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Influence of Water Flow Speed on the Torque Behaviour of the Hybrid HKT Having Straight and Helical Bladed Savonius Rotor

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ABSTRACT

Flow streams in rivers, canals, and the tail race of a hydropower plant can be transformed into usable kinetic energy with the help of a hydrokinetic turbine. In this work, the torque characteristics of the hybrid turbine having Savonius helical blade angles of 0˚ and 180˚ have been evaluated using a numerical technique. The characteristics of the turbine are driven for the range of water speed of 0.5 to 2.0 m/s and TSR of 0.3 to 1.5. It is observed from numerical analysis that the flow speed of water significantly affects the mean torque and static torque established by the hybrid turbine. The torque developed by the hybrid turbine enhances as water speed increases. However, the structure of the Savonius blade can alter the torque characteristics of the turbine. The mean torque and static torque growth by the hybrid turbine with a Savonius helical blade angle of 0˚ is more optimum than the hybrid turbine with a Savonius helical blade angle of 180˚. Although, the positive magnitude of torque is achieved at every rotor angle over one revolution by introducing a twist angle to the traditional Savonius blade in the hybrid configuration.

1. Introduction

India has vast potential for hydro energy in the form of a free stream of water in rivers, irrigation canals and tailrace of hydropower plants [1, 2]. The construction of dams or reservoirs in these hydro potential sites is not feasible because it requires a large amount of civil work that needs a huge land area. However, it also leads to a negative environmental impact, affects the marine life, deteriorates the river characteristics and changes the water quality [3, 4]. Thus, hydrokinetic technology can be employed to harness the untapped energy from free streamflow.

Some of the benefits of this technology include being environmentally friendly, having a small impact on marine life, being inexpensive to implement, and being highly predictable [5-7]. However, its biggest drawback is lower conversion efficiency than the traditional turbine [8]. A hydrokinetic

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turbine is used as a converter to turn the available kinetic energy of free stream flow into some useful form of energy. A cross-flow hydrokinetic turbine can be more beneficial for riverine applications with shallow water depths [9]. The main advantage of having cross-flow hydrokinetic turbines is that it shows better self-starting characteristics at lower speed of water than hydrokinetic turbines with axial-flow. Although, it suffers from low efficiency.

The concept of hybridization of the two most popular hydrokinetic turbines, i.e., Darrieus and Savonius turbine, utilizes the inherent performance characteristic of individual hydrokinetic turbines.

To determine the impact of R.R and attachment angle on the hybrid turbine (HT) performance characteristics, Liang *et al.,* [10] shows a computer examine on the HT. The HTs made up of Darrieus turbines with two straight blades and Savonius turbines with two semi-circular blades. This study considered the R.R and attachment angle, which varied from 0.2 to 0.33 and 0° to 180°, respectively. According to a report, a perfect hybrid construction with a R.R and attachment angle of 0.25 and 0o, respectively, would have a optimum power coefficient of 0.363. As the water speed rises, the HT torque is said to increase as well. The HT self-starting capabilities, however, were also identified.

The physical placement of turbines in the hybrid setup plays an important role in the performance of the HT. Given this, Ali [11] performed a numerical examination on a HT with a Savonius turbine on top and a Darrieus turbine on the bottom, with a phase angle of 0^o and 90^o. The HT with a Savonius turbine on the bottom and a Darrieus turbine on top with a 90^o shifts stage performed better than the other hybrid designs, according to study. The optimized HT was found to have higher self-starting capabilities at low speeds.

In order to analyse the HT self-starting properties, Jahangir and Iqbal [12] conducted an examination analysis. On the Darrieus turbine's bottom side, a two-staged Savonius turbine was deposits. The performance of a standalone Savonius turbine was superior to that of a HT under identical operating conditions. Based on study, the HT self-starting characteristic was determined to be superior to the single Darrieus HKT. Bhuyan and Biswas [13], on the other hand, assessed the self-starting properties of the HT as well as the performance traits of an H-Darrieus and a Savonius turbine. The hydrofoil profile S818 from NREL was used to create the Darrieus blade. Unsymmetrical hydrofoil profile freestanding Darrieus turbine (NREL S818) was found to be unable to self-start. However, the HT is more likely to kick off on its own. The impact of overlap on the efficiency of the HT has also been studied. The best power coefficient was found to be 0.15, and a single H-Darrieus turbine was found to be superior to a HT.

Kamal *et al.,* [14] investigated numerically the influence of flow and design parameters on the performance characteristics of the rotor. It was reported that the hybrid configuration having radius ratio 0.4 and attachment angle 90^o, develops a positive value of instantaneous torque at each rotor angle for one revolution that suggests that this configuration is more favourable to self-start on its own compared to other considered configurations.

Adding a helical angle to the Savonius turbine blade has been shown in prior research [15] to enhance the efficiency of hybrid hydrokinetic turbines. Studies show that the optimum coefficient of power for a HT with a 45^o Savonius blade helical angle is 4.7% higher than that of a HT with a 0^o Savonius blade helical angle (a conventional Savonius blade). In previous paper, the influence of helical angles on the performance of the hybrid rotor as presented. The influence of the water speeds on the torque behaviour as not explored in that paper. Therefore, there is a scope to study the impact of water flow speed on the torque behaviour of the HT. Therefore, the effect of water speed on torque development by the HT is explored in this work.

2. CFD Modelling

A group of governing equations characterizing the flow dynamics is can be solved by employing a CFD techniques. It is taken out by solving that represent conservation laws such as mass conservation and momentum conservation [16].

Conservation of mass;

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V_m)}{\partial X_m}=0 \tag{1}$$

Conservation of momentum;

$$\frac{\partial(\rho V_i)}{\partial t}+\frac{\partial(\rho V_i V_m)}{\partial X_m}=-\frac{\partial p}{\partial X_i}+\frac{\partial}{\partial X_m}\left[(\mu+\mu_t)\left(\frac{\partial V_i}{\partial X_m}+\frac{\partial V_m}{\partial X_i}\right)-\frac{2}{3}k\delta_{im}\right] \tag{2}$$

2.1 3D Modelling of a Computational Domain

In the CFD study, the generation of a 3D model is the foremost step. The design parameters to model the HT have been taken from the earlier study. Table 1 lists all of the variables that were considered during this study's design and flow calculations. The reason behind foe the selection of these design parameters is discussed in the previous paper of the author [15]. The computational domain comprises a channel which is a stationary domain and an enclosure that rotates at a desired RPM. Both components of the computational domain are modelled in ’ANSYS Design Modeler’. However, the 3D modelling of the HT is carried out in ‘Solid Works’. A schematic view of the CFD domain is depicted in Figure 1.

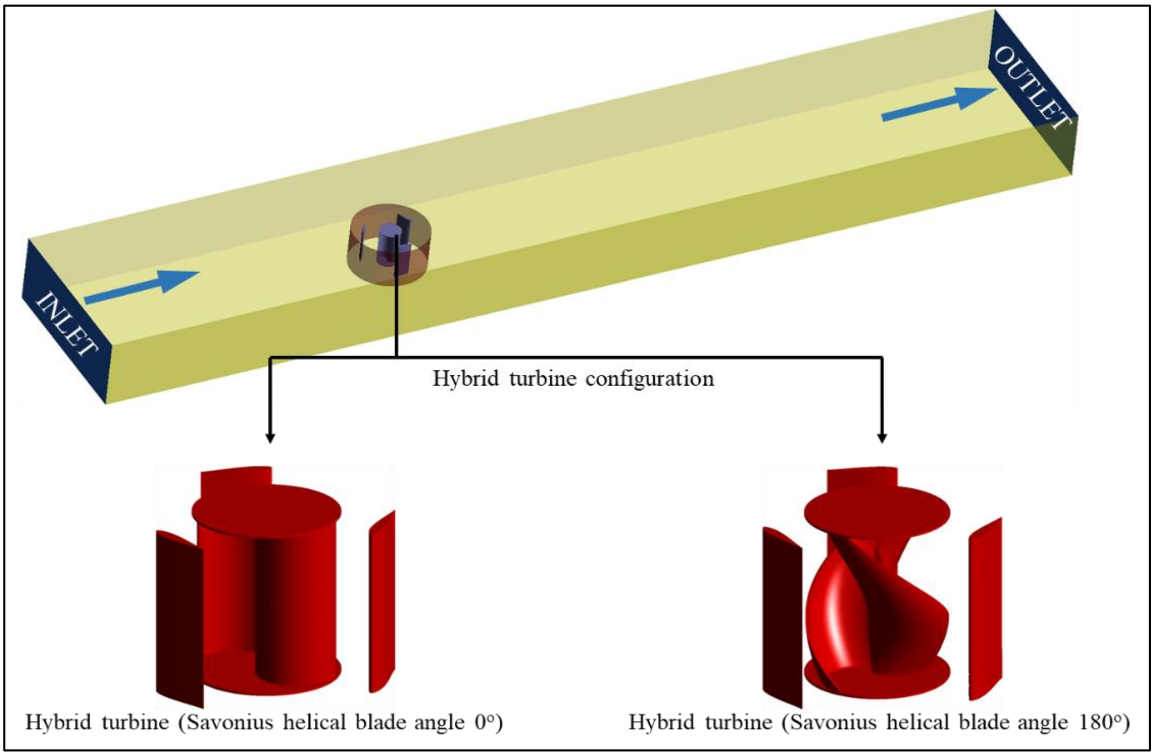


Fig. 1. Schematic of the computational domain and different configurations of the HT

Table 1
Specifications of design parameters considered under the present investigation

Design parameter	Specification
Hybrid cross-flow HKT	
Darrieus turbine height (mm)	150
Chord length of Darrieus turbine (mm)	60
Darrieus turbine diameter (mm)	200
Profile of Darrieus blade	S1046 hydrofoil
Number of blades (Darrieus)	3
Savonius turbine diameter (mm)	120
Savonius turbine height (mm)	150
Shape of Savonius blade	S-type
Number of blades (Savonius)	2
Height of enclosure (mm)	150
Diameter of enclosure (mm)	300
Aspect ratio (AR)	0.75
Savonius helical blade angle (degree)	0 and 180
Attachment angle (degree)	90
Radius ratio (RR)	0.6
Endplate area ratio (EPR)	1.0
Overlap ratio (OR)	0.1
Channel	
Shape of channel	Rectangular
Channel length (mm)	4000
Channel width (mm)	700
Channel height (depth of water) (mm)	300

2.2 Meshing and Solver Setup

The model generation of a computational domain is followed by mesh generation. This process is used to divide the complete domain into number of small volumes. An unstructured meshing has been chosen [16] while the turbine has meshed with a hybrid meshing technique. Tetrahedron elements have been used for unstructured meshing and hexahedron elements have been used for structured meshing [17]. The meshing is dome by using 'ANSYS Mesh'. The quality of mesh has been found within an acceptable limit. Meshing of a CFD domain is presented in Figure 2. The mesh independence test with different mesh densities as done and discussed in in the previous study of the author [15].

The success of a computational fluid dynamics (CFD) analysis relies heavily on the accuracy with which boundary conditions are specified for the flow domain. These are the simulation boundary conditions; Sidewalls, the bottom surface of the water channel and turbine, and the top surface of the water channel, both have different effects on the turbine: inlet, water velocity; outlet, air pressure. In order to model the fluctuating components of flow variables in the flow field, RNG k-ε model is selected [18, 19]. In order to perform transient simulation, the residual value has been chosen as 10^{-5} [20]. The time-step size based on increment rotor angle has been chosen as 10^{o}/time-step size. The rotor is allowed to rotate 5 revolutions per simulation. An 'ANSYS CFX v15' solver code has been employed to accomplish the numerical simulations.

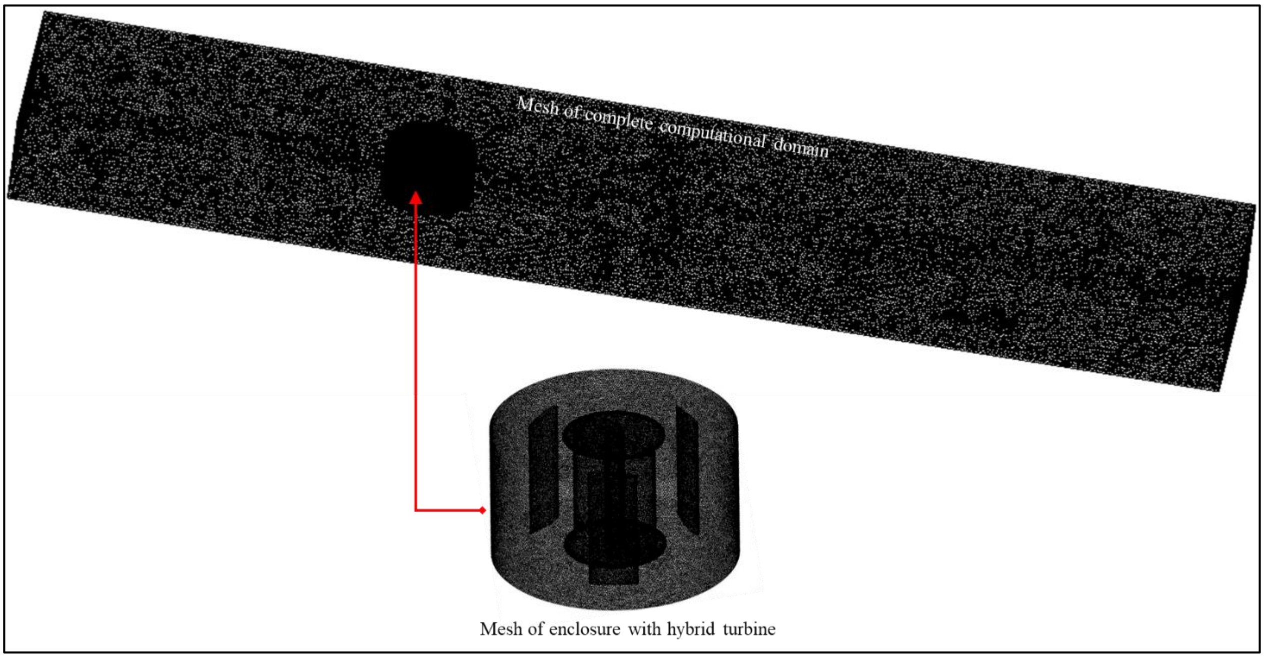


Fig. 2. Schematic of meshing of a computational domain

3. Results

Under the present investigation, the static torque and the mean torque developed by the different configurations of the HT have been evaluated under varying operating conditions such as water speed (0.5–2.0 m/s) and TSR value (0.3 – 1.5). Validation with experimental results is necessary for assessing the validity and trustworthiness of CFD results. Specifically, the "Hydraulic measurement laboratory, IIT Roorkee" was where the experiments were taken out. The performance of the present model of the hydrokinetic turbine was successfully validated with experimental results in the previous study of the author [15].

3.1 Effect of the Flow Speed of Water on the Mean Torque Developed by the HT

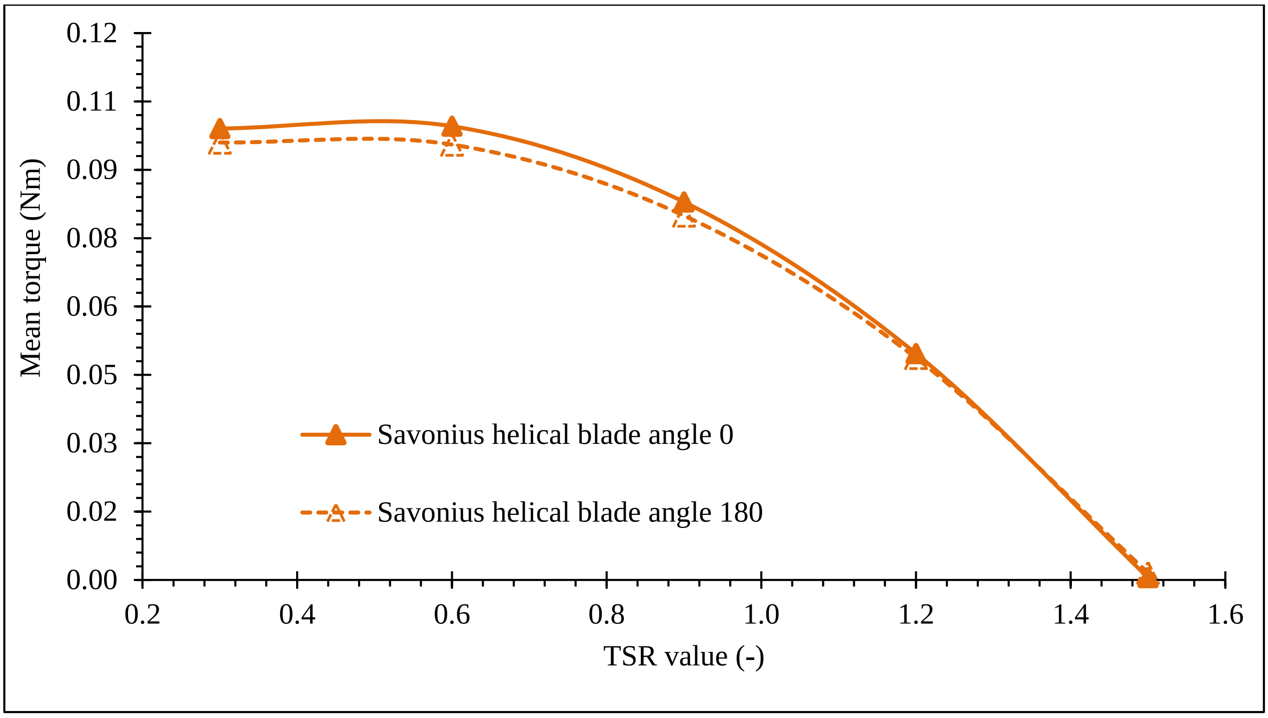
The speed carried by flowing fluid plays an important role in the power development by the rotor. In order to simulate the flow conditions of the hydropotential site, the flow speed of water in the channel domain is varied in the range of 0.5 m/s to 2.0 m/s. The impact of flow conditions on the performance of the HT having Savonius helical blade angles of 0^o and 180^o, has been evaluated.

The graphical overview of mean torque released by the HT with Savonius helical blade angles of 0^o and 180^o at different water velocities and TSR values (RPM of the turbine) has been presented in Figure 3(a-d) respectively. The mean torque was obtained through the post-processing module. However, the value of TSR is computed by dividing the peripheral speed of the blade by the flow speed of the water. It can be described as;

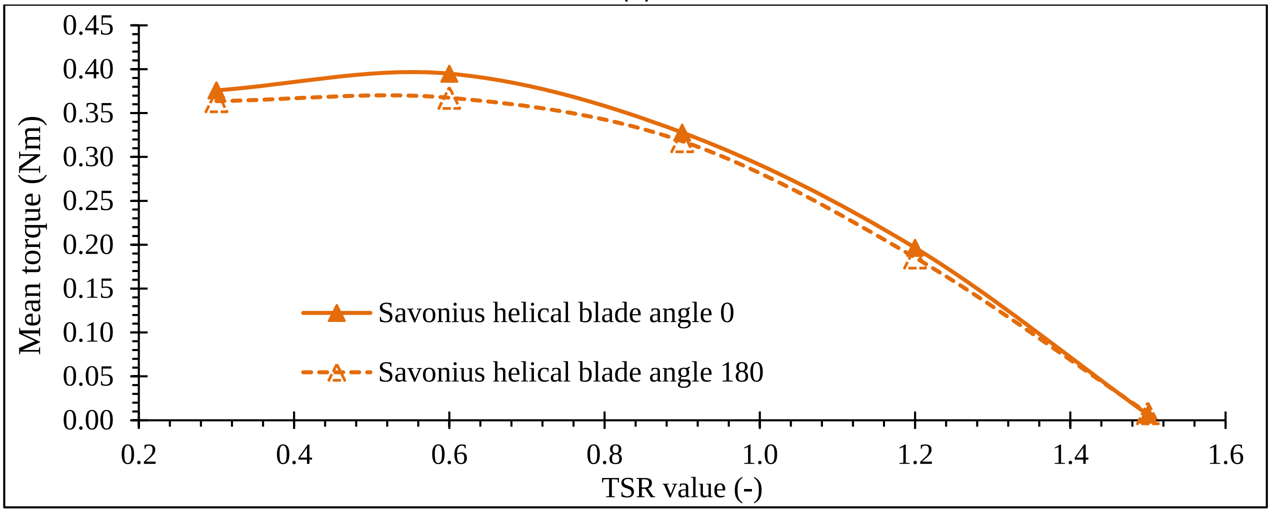
$$(\text{TSR}) = \frac{\omega \times R}{V} \tag{3}$$

Based on Figure 3, it is found that the mean torque developed by both HT rotors increases as the magnitude of water speed enhance. It is because the large momentum change occurs at higher speed of water that contributes to more power generation by the HT. Thus, the complete performance of the HT gets enhanced. Further, the mean torque developed by the HT having a Savonius helical blade angle of 0° was higher than the hybrid configuration with a Savonius helical blade angle of 180°. It is due to the complex shape of the Savonius turbine having a Savonius helical blade angle of 180° which minimizes the exposure of the advancing blade to the incoming flow. However, it is perceived that the effect of Savonius helical blade angle gets vanishes at higher RPM (TSR value) of the HT.

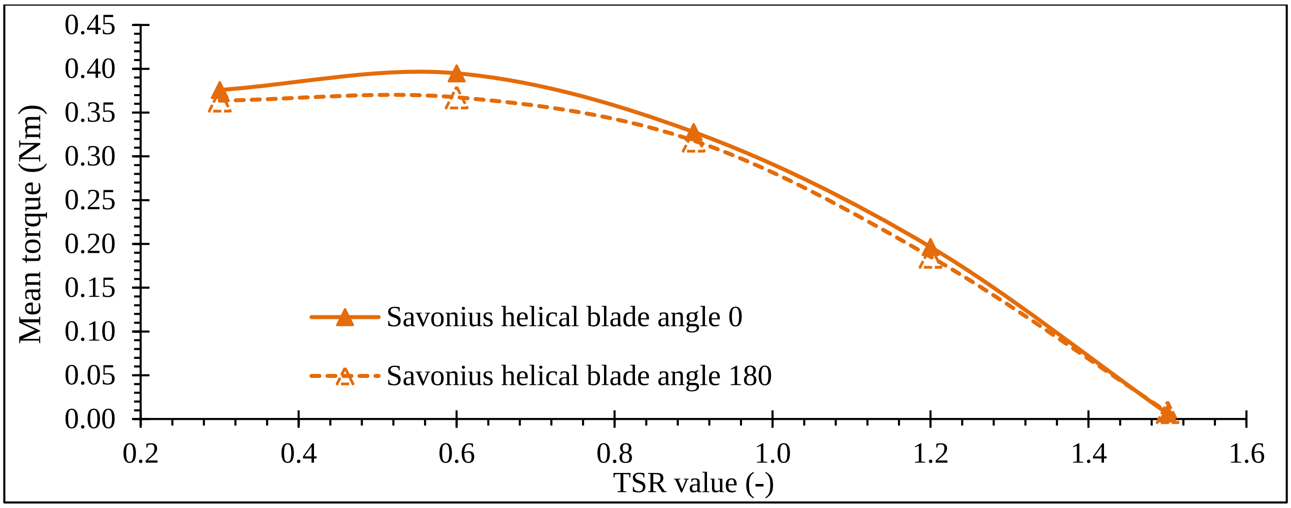
The maximum mean torque was obtained as 0.099, 0.395, 0.883 and 1.554 for the HT with Savonius helical blade angle of 0° corresponding to the water speed of 0.5-2.0 m/s respectively and TSR value of 0.6. The maximum drop in mean torque developed by the HT with Savonius helical blade angles of 0° and 180° was obtained as 4.1%, 6.9%, 9.4% and 10.5% at the water speed of 0.5-2.0 m/s and TSR value of 0.6.



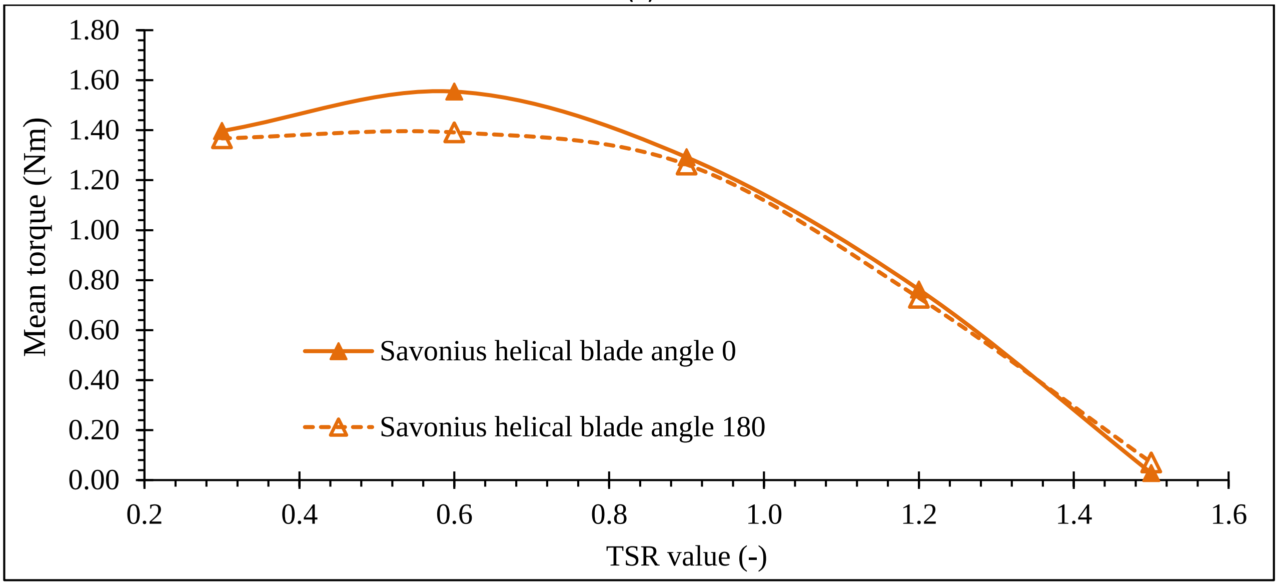
(a)



(b)



(c)



(d)

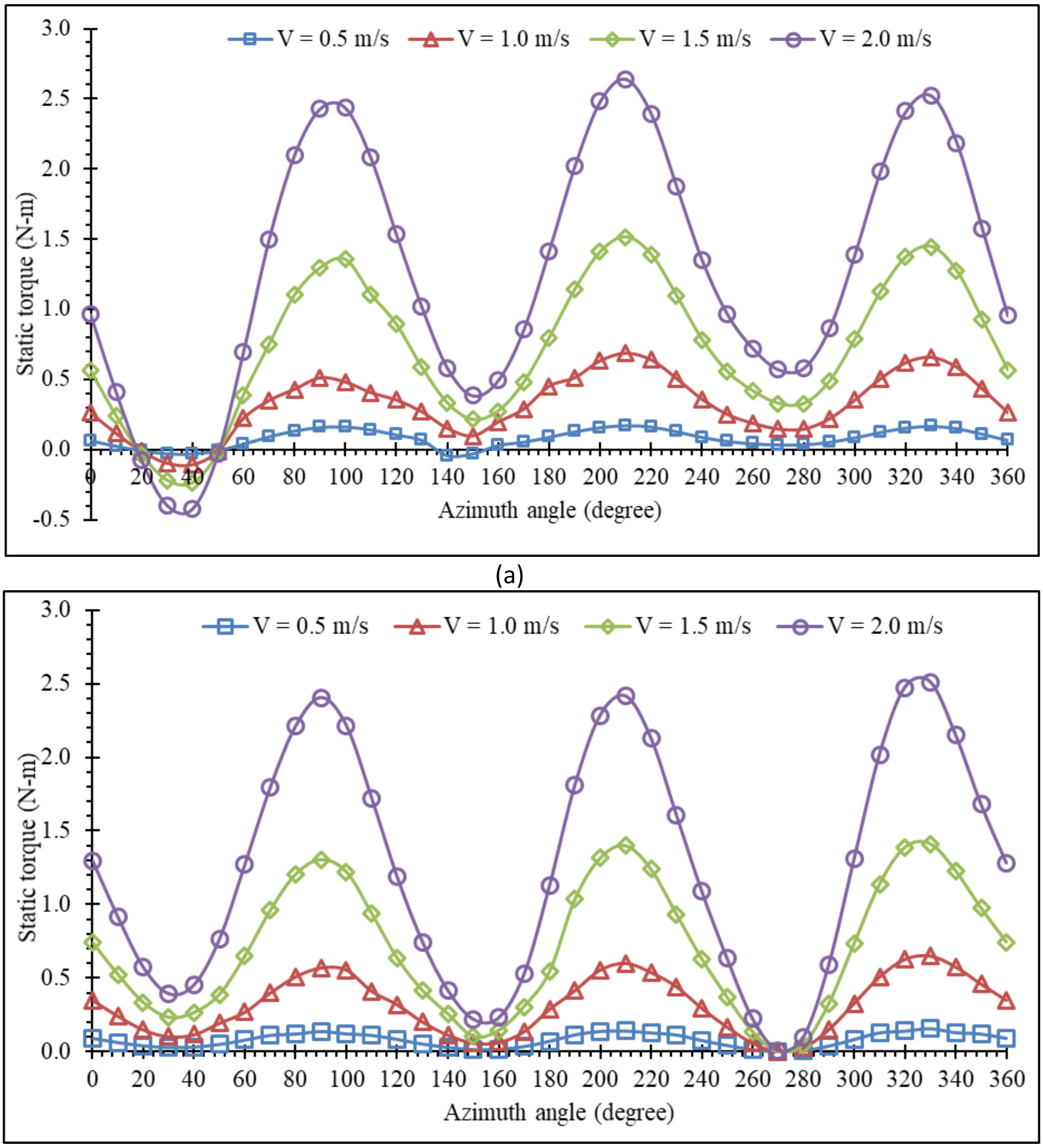
Fig. 3. (a) Variations in mean torque developed by the HT corresponding to the water speed of 0.5 m/s (b) Variations in mean torque developed by the HT corresponding to the water speed of 1.0 m/s (c) Variations in mean torque developed by the HT corresponding to the water speed of 1.5 m/s (d) Variations in mean torque developed by the HT corresponding to the water speed of 2.0 m/s

3.2. Effect of the Flow Speed of Water on the Static Torque Developed by the HT

In order to determine the different nature of static torque developed by the HT over one revolution, a graph of static torque generated by the turbine has been plotted against the different azimuth angles during one revolution. The graph of static torque developed by the HT having Savonius helical blade angles of 0° and 180° is presented in Figures 4(a) and 4(b).

Figure 4 reveals that there is a clear correlation between the rate of water flow and the amount of torque that is produced by the HT. This correlation can be seen to be significant when looking at the graph. The cyclic behavior of torque generation has been observed for the HT. Three peaks of static torque developed by the HT with Savonius helical blade angles of 0° and 180° have been found at an azimuth angle of 100˚, 210˚ and 330˚, during one revolution. The maximum static torque was obtained as 0.175, 0.686, 1.447 and 2.641, for the HT with Savonius helical blade angle of 0˚ corresponding to the speed of water from 0.5-2.0 m/s. It is found that the initiate characteristics of the rotor improve as the flow speed of water increases. It signifies that the most favorable condition for the self-start of the turbine, is at the higher speed of the water.

It is noteworthy to mention that the hybrid turbine with a Savonius helical blade angle of 180° developed a positive magnitude of static torque at each rotor angle over one revolution, irrespective of the flow speed of the water. However, the hybrid turbine having the Savonius helical blade angle of 0˚ generated a negative magnitude of static torque at 20˚ to 50˚ azimuth angle. The negative torque became large at a higher speed of the water. It implies that the hydrodynamic loading on the HT will get reduced. Therefore, replacing the traditional Savonius blade (straight blade) with a helical Savonius blade will enhance the structural behaviour of the HT. Similar observations have been made in earlier studies [21, 22]. The HT twisted Savonius blade allows for this capability, but at the cost of some efficiency.



(a)

(b)

Fig. 4. (a) Static torque developed by the HT with Savonius helical blade angle of 0o during one cycle of revolution at different water velocities (b) Static torque developed by the HT with Savonius helical blade angle of 180° during one cycle of revolution at different water velocities

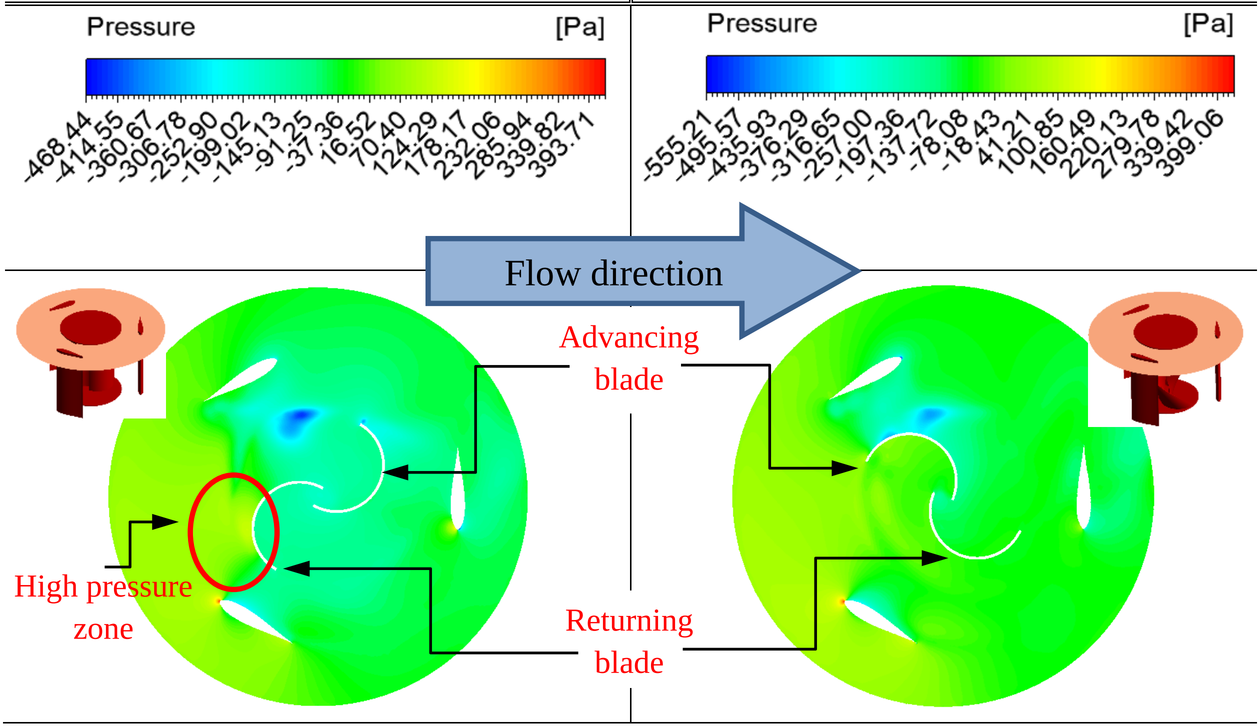
3.3 Flow Characteristics across the HT

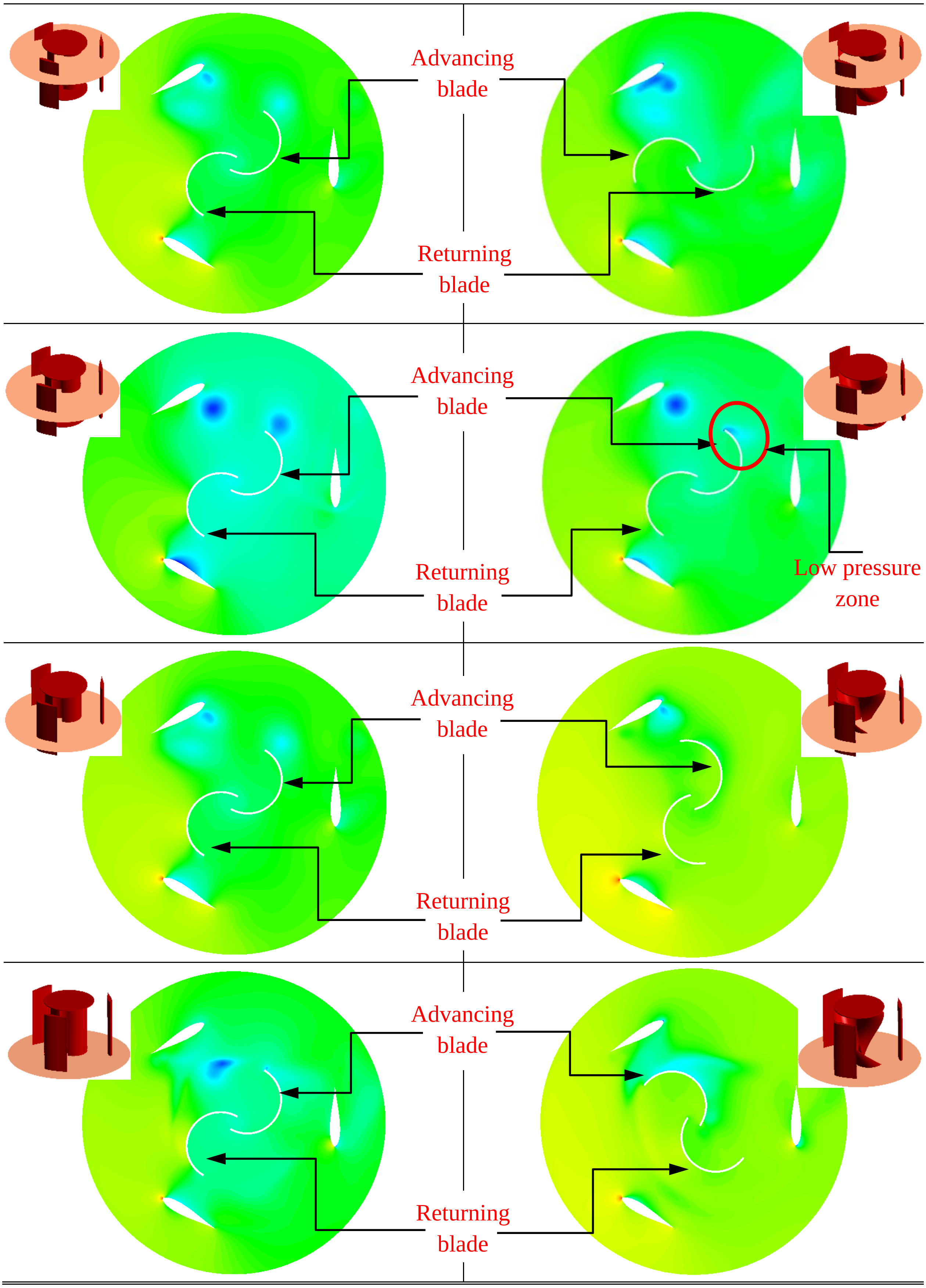
For the purpose of deducing why a HT with a Savonius helical blade angle of 0° generates negative torque, pressure contours have been plotted at five different planes corresponding to an azimuth angle of 30˚ (at which maximum negative static torque is obtained). and TSR value of 0.6. The pressure contours for different rotor configurations are presented in Table 2.

At this angular location of the HT (azimuth angle of 30˚), it appears from the pressure contours plot that the convex edge of the returning blade of a conventional Savonius blade is subjected to greater pressure than the concave side of the advancing blade. In other words, the drag produced by the returning blade will be greater than that of the forward-moving blade. Therefore, the HT performance is negatively impacted because the Savonius turbine generates a negative magnitude of torque at this rotor angle and the Savonius turbine experiences retarding motion at this azimuth angle. However, the HT with the Savonius helical blade angle of 180˚ always has its leading blade pointing into the direction of the incoming water flow, allowing the Savonius turbine to generate a positive torque.

Table 2
Pressure contours plot at different planes of the HT

Savonius helical blade angle 0°	**Savonius helical blade angle 180°**




Advancing blade
Returning blade
Advancing blade
Returning blade
Low pressure zone
Advancing blade
Returning blade
Advancing blade
Returning blade

4. Conclusions

Under the present investigation, the working of the hybrid rotor has been evaluated in terms of torque developed by the turbine under various operating conditions. The flow speed of water and TSR value in this study are chosen in the range of 0.5-2.0 m/s and 0.3 to 1.5, respectively. An attempt has also been made to visualize the flow across the turbines to understand the reason for generating negative torque by the HT at a specific range of azimuth angles.

i. It is found that the mean torque developed by the hybrid turbine increases as the water speed increases. The mean torque generated by the hybrid rotor with a Savonius helical blade angle of 0˚ is optimum than the HT with a Savonius helical blade angle of 180˚. It is perceived that the effect of Savonius helical blade angle gets vanishes at higher RPM (TSR value) of the hybrid turbine irrespective of water velocities.
ii. The maximum mean torque was recorded as 0.099, 0.395, 0.883 and 1.554, for the HT having Savonius helical blade angle of 0˚ corresponding to the water speed of 0.5 to 2.0 m/s, respectively and TSR value of 0.6.
iii. The torque developed by the HT is found in cyclic nature. The maximum static torque was recorded as 0.175, 0.686, 1.447 and 2.641, for the HT having a Savonius helical blade angle of 0˚ corresponding to the water speed of 0.5-2.0 m/s. It is found that the HT having a Savonius helical blade angle of 0˚ produced 5% higher peak torque than the HT having a Savonius helical blade angle of 180˚.
iv. It is concluded that the negative magnitude of torque produced by the HT having a traditional Savonius blade can be mitigated by replacing it with a helical Savonius blade. However, there is a drop-in torque generation has been observed.
v. Based on flow visualization, it is examined that the traditional Savonius blade in the hybrid setup experiences higher drag compared to the helical Savonius blade.

In future, there is scope to assess the cascading effect on the torque behaviour of the hybrid rotor under different flow conditions. It will help in array design of the hybrid rotor.

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