

## Performance analysis of Savonius Hydrokinetic Turbine in Open Channel

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The hydrokinetic turbine (HKT) can be installed at remote locations which are far from current electrical grids and has a great deal of potential for small-scale power generation from freely flowing water. In the present investigation, performance analysis Savonius HKT (SHKT) is carried out in a trapezoidal open channel for a canal located on Tapi River, Surat, Gujarat, India. For numerical analysis,  $k - \epsilon$  Realizable turbulence model has been applied to the Reynolds-Averaged Navier-Stokes (RANS) solver with two different inlet mean flow velocities ( $U_m$ ) 0.4242 m/s and 1.0606 m/s for a wide range of 0.1 to 0.9 tip speed ratio (TSR). Based on the investigation, the maximum power coefficient ( $C_{Pmax}$ ) obtained is 0.0648 and 0.0721 at 0.6 TSR for SHKT at 0.4242 m/s and 1.0606 m/s velocity, respectively. Additionally, the fluid flow visualisations surrounding the rotors have been examined.

**Keywords:** Hydrokinetic turbine; Savonius; Power coefficient; Tip speed ratio**1. Introduction**

The depletion of fossil fuel supply due to excessive usage and its negative environmental repercussions are the main factors driving the search for creative, sustainable methods of producing clean energy. Between 1995 and 2015, the percentage of primary energy consumed from fossil fuels decreased from 87% to 85%, and by 2035, consumption is predicted to drop even further to 78% [1]. In recent years, renewable energy sources have added over 2179 GW (~34% of installed power capacity worldwide) to the global energy generation. Hydropower is the biggest contribution, making up over 1151 GW, or nearly 18% of the installed power capacity globally [2,3]. However, about 1.5 billion people worldwide do not have access to sufficient power, especially in developing and underprivileged nations. [4]. The conventional electricity produced by the hydroelectric plant is generally unaffordable and inaccessible to rural and isolated people. Given the catastrophic effects of climate change and the world's continually increasing demand for power, it is critical to quickly accelerate this trend and transition to a portfolio dominated by renewable energy that significantly lowers carbon emissions within the next ten years. Utilizing proven and affordable renewable energy conversion technologies, such solar, hydro, and wind turbines, to quickly grow utility-scale renewable energy projects and markets is a major way to do this. The hydrokinetic turbine (HKT), which generates electricity from open water channels, is the most cost-effective solution for meeting these locations' power needs. Using the potential of rivers, canals, and oceans to generate electricity is also a clean, sustainable, and practical solution.

Hydrokinetic (HK) energy generation avoids many of the problems associated with more traditional forms of hydropower, such as high civil works costs and the need for a viable and exploitable potential energy head. In 1920, Sigurd J. Savonius developed drag-based and "S" shaped HKT known as Savonius HKT (SHKT) [5]. The design of SHKT was originated from cutting cylinder along its axis into two halves and then putting the two half surfaces sideways. Kumar and Saini [6,7] optimised the blade arc angle, blade twist angle and blade shape factor of single stage SHKT using numerical analysis. They found that at 0.9 TSR and mean flow velocity ( $U_m$ ) of 2 m/s, the maximum power coefficient ( $C_{Pmax}$ ) of 0.426 was obtained for 150° blade arc angle and 0.6 blade shape factor; while 0.390 for 12.5° blade twist angle. Talukdar et al. [8] evaluated the performance of SHKT by varying the no. of blades (two and three); shape of blade (semi-circular and elliptical) and depth of immersion (100% fully submerged and 60% partially submerged). The two bladed semi-circular fully submerged SHKT imparts the highest  $C_{Pmax}$  of 0.28 at 0.89 TSR. A novel deflector plate added SHKT with NACA6409 blades instead of conventional semi-circular blades were numerically investigated by Chaudhari and Shah [9]. Their study found that the  $C_{Pmax}$  for NACA6409 blades SHKT and conventional SHKT with deflector is 0.227 at 0.8 TSR and 0.25 at 0.8 TSR, respectively. Also, NACA6409 blades SHKT with deflector has a lesser performance than conventional SHKT with deflector. Shanegowda et al. [10] numerically investigated the performance of SHKT for straight and curved (30°, 60° and 90°) bend channels. The most efficient bend condition is 30° with  $C_{Pmax}$  of 0.24 at 1 TSR.

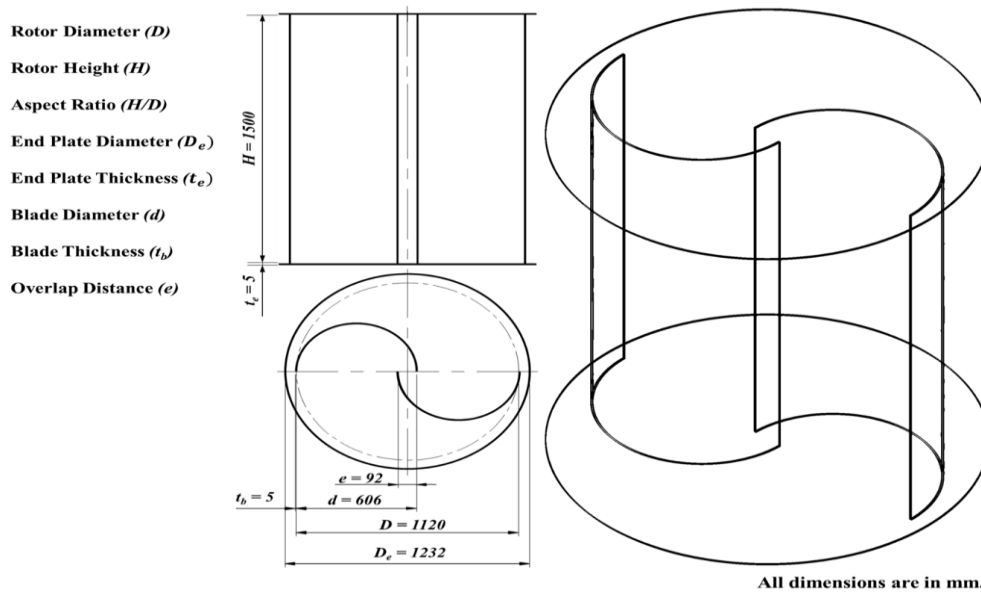
The main objectives of this study are to evaluate the performance of vertical axis oriented SHKT in terms of torque coefficient ( $C_T$ ) and power coefficient ( $C_P$ ) for a hydro canal located on Tapi River, Surat, Gujarat, India by submerging them vertically. For numerical analysis,  $k - \epsilon$  Realizable turbulence model has been applied to the Reynolds-Averaged Navier-Stokes (RANS) solver with two different velocities for various tip speed ratio (TSR). This article's structure is as follows: Section 1 provides the current energy scenario along with pertinent background data of HKTs and relevant literature of SHKT. The whole numerical modelling of various HKT models is depicted in Section 2. Section 3 elaborates the results obtained with thorough discussion, whereas the closing remarks are concluded in Section 4.

**2. Numerical Methodology**

Because of the flow separation and wake creation, the flow field surrounding the HKTs is complex and time-dependent. Using conventional methods like the stream tube model, which is based on blade element momentum theory, it is challenging to describe this type of intricate unsteady flow physics. Additionally, artificial neural networks (ANN), fuzzy logic, and genetic algorithms are examples of soft computing techniques that show promise in predicting the power factor of various energy systems. Additionally, compared to other soft computing methods, the adaptive neuro-fuzzy inference system (ANFIS) provides an efficient way to predict the power output. The most effective method available today for resolving a variety of industrial and non-industrial fluid flow issues is computational fluid dynamics (CFD). Creating the computational domain, dividing it into smaller areas for solving the equations, choosing appropriate boundary conditions, and allocating appropriate values to modelling parameters are prerequisites for carrying out numerical simulation of any phenomenon. The numerical simulations were created in a similar step-by-step process. Initially, the "Design modeller" module is used to model the HKT and its flow domain, followed by the "Mesh module" for grid/mesh production. The third stage involves selecting a solution and applying boundary conditions to specify the HKT's operating conditions. The next step is to analyse the simulation results in the "CFD-post module".

**2.1. Geometry Design**

The schematic of the SHKTs along with the geometrical parameters used in present study are shown in Fig. 1. These geometrical parameters were calculated for theoretical 1 kw power generation. The two bladed SHKT shown in Fig. 1 has semi-circular blade profile with overlap ratio of 0.15. Many researchers have reported earlier that two bladed SHKT shows better performance in compare to the three bladed SHKT [11,12,13].



**Fig. 1. Schematic and geometrical parameters of SHKT.**

**2.2. Performance Parameters**

The performance of a SHKTs with geometrical parameters taken into consideration is investigated numerically in the current work. Modelling and meshing of the computational domain are finished in order to fulfil the study's objectives, as described in the paper's preceding section. The performance of the SHKT is evaluated by the value  $C_T$  and  $C_P$  corresponds to TSR. The following equations are used to obtain characteristic curves ( $C_T$  vs. TSR and  $C_P$  vs. TSR) for various geometrical and flow parameters.

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

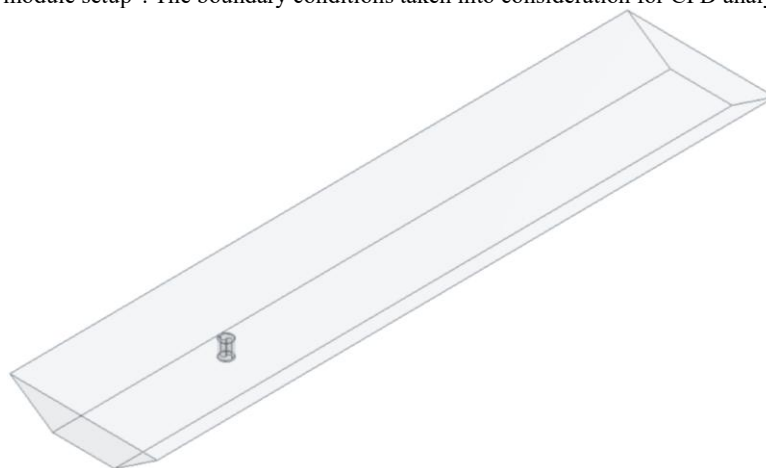
$$C_T = \frac{4T}{\rho U_m^3 D^2 H} \tag{2}$$

$$C_P = \frac{P_{HKT}}{P_{available}} = \frac{2T\omega}{\rho A_s U_m^3} = \frac{2T\omega}{\rho D H U_m^3} = C_T \times TSR \tag{3}$$

where  $\omega$  is angular velocity in rad/s,  $T$  is torque in N·m,  $\rho$  is density in kg/m<sup>3</sup>,  $P_{HKT}$  is power developed by HKT in W,  $P_{available}$  is hydraulic power available in W,  $A_s$  is HKT swept area in m<sup>2</sup>.

**2.3. Computation Domain**

In this study, ANSYS 2020 R1 "Design Modeller" was used to construct a 3-D model of SHKT as shown in Fig. 2. In order to carry out the rotating simulation, SHKTs have been enclosed by cylindrical volumes that have been created about the Y-axis so that, when subjected to numerical analysis, the HKT can rotate at a specified angular velocity. Under this study, diameter for the rotating domain is considered as 1.2 times of HKT diameter. To simulate the performance of the HKT in a canal, a 3-D computational stationary domain has been modelled for numerical analysis. After the domain is constructed, the geometry is given the proper domain names to suit the respective boundary conditions. This process is called "physics module setup". The boundary conditions taken into consideration for CFD analysis are listed in Table 2.



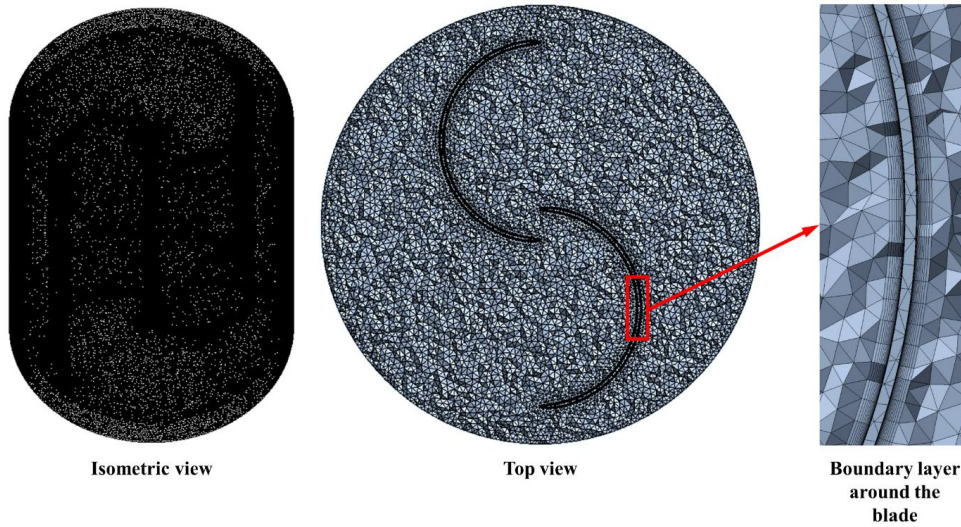
**Fig. 2. 3D computation domain of canal**

**Table 2. Boundary conditions for 3-D computational domain of canal.**

Name	Boundary Type	Boundary Conditions
Inlet	Velocity inlet	0.4242 m/s & 1.0606 m/s, uniform flow
Water surface	Symmetry	Symmetry
Canal bed	Wall	Stationary
Canal side wall	Wall	Stationary
Outlet	Pressure outlet	Pressure outlet
Turbine	No slip wall	Rotates at desired RPM

2.4. *Meshing of Computational Domain*

The convergence and stability of the numerical solution depend on the construction of an appropriate computing mesh/grid. To apply the partial differential equations governing fluid flow to each subdomain and solve them using one of the three methods - finite volume, finite element, or finite difference. An estimated solution of the entire fluid domain is then generated by assembling the solutions found in each of the domain's cells. In the present study, a mesh for the whole flow domain is created by ANSYS MESH considering an unstructured grid of tetrahedral elements. The meshing of inner rotating zone containing rotor such as SHKT is depicted Fig. 3.



**Fig. 3. Meshing of the computational fluid domain of SHKT.**

2.5. *Turbulence Model*

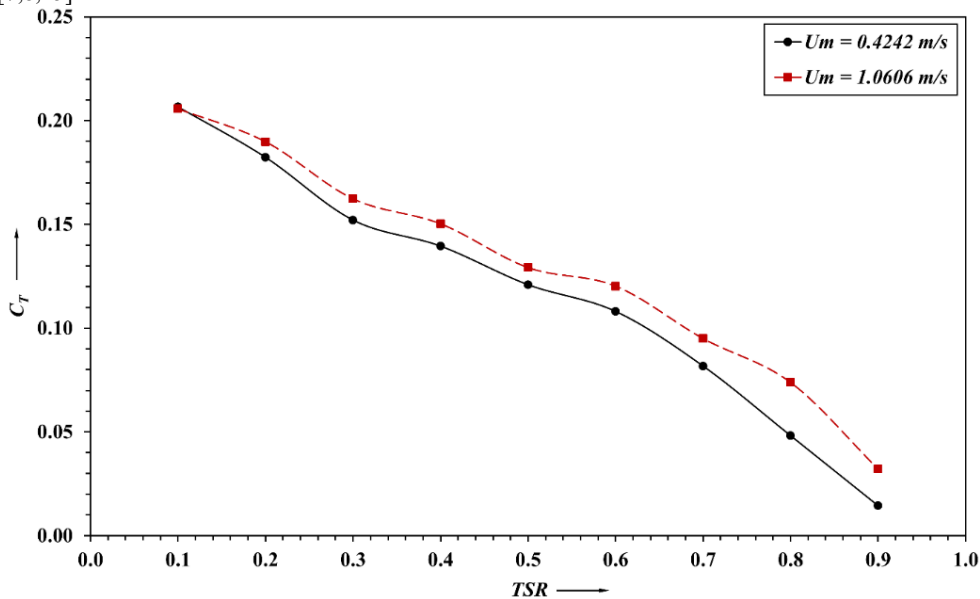
For all residual of the momentum, continuity, and turbulence equations, the convergence conditions were set up as  $1 \times 10^{-5}$ . At the inlet of the canal, 2.2% turbulent intensity and 7.6 m hydraulic diameter was applied considering the fact that  $C_P$  decreases with increases above values [14]. In this investigation,  $k - \epsilon$  Realizable turbulence models was employed.

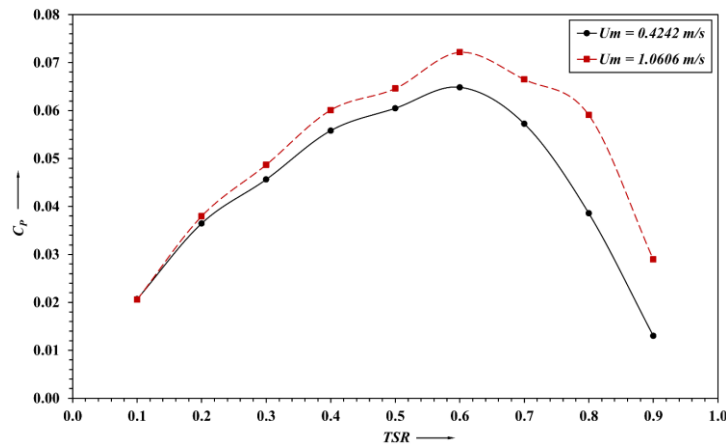
3. **Results and Discussion**

This section presents comprehensive numerical results of SHKT for two velocities 0.4242 m/s and 1.0606 m/s for different values of TSR. For every value of the parameters taken into consideration, simulation results have been obtained. Nonetheless, the flow distribution surrounding the HKT is explained correspondence to the  $C_{P,max}$  value.

3.1. *Performance Characteristics Curves*

In this study, dimensionless parameters  $C_T$ ,  $C_P$  and TSR stated in Section 3.1 are used to characterise the performance of SHKT. Using Eqs. (1) to (3), the performance characteristic curves were obtained SHKT. The variation of  $C_T$  and  $C_P$  with TSR for SHKT is shown in Fig. 4. For a velocity of 0.4242 m/s and 1.0606 m/s, the  $C_{P,max}$  obtained is 0.0648 and 0.0721 at 0.6 TSR for SHKT. Similarly, corresponding  $C_{T,max}$  at respective TSR are 0.1081 and 0.1202 for SHKT. For SHKT, the returning blade encounters more substantial negative drag and resistance as the turbine rotates faster at higher TSR, thereby opposing the advancing blade's positive torque and resulting in a decreased net driving force and torque [7,8,15].

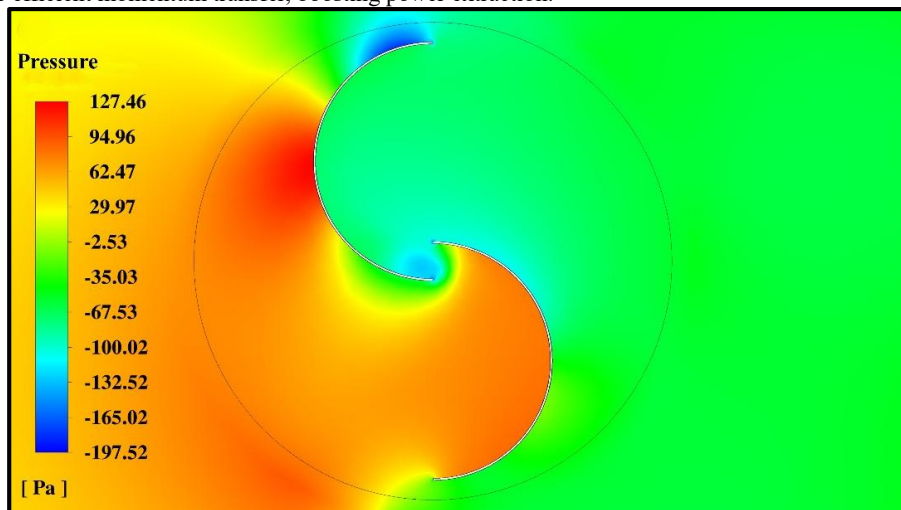




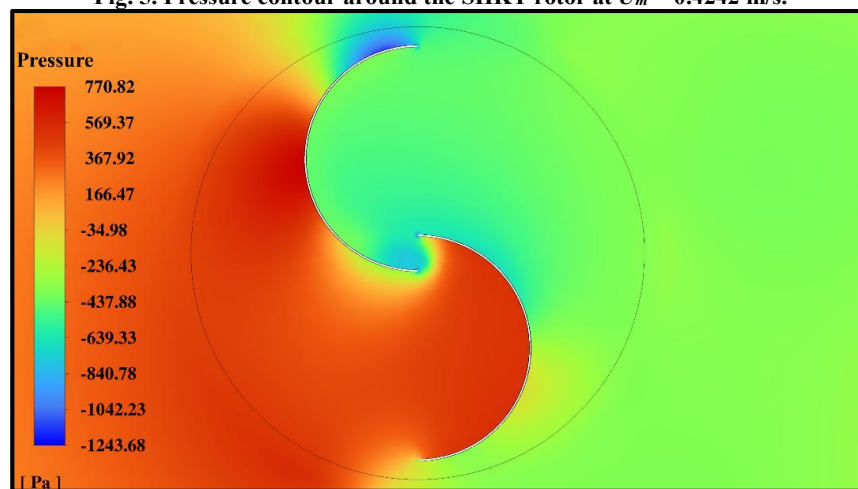
**Fig. 4.** Variation of  $C_T$  and  $C_P$  with TSR for SHKT.

### 3.2. Pressure contours

To understand the complex dynamics of fluid motion, pressure contours of SHKT, is depicted in Fig. 5 at  $U_m = 0.4242$  m/s and in Fig. 6 at  $U_m = 1.0606$  m/s respectively. A noticeable intensification of the pressure differential across the SHKT with increasing flow velocity is revealed by the pressure contour comparisons (Fig. 5 and 6). The concave side of the advancing blade encounters moderate positive pressure (orange–red zones, up to  $\sim 127$  Pa) at  $0.4242$  m/s, whereas the convex side suffers low negative pressure (blue–green zone, down to  $\sim -197$  Pa). The torque of the rotor is produced by this slight but noticeable pressure asymmetry. The amplitude of both high- and low-pressure zones increases significantly as the flow velocity reaches to  $1.0606$  m/s, with the suction region deepening to  $\sim -1244$  Pa and the positive pressure on the advancing blade reaching  $\sim 770$  Pa. The net pressure difference is greatly increased by the concave blade's stronger stagnation zone and the convex blade's increased separation, which suggests larger aerodynamic (hydrodynamic) forces and increased torque generation. The deeper suction trough and larger high-pressure footprint at the higher velocity both indicate increased structural strain on the blades and confirm that the SHKT experiences more efficient momentum transfer, boosting power extraction.



**Fig. 5.** Pressure contour around the SHKT rotor at  $U_m = 0.4242$  m/s.

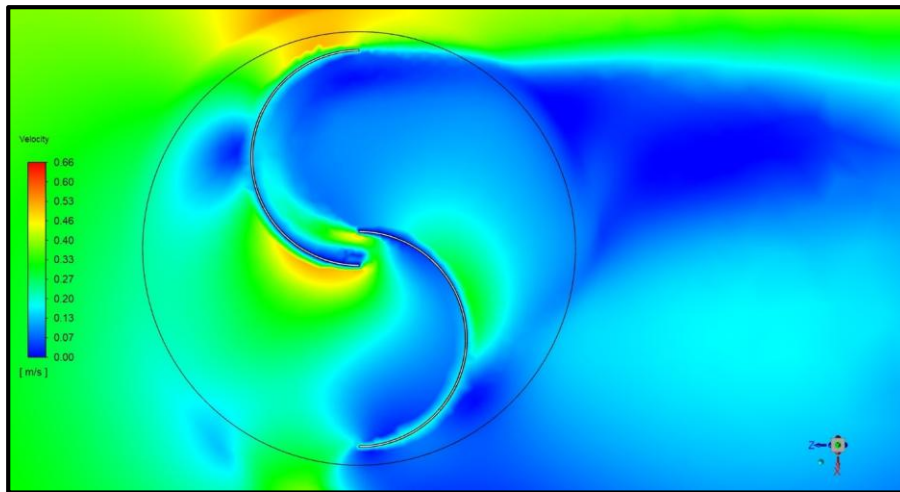


**Fig. 6.** Pressure contour around the SHKT rotor at  $U_m = 1.0606$  m/s.

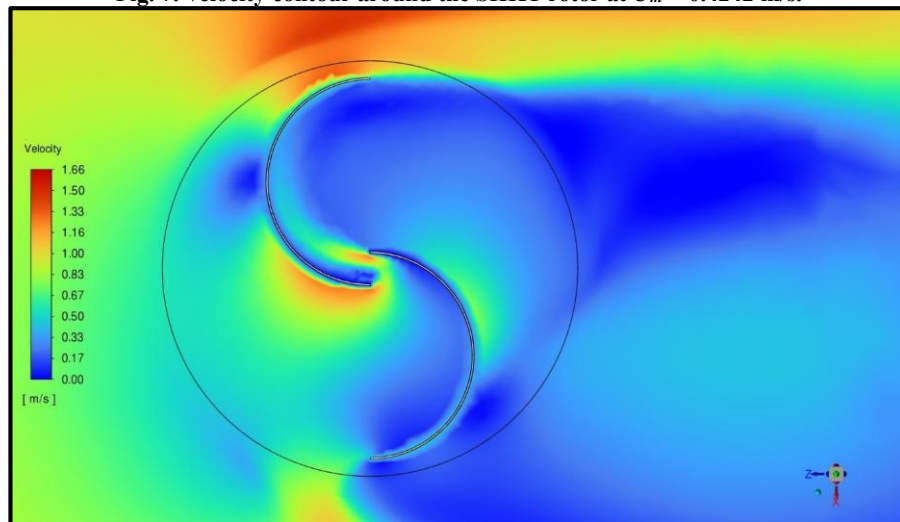
### 3.3. Velocity contours

The velocity contours demonstrate how raising the flow velocity from  $0.4242$  m/s to  $1.0606$  m/s deepens shear around the blade tips and increases flow acceleration along the concave moving blade (Fig. 7 and 8). At the greater velocity, peak speeds surpass  $1.6$  m/s, resulting in a

longer wake and more powerful vortex formation, while at the lower velocity, the wake is compact with modest deceleration zones. Higher torque generation and improved momentum transfer are indicated by the steeper velocity gradients at 1.0606 m/s, together with greater unstable hydrodynamic loading on the rotor.



**Fig. 7. Velocity contour around the SHKT rotor at  $U_m = 0.4242$  m/s.**



**Fig. 8. Velocity contour around the SHKT rotor at  $U_m = 1.0606$  m/s.**

#### 4. Conclusion

In the present investigation, performance analysis of SHKT is carried out for a trapezoidal section hydro canal located on Tapi River, Surat, Gujarat, India. Using the PCM, actual flow velocities of canal was determined. Based on the measured and maximum obtainable velocity, the CFD analysis of the SHKT have been carried out using the  $k - \epsilon$  Realizable turbulence model to obtain the performance characteristic curves. The numerical flow visualisation tools were also assessed for in depth analysis and more idea about the performance. The concluding remarks of the current study are as follows:

- SHKT shows the power extraction efficiency, with performance monitored by drag-based operation, though it remains useful in low-speed, high-torque conditions.
- The pressure differential, flow circulation, and vortex strength surrounding the SHKT blades are intensified by increasing the inlet flow velocity. This leads to much greater torque generation and better momentum transfer for increased power extraction.
- Stronger shear, deeper suction zones, and larger hydrodynamic loading are produced by higher velocities, which indicate more effective energy conversion but also put more structural strain on the SHKT rotor blades.

#### CRediT authorship contribution statement

**Amit Mehta:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing.

**Pankaj Gohil:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization.

#### Disclosure statement

No potential conflict of interest was reported by the author(s).

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#### Data availability statement

Data will be made available on request.

#### Ethical Approval

This article contains no studies performed by authors with human participants or animals.

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