrow channel, then it might indicate more coefficient of power compared to its real performance, if it is used in wide real canal or river. To predict the correct performance of the turbine, even if it experimented in the limited width of the canal, the velocity correction methodology, specifically for hydrokinetic turbine, is explained by Patel et al. [5]. To avoid this blockage effect, all experiments were conducted in the wide real irrigation canal with sufficient wide and depth of water flow in the presented investigation [6]. The performance of the Savonius turbine can be improved using specific shape and number of the vanes [7]. The effect of helical shape of the Savonius turbine is investigated by Kamoji et al. [8]. They concluded that the coefficient of power, using the helical shape of the vane, not improved much compared to the simple cylindrical vanes. The maximum coefficient of power they obtained using helical vanes is 0.18. Yakoob et al. [9] experimentally investigated that the effect of staking of the rotor vanes at specific angles can also enhance the performance of Savonius turbine.

After the rigorous literature survey, it is noted that there is a need of performance improvement of Savonius turbine, to enhance practical acceptability. In the present investigation, it is decided to improve the performance of Savonius turbine by exploring innovative vane shapes of the turbine.

The Savonius turbine is very simple in construction. There is no need of yawing mechanism. Also, due to vertical axis of the turbine, the power generator can be placed above the water level. Hence, maintenance of the turbine will become very simple compared to any other type of turbines.
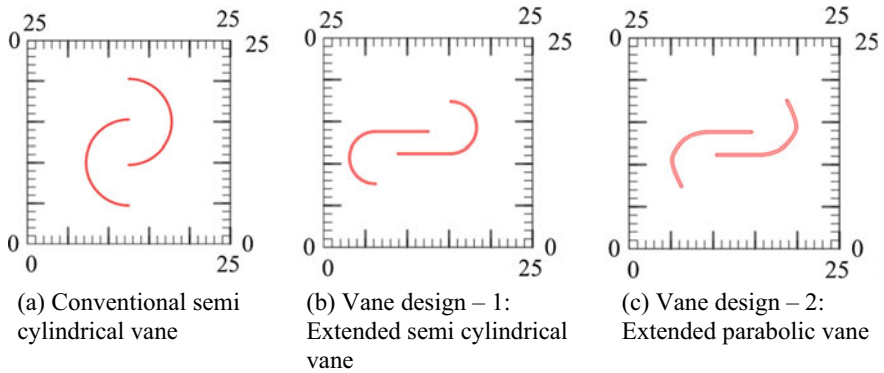
(a) Conventional semi cylindrical vane　　(b) Vane design – 1: Extended semi cylindrical vane　　(c) Vane design – 2: Extended parabolic vane

Fig. 3 Designs of the vanes investigated in the present study (Dimensions cm)

2　Conceptual Discussion

In the case of regular semicircular vane, as shown in Fig. 2, the generation of stagnation pressure centre emerges at the radius r_1. Also, the flow divergence will be such that the flow focal point will be relatively located at less radius ($r_1 < r_2$). Subsequently, torque generation on vane will also be relatively less. If the shape of the vane changed such that the stagnation pressure centre shifts from radius r to the radius r_2, then greater torque can be produced by the vane. Also, the shape of the retarding vane can be made, such that, it diverts the flow by which the stagnation pressure point can generate at relatively higher radius ($r_2 > r_1$). It might enhance the torque development with the use of modified rotor vane and subsequently the coefficient of power.

Considering the effect of stagnation pressure point shifting and designed flow diversion, two types of vanes designs are considered. (i) Semicircular ended vane and (ii) Parabolic ended vane. For performance comparison with conventional vane Savonius turbine, third rotor with conventional semi-cylindrical vane is also considered for the experimentation purpose. Figure 3 indicates the shape of the vane considered for the present investigation.

3　Data Reduction

3.1　Tip Speed Ratio (TSR)

Tip speed ratio is the ratio of the tangential velocity of the rotor vane at the tip to the free stream velocity of water

$$\text{TSR} = \frac{\omega D}{2V} \tag{1}$$

3.2 Coefficient of Power (Cp)

Coefficient of power is the ratio of mechanical power developed by the turbine rotor to the actual hydrokinetic power available from the projected area covered by the rotor. Indirectly, it indicates the efficiency of the turbine.

$$C_\mathrm{p} = \frac{2P_\mathrm{T}}{\rho D H V_i^3} \tag{2}$$

where P_T indicates mechanical power developed by the rotor.

3.3 Coefficient of Torque (C_t)

It indicates the ideal torque development after locating the complete pressure force at the tip of the vane, which is generated due to ideal conversion of complete kinetic energy of the flow available in the cross section of the rotor domain to the pressure force.

$$C_\mathrm{t} = \frac{4T}{\rho V^2 D^2 H} \tag{3}$$

4 Experimental Investigation

4.1 Experimental Setups and Organization

Considering the effect of stagnation pressure point shifting and designed flow diversion, two types of vanes designs are considered. (i) Semicircular ended vane and (ii) Parabolic ended vane. For performance comparison with conventional vane Savonius turbine, third rotor with conventional semi-cylindrical vane is also considered for the experimentation purpose. The diameter and height of all three vanes are kept same for fair comparison. To investigate the effect of vane shape, three different types of vanes are fabricated, i.e. (a) Conventional semi-cylindrical vane (b) Vane design—1: Extended semi-cylindrical (c) Vane design—2: Extended parabolic. The design of
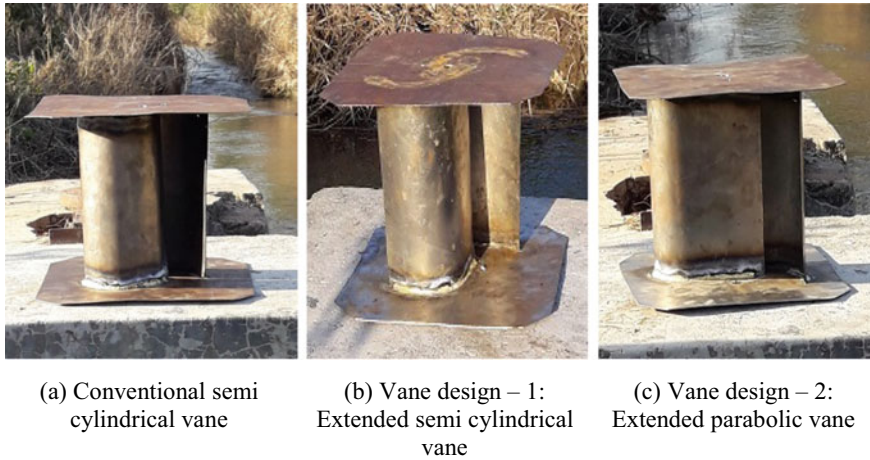
| (a) Conventional semi cylindrical vane | (b) Vane design – 1: Extended semi cylindrical vane | (c) Vane design – 2: Extended parabolic vane |

Fig. 4 Evaluated vanes in the present investigation

the vanes considered for the present experimental investigation is shown to the scale in Fig. 4.

The complete rotor is mounted on the fabricated structure. The complete structure is fabricated using studs and acrylic sheet plates. The vanes used in the rotor are made from the M. S. plates. The acrylic sheet support is held in place by means of washers and nuts for easy replacement of different designed rotors using the same structure. Rotors are mounted on two bearings.

A rope brake dynamometer arrangement is used for measurement of torque and subsequently power developed by Savonius turbine. For measurement of tight side and slack side tensions, two load cells with 0.01 kg accuracy are used along with the setup. The details of the torque and power measurement methodology used in the present investigation are described in detail by Patel et al. [3]. The other details of the setup are shown in Table 1, and the conceptual representation of complete setup and the experimental setup used in the present investigation is shown in Fig. 5.

Table 1 Details of the experimental setup

S. No.	Parameter	Value
1	Width of canal	0.75 m
2	Depth of water in canal	0.3 m
3	Free stream velocity	0.85 m/s
4	Diameter of the rotor	0.2 m
5	Height of the rotor	0.2 m
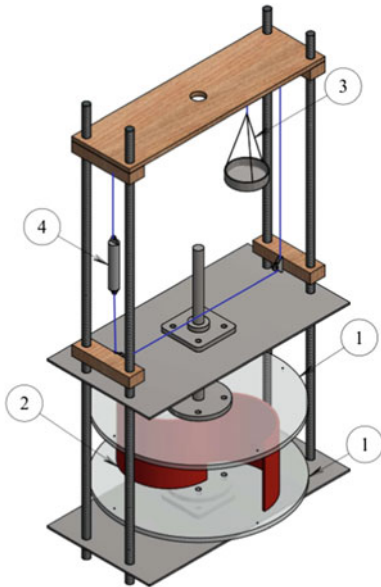
(A) Conceptual representation of the experimental set up [3]

(B) Experimental set up used in the present investigation

(1) Rotor end plates (2) Turbine vane (3) Load pan (4) Spring balance

Fig. 5 Details of experimental setup

5 Results and Discussion

The experiments are carried out in the conventional irrigation canal. Initially, experiments are done for the conventional semi-cylindrical vanes. The revolutions of the runners are measured for the specific time for calculation of angular velocity of the rotor.

The torque is varied on the rotor by changing the tight side and slack side tensions using rope tightening mechanism. The torque is calculated by measuring the tight side and slack side rope tensions using the load cells. The angular velocity of the rotor is measured for each set of the load condition on the shaft, by measuring the time for specific revolutions of the rotor. Same method is repeated for the other designs of rotor also, by changing the rotor in the same structure. The obtained results are represented in form of dimensional terms like power output, torque available at the turbine shaft, angular velocity of the rotor and non-dimensional terms like coefficient of power (C_p), coefficient of torque (C_t) and tip speed ratio (TSR). Figure 6 indicates the comparison between the power developments using different rotor vane design at various angular velocities of the turbine rotor. The result indicates that the power development from both novel designs indicates relatively higher power
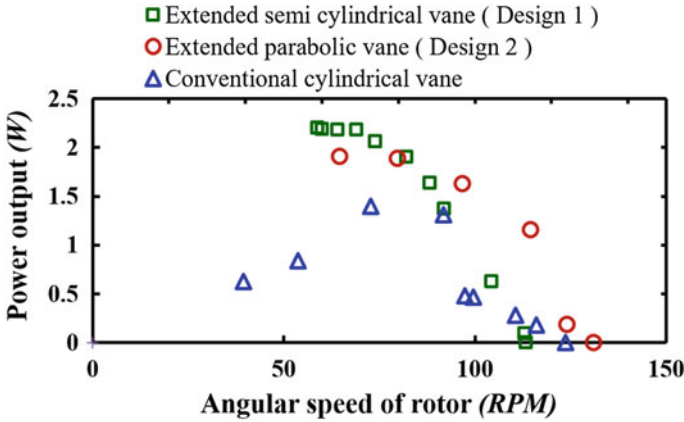
Fig. 6 Variation of power output at different angular velocity of turbine rotor

output compared to the conventional vane design. More specifically, extended semi-cylindrical vane design provides the highest power output among all investigated turbine vane designs.

Figure 7 indicates the comparison between the torques available at turbine shaft using different rotor vane design at various angular velocities of the turbine rotor. The result indicates that the available torque with both novel designs indicates relatively higher compared to the conventional vane design. More specifically, extended semi-cylindrical vane design provides the highest torque among all investigated turbine vane designs.

Figure 8 indicates the comparison between the coefficients of power (C_p) using different rotor vane design at various tip speed ratios (TSR). The result indicates that
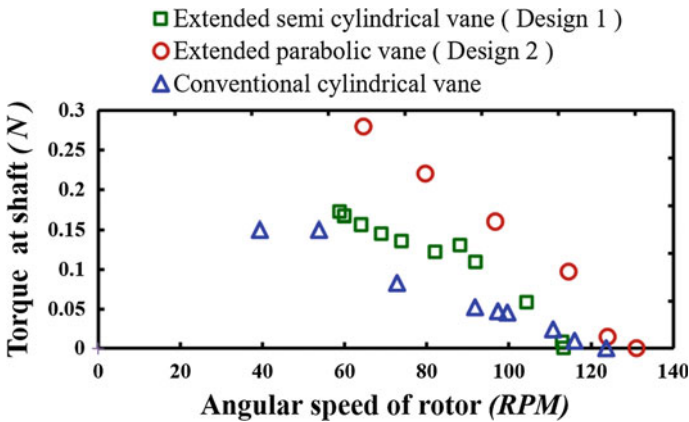

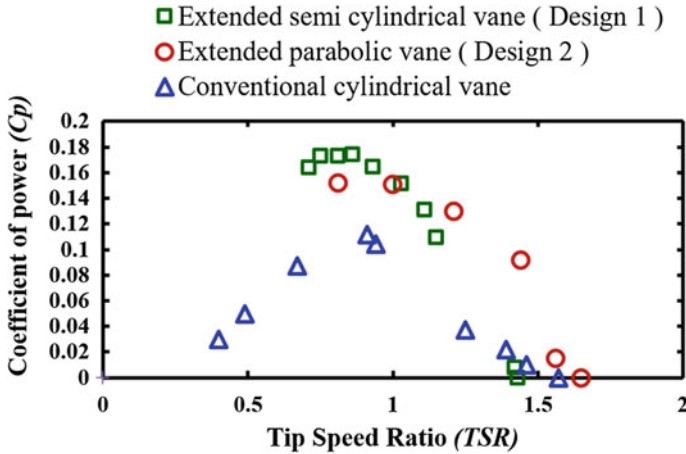**Fig. 7** Variation of torque available at different angular velocity of turbine rotor

Fig. 8 Variation of coefficient of power at different tip speed ratio

the performance in the form of coefficient of power (C_p) with both novel designs indicates relatively higher compared to the conventional vane design. More specifically, extended semi-cylindrical vane design provides the highest performance compared to all investigated turbine vane designs.

Figure 9 indicates the comparison between the coefficients of torque (C_t) using different rotor vane design at various tip speed ratios (TSR). The result indicates that the coefficient of torque (C_t) with both novel designs indicates relatively higher compared to the conventional vane design. More specifically, extended semi-cylindrical vane design provides the torque coefficient compared to all investigated turbine vane designs.
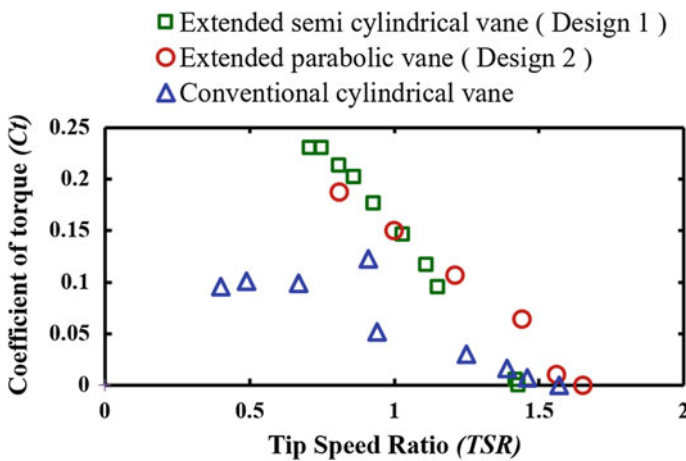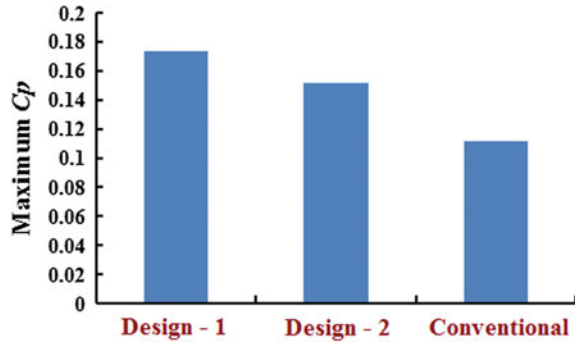

Fig. 9 Variation of coefficient of torque at different tip speed ratio

Fig. 10 Maximum coefficient of power obtained with different investigated vane design

6   Conclusion

In the present investigation, two novel turbine vane designs are investigated, and its performance is compared experimentally. The performances of all three turbine designs are compared with non-dimensional number C_p. To conclude about the best performing turbine vane, the maximum coefficient of power obtained with all different turbine vane designs is compared on one plot as shown in Fig. 10. The comparison indicates that the Design—1 provides 59% improvement, while that of Design—2 provides 36% improvement over the performance of conventional cylindrical vane. The comparison indicates the extended semi-cylindrical vane provides the best performance compared to all investigated turbine vane designs.

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