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RESEARCH ARTICLE

Enhancing the performance of Gravitational Water Vortex Turbine through Novel Blade Shape by Flow Simulation Analysis

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Abstract

The demand for renewable energy is increasing in developing countries. Producing electricity from low-head micro-hydropower, especially using the gravitational water vortex method, attracts researchers worldwide. The present study investigates the detailed performance evaluation of single-stage Gravitational water vortex turbine assembled in a conical basin. A detailed numerical study has been conducted on five different runners' shapes. The three best runners were selected for experimentation based on the water pressure inserted on the blades. The effects of blade shape on the performance parameters of single-stage Gravitational water vortex turbine have been investigated, including rotational speed, brake torque, and mechanical efficiency. The results showed that the round-curved runner performed better at the various flow rate levels regarding rotational speed, brake torque, and mechanical efficiency. Moreover, round curved runners absorbed maximum torque, producing higher rotational speed and mechanical efficiency. The blades of the round curved runner give an efficiency of 48.02 %, while the blades of the conical J shape runner and helical runner give an efficiency of 42.17 % and 38.64 %, respectively.

Keywords: Renewable Energy, GWVT, CFD, Blade Shape, Efficiency

Introduction

Today, mini and micro hydro-turbines are economical and viable power generation solutions to resolve the energy crisis (Shoukat, Noon et al. , Ullah, Siddiqi et al. , Ullah and Sharif 2022). Nowadays, conventional turbines like Kaplan and Pelton turbines are gaining interest, but their heads are greater than 3 m. Moreover, they require higher flow rates for effective operation (Abbasi, Abbasi et al. 2011, Power, McNabola et al. 2016). An alternate option to generate electricity from the low head and flow rate sites is installing the Gravitational water vortex turbine (Sharif, Siddiqi et al. 2020). Since the head of Gravitational water vortex turbine is as low as 0.7 m to 3 m, it can be installed on the rivers, streams, and irrigation canals to generate electricity from 1 kW to 100 kW for a few houses (Sharif, Siddiqi et al. , Sharif, Tipu et al. , Dhakal, Nepal et al. 2016, Timilsina, Mulligan et al. 2018, Muhammad, Sharif et al. 2022). The effective area of the blades of the Gravitational water vortex turbine is greater than that of the conventional turbine (Saleem, Cheema et al. 2020, Shoukat, Noon et al. 2021). Hence, GWVT produced more power output than conventional turbines (Tipu, Arif et al. , Ullah, Cheema et al. 2019).

Literature Review

Several studies were performed to evaluate the performance of Gravitational water vortex turbine. A numerical simulation was used to analyze the stable and optimum vortex pool formation of a Gravitational water vortex turbine (Shabara, Yaakob et al. 2015). The strength and the formation of the vortex in a conical basin have been analyzed numerically by changing the design parameters such as cone angle, basin height, basin inlet, and outlet diameter, and notch angle at a constant inflow rate (Dhakal, Timilsina et al. 2014). It was found through the CFD tool ANSYS Fluent that a conical basin produced more output and efficiency as compared to a cylindrical basin on the same inlet and outlet conditions through a runner position placed at 65 %-75 % from the top of the basin (Dhakal, Timilsina et al. 2015). The volume of fluid (VOF) method is used in ANSYS CFX to absorbed unsteady-state multiphase flow to influence the shape of the free surface vortex with the runner present in the basin (Nishi and Inagaki 2017). The two-phase flow analysis was carried out on different basin parameters through a CFD tool for determining the best basin configuration for the Gravitational water vortex turbine (Khan, Cheema et al. 2018). It was analyzed that an angle of 19º between the blade and hub extracted more power output (Dhakal, Bajracharya et al. 2017). The blades are curved vertically (Chattha, Cheema et al. 2017, Kueh, Beh et al. 2017, Khan, Cheema et al. 2018) and a horizontal plane (Dhakal, Timilsina et al. 2015) to accelerate the turbine's efficiency. A curve blades have better efficiency than straight blades when the curves are added at the exit of the turbine blades (Kueh, Beh et al. 2017). The geometry of the blades of the centrifugal (Nishi and Inagaki 2017), Francis (Gheorghe-Marius, Tudor et al. 2013), and impulse paddle-type (Power, McNabola et al. 2016, Kueh, Beh et al. 2017) blades configuration is also designed to investigate the overall performance of Gravitational water vortex turbine. The overall performance of a Gravitational water vortex turbine is reduced when the number of blades is increased from 6 to 12 (Dhakal, Nakarmi et al. 2014); however, when the number of blades is increased from 2 to 4 efficiency of the Gravitational water vortex turbine improved (Power, McNabola et al. 2016).

Various efforts have been made to investigate different aspects of Gravitational water vortex turbine; nevertheless, a novel design of the runner shape must be developed to increase the overall performance of single-stage Gravitational water vortex turbine. The authors were encouraged to use comprehensive numerical and experimental studies to propose a novel blade shape for Gravitational water vortex turbine based on the abovementioned concerns. As a result, the aim of this research involves a complete numerical and experimental examination of several runner shapes of a single-stage Gravitational water vortex turbine designed in a conical basin.

Materials and Method

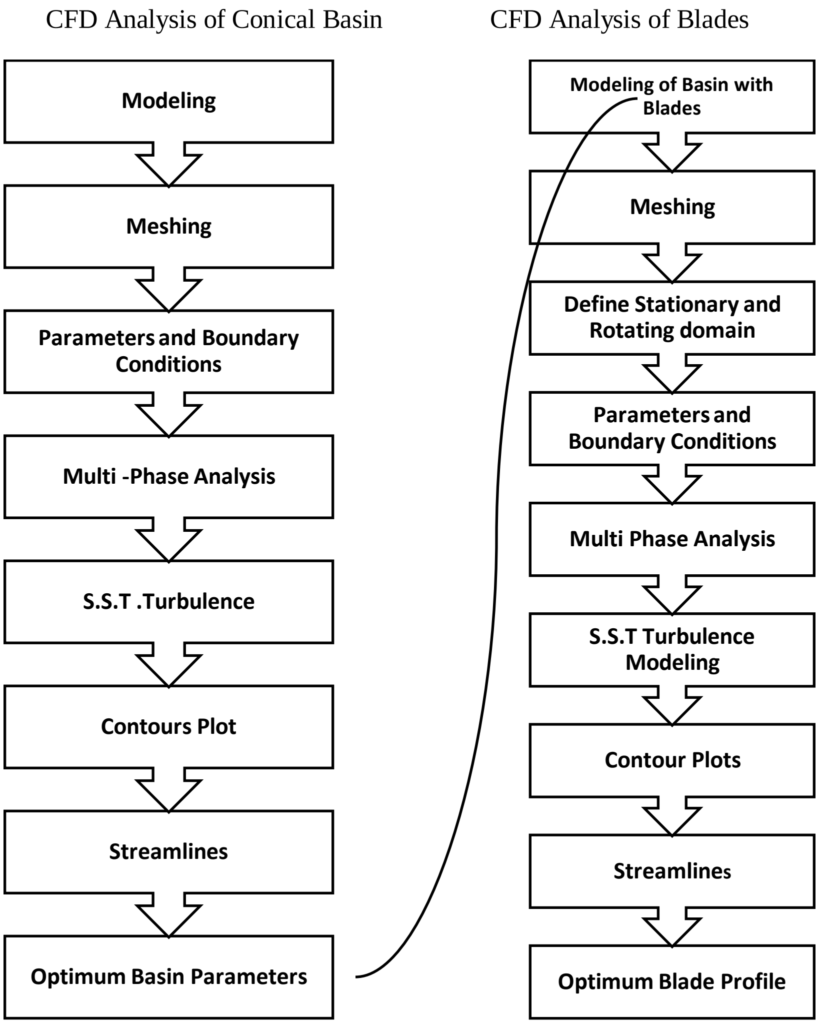
Conical basin and Gravitational water vortex turbine

A Gravitational water vortex turbine setup mainly consists of a stationary or outer domain (a basin), and another is a rotary or inner domain called (turbine). A stationary basin portion is a big conical or cylindrical cross-section tank that creates a gravitational water vortex. The inner rotary domain, known as the blade domain, comprises a turbine with many blades that allow the blades to rotate symmetrically without affecting the basin domain's stationary state. The turbine's rotary component comprises one or more stages of a runner. Each runner is made up of several blades. The current study considered a conical basin and single-stage novel turbine configuration.

Numerical Method and Implementation

Simulation of Blades

The simulation of Gravitational water vortex turbine is divided into two steps as shown in Figure 1. The first step is selecting a conical basin and the second step is selecting the best three runners for experimentation.



CFD Analysis of Conical Basin

CFD Analysis of Blades

Figure 1: Simulation Methodology

The placement of the blades into the conical basin causes flow distortion. This water vortex distortion reduced tangential velocity while increasing radial and axial velocity. The vortex formation, height, and shape depend on the design of the blade. The current study analysis was implemented on several runners to obtain the best blade design for experimentation. Many factors play a role in the design of vortex turbines. One knows the pressure distribution on the turbine blades, which is essential in investigating the performance of turbine blades. The CFD study explores the water pressure pattern on the blades of Gravitational water vortex turbine. At a flow velocity of 0.1 m/s and a head of 0.61 m, the analysis was performed to affect water pressure on the turbine blades. Three different best-shape runners are selected through CFD analysis based on water pressure inserted on the blades. Figure 2 shows the maximum water pressure inserted on round curved blades. The energy of the water vortex was hit by the round curved runner and the conical J shape runner both horizontally and vertically. The runners are designed in such a way that maximal water hits the runner blades vertically and horizontally, ensuring that the vortex generated in a basin is not disrupted. The primary goal of the CFD study is to identify the optimal runner for Gravitational water vortex turbine that operates efficiently at various flow rates.

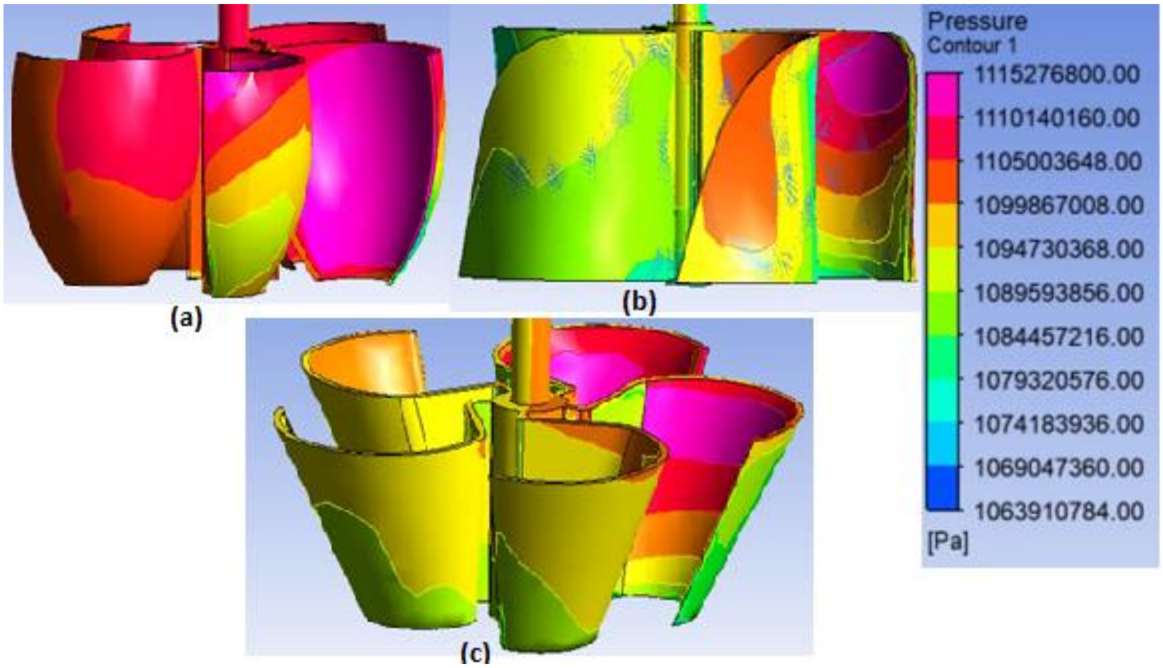


Figure 2. Water pressure inserted on (a) Round curved runner, (b) Helical runner (c) Conical J Shape runner

Selection of Blades

In twenty conceptual designs, ten best conceptual designs were modeled in solid work 18 for further simulation. Based on CFD analysis, the three best runners were selected and fabricated for experimental analysis.. Each runner has a different blade profile with round curved, helical and J shape conical configurations as shown in Figure 3. The current blades profiles are different from centrifugal, paddle and impulse type runners used in previous studies. The taper angle, impact angle, inlet, and outlet angle of each blade are different. The different three runner blades are designed to compel the vortex to give more power output. These blades can be easily manufactured to reduce the cost of casting and manufacturing. In the present study, 1 mm blades thicknesses have been modeled for numerical and manufactured for experimentation. Table 1 describes the dimension of each type of blade, respectively.

Table 1. Specification of the blade

Description	Symbol	Dimension
Blade length	l_b	85 mm
Blade height	h_b	67 mm
Hub height	h_h	70 mm
Hub radius	h_r	15 mm

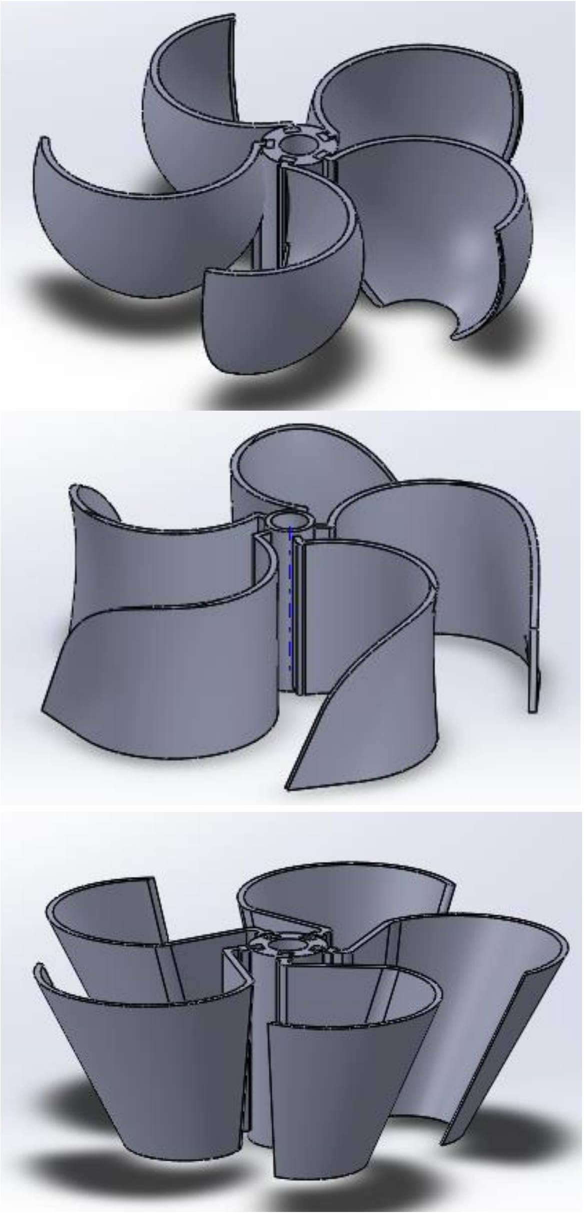


Figure 3. Modeling of the runners (a) round curved runner (b) helical runner (c) conical J shape runner

Experimental Set Up

The experimental setup of Gravitational water vortex turbine is divided into two-part, the static (conical basin and the upper channel) and the dynamic (turbine) part. The turbine setup has been assembled in a conical basin, with the runner having five blades. Mild steel of grade 1025 has been used to manufacture the upper stream and conical basin. . The experimental setup consists of a water storage tank (1000 L), a centrifugal pump (6hp), a conical basin, a Gravitational water vortex turbine assembly, and a supporting frame as shown in Figure 4. The supporting frame has the position of a step used for varying the water inlet head. The upper channel has a deflector directly connected to the top portion of the conical basin, which helps in water circulation and produces a strong vortex formation. Ball bearings supported the turbine's shaft to enhance the measurement of rpm and torque. The different level of water flow rates Q is measured with the help of a digital flow meter having an accuracy of ±0.02 %. The digital tachometer (Lutron DT-2236B, Accuracy ±0.05% + 1digit) measures the runner's rotational speed. The equations were references from past literature to measure the various input and output parameters (Khan, Cheema et al. 2018, Saleem, Cheema et al. 2020).

Figure 4. Experimental set up of Gravitational water vortex turbine

Results and discussions

Effect of blade shape on torque, rotational speed and mechanical efficiency

The torque increased as the water pressure on the runners increased (Sharif, Tipu et al.). As shown in Figure 5, the water flow rate level increases the brake force up to some level, but in the maximum water flow rate, the water pressure disturbs the runner blades, resulting in a reduction of torque. As torque is the product of moment arm and force, the greater resistance force applied on the runner produces greater torque. In three different runner shapes, the round curved runner shows maximum torque of 0.85 N-m, the conical J-shape runner absorbs median torque of 0.69 N-m, and the helical runner absorbs lesser torque of 0.61 N-m.

In the absence of no braking force applied on the runner shaft, all the runners showed maximum rotational speed. When force is applied on the shaft of the runners, the corresponding values of the rotational speed decrease (Sharif, Siddiqi et al.). Figure 6 shows that increasing the water flow rates from 0.004 m³/s to 0.008 m³/s increases the height of the water vortex, significantly increasing the runner's rotational speed. Water circulation increases due to increase in vortex height, the resultant formation of vortex vorticity. Vorticity measures the rotation of the fluid; therefore, increasing vorticity can increase the rotational speed (Ullah and Sharif 2022). Moreover, it can be absorbs that the maximum rpm of all three runners can be achieved under more significant vortex height. The water vortex height and water pressure decrease at 0.008 m³/s, influencing the runner's rotational speed reduction. The decrease in rpm values in the graph shows no contact of the water vortex with the blades due to the small vortex height. As shown in Figure 6, the round curved runner showed maximum rotational speed of 141 rpm ; the conical J-shape runner absorbed 129 rpm, while helical runners showed lesser rotational speed of 121 rpm.

Three different runner-shapes, round curved, helical, and conical J-shape runners, have been developed to generate maximum efficiency. The mechanical efficiency is a ratio of brake shaft power to input hydraulic power (Ullah, Siddiqi et al.). The product of the applied torque and rotational speed both reflect the brake shaft power. Therefore, the efficiency of all the runners reflects the combined effects of applied torque and rotational speed as both the runner's applied torque and rotational speed perform better at an optimum level of water flow rates, producing maximum brake shaft power (Muhammad, Sharif et al. 2022). Therefore, the efficiency of all the runners performed best in the midrange level of water flow rates between the minimum and maximum levels. The round curved runner's value efficiencies have 37.06 %, 48.02 %, and 38.68 %, at 0.004 m³/s, 0.006 m³/s, and 0.008 m³/s, respectively. This is because a round curved runner has been manufactured according to the vortex profile. Moreover, the mechanical efficiency of the round-curved runner is higher than the rest of the runners due to the area of contact of the blade configuration, with the water vortex being more than other runners. Hence, the blades of the round curve runner are preferred for power generation. The J shape runner (41.12 %) and helical runner showed the least efficiency of (37.55 %) compared to the round shape runner due to the low torque generated from these blades as shown in Figure 7. The low torque generated from these runners is due to the low extraction of energy from the vortex formation and caused a reduction in vortex height which absorbed the least efficiency.

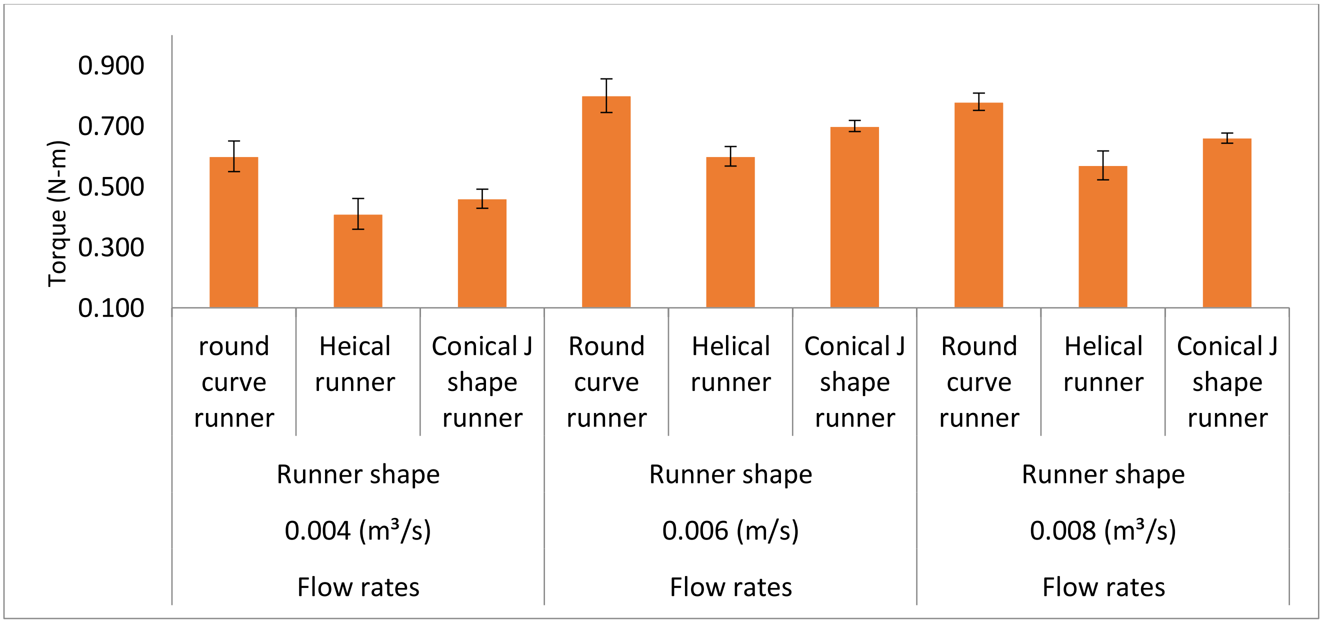


Figure 5. Effect of runner shape on torque

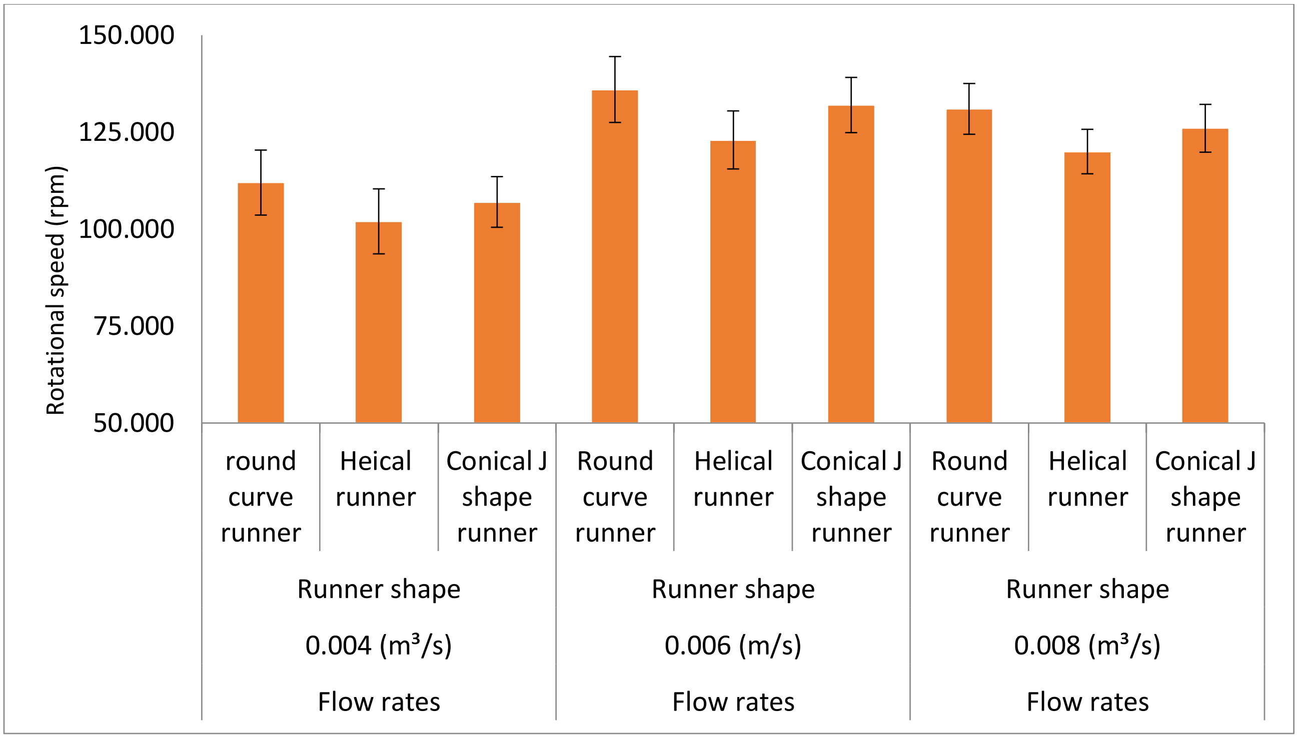


Figure 6. Effect of runner shape on rotational speed

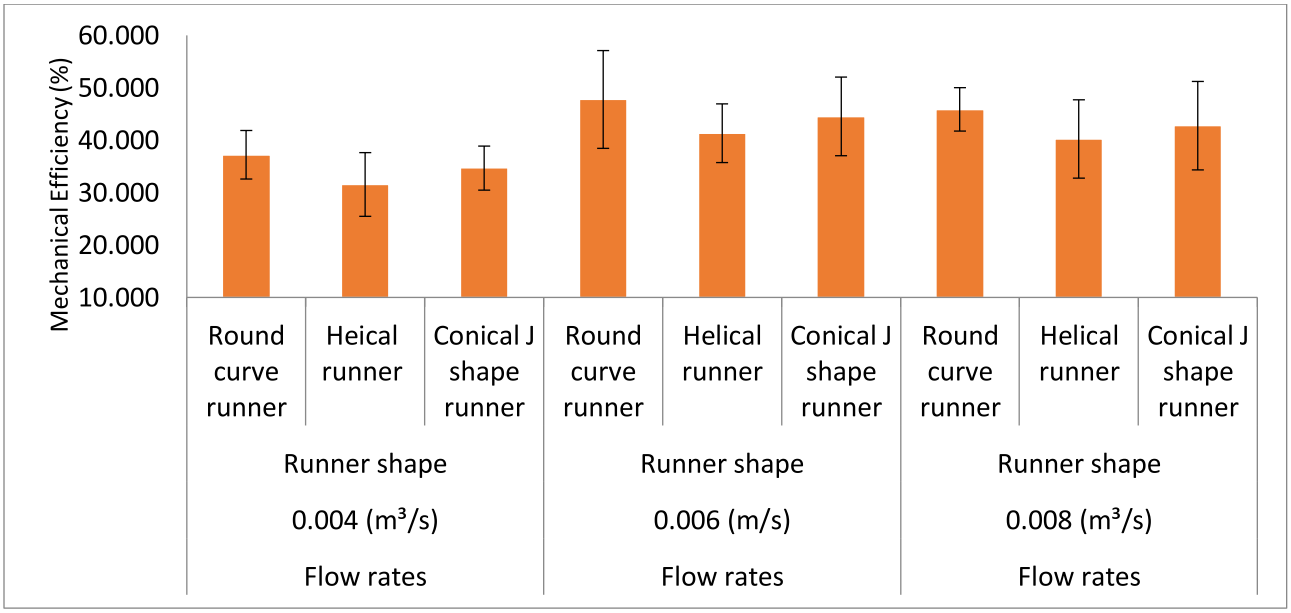


Figure 7. Effect of runner shape on mechanical efficiency

Conclusion

In the current study, the numerical and experimental investigation has been carried out in a conical basin of Gravitational water vortex turbine with three different runners shape configurations. The performance parameters are rotational speed, torque, and mechanical efficiency. The key findings of the above numerical and experimental study are summarized as follows;

The CFD analysis on Gravitational water vortex turbine runner blades showed that more significant water pressure was inserted on the blades of round curved runner blades. When the load on the turbine increased, the runner's rotational speed decreased. All the runners perform better in a median applied torque which resultants higher rotational speed. The performance parameters of the round-curved runner are more significant among all the runners through different flow conditions in terms of rotational speed, brake torque, and efficiency. The blades of the round curved runner give an efficiency of 48.02 %, while the blades of the conical J shape runner and helical runner give an efficiency of 42.17 % and 38.64 %, respectively.

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Data availability: The data presented in this study are available on request

Authors contribution: Conceptualization, A.S.; methodology, A.S, A.N, R.M,; investigation, A.S, A.N, R.M, W.A,; writing- original draft preparation, A.S, W.A, writing- review and editing, A.N, R.M. All authors have read and agreed to the published version of the manuscript.

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