Research Article

Performance Investigation of a Single-Stage Gravitational Water Vortex Turbine Accounting for Water Vortex Configuration and Rotational Speed

Riaz Muhammad[1*], Aamer Sharif[2] and Muftooh ur Rehman Siddiqi[3]

[1]Mechanical Engineering Department, College of Engineering, University of Bahrain, Bahrain, Isa Town Campus; [2]Department of Mechanical Engineering, CECOS University of IT and Emerging Science, Peshawar, Pakistan; [3]Mechanical, Biomedical and Design Engineering Department, School of Engineering and Technology, Aston University, England.

Abstract: Gravitational water vortex power plant is an emerging technology among various micro hydro-power plants because of its low head, cost-effectiveness, environmentally friendly and minimal installation and setup time. In the present study, the performance of single-stage gravitational water vortex turbine assembled in a conical basin with curved blade has been analyzed at different head and flow rate to investigate the performance parameters such as vortex formation, vortex height and rotational speed. In addition to that, the influence of vortex formation, vortex height and vortex shape on rotational speed is also investigated. A two input factors, i.e. water head and flow rate, and each having five-level has been selected in a present study. The results showed that at median head 0.70 m and flow rate 0.004 m^3/s, the maximum rotational speed 172 rpm and vortex height 0.59 m, respectively, with strong and fully developed air core is achieved which results in high output power and efficiency. However, the water disturbance, weak shape vortex formation and decrease in the vortex height and rotational speed occurred at a minimum and maximum inlet head of 0.6 m and 0.8 m and flow rates of 0.002 m^3/s and 0.006m^3/s flow rates, respectively, which results in a decrease in the overall performance of Gravitational water vortex turbine. Further, the vortex formation, vortex height and vortex shape strongly influence the rotational speed. Overall, 0.7 m head and 0.004 m^3/s developed a strong vortex with a rotational speed of 172 rpm and vortex height of 0.59 m. Furthermore, Analysis of Variance was performed to investigate the percentage contribution and significance of each input parameter on response.

Received: May 14, 2022; **Accepted:** June 25, 2022; **Published:** June 30, 2022
***Correspondence:** Riaz Muhammad, Mechanical Engineering Department, College of Engineering, University of Bahrain, Bahrain, Isa Town Campus; **Email:** rmuhammad@uob.edu.bh
Citation: Muhammad, R., A. Sharif and M.R. Siddiqi. 2022. Performance investigation of a single-stage gravitational water vortex turbine accounting for water vortex configuration and rotational speed. *Journal of Engineering and Applied Sciences,* 41: 44-55.
DOI: https://dx.doi.org/10.17582/journal.jeas/41.44.55
Keywords: Conical basin, GWVT, Micro hydro-power, Rotational speed, Vortex height

Copyright: 2022 by the authors. Licensee ResearchersLinks Ltd, England, UK.
This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Introduction

Water is abundant, covering about three-quarters of the Earth's land (Ullah *et al*., 2022; Shoukat *et al*., 2021). However, only 3% of these resources can be used. The micro hydropower turbine is the biggest invention to utilize water resources. In micro-hydropower, gravitational water vortex turbine

Links Researchers

GWVT is a new addition in the micro-hydro turbine family which originates power from rivers, water streams, and irrigation canals (Guzmán *et al*., 2021; Ullah and Sharif, 2022). GWVT is a low head 0.7 m^{-3} m, cost-effective, and environmentally friendly micro hydropower system that needs no dam or large reservoir for operation (Wanchat and Suntivarakorn, 2012). In a GWVT, the water passed through an open channel from the bank of the river or water streams into a cylindrical or conical tank having a small outlet at the bottom of the basin to generate a water vortex (Gheorghe-Marius *et al*., 2013). The GWVT runner having blades extracted energy from a vortex into mechanical power. A shaft connected with the turbine runner is conjoined with the generator, which generates electric power (Saleem *et al*., 2020). The conventional micro-hydro turbines such as Kaplan and Pelton turbines require a larger flow rate and head, but it is expensive, and lots of capital cost is wasted on civil works (Power *et al*., 2016; Abbasi *et al*., 2011; Shoukat *et al*., 2021). Therefore, GWVT, a small hydraulic turbine, should be designed to produced power from the low head and low water flow rates (Campbell, 2010; Nishi and Inagaki, 2017b). The installation of GWVT mainly on the bank of the river, water stream, and irrigation canal to enhance electrical energy for a small village to a few houses or a provide electricity to small industries (Dhakal *et al*., 2016, Sharif *et al*., 2020). As no water reservoirs and dams are required, civil work is reduced, reducing the capital cost (Venukumar, 2013). Such type of micro-hydro power turbine can be installed in running river systems (Hoseinzadeh *et al*., 2020a, b). Numerous GWVT can be operated at the same river, irrigation canal, and water stream without affecting the water flow and the output power of one another (Saleem *et al*., 2020; Sharif *et al*., 2020). The GWVT generates more power output than conventional turbines on the same head and flow rates (Chattha *et al*., 2017). The total capital cost, including manufacturing installation cost, is half of the conventional turbines (Campbell, 2010; Tipu *et al*., Year). Therefore, these aspects make GWVT a prominent member of the current energy technologies. Until 2015 only five percent of the low head micro-hydro power has been used globally, having a capacity of 150-200 GW (Hamududu and Killingtveit, 2012; Sharif *et al*., 2020).

In the past, numerous researchers have shown interest to improve the design and performance of GWVTs over different methods and analysis. Some researchers used experimental and numerical, and analytical methods to increase the efficiency of GWVT. A basin structures with three different geometries were investigated and it was observed that a basin with a conical design has greater output than a conical and cylindrical basin (Dhakal *et al*., 2015a). It was observed through CFD and experimental analysis that outlet diameter should be placed at bottom center of the cylindrical basin. Further, they reported that outlet diameter should be in the range of 0.2 m-0.3 m of the cylindrical basin (Wanchat and Suntivarakorn, 2012). A studied is performed and absorbed that water passed through a straight channel that further falls tangentially into a round basin and formed a free vortex that extracted energy using a turbine (Mulligan *et al*., 2010). It is investigated earlier, that a cylindrical basin generates a stable vortex formation (Zotlöterer, 2008). Later, it was found that low and high head sites have orifice to basin inlet diameter ratios (d/D) of 14%-18%, respectively for free vortex generation (Mulligan and Casserly, 2010). A experimental and CFD is performed and investigated that a conical basin's efficiency was more significant than the cylindrical basin. They further reported that the turbine should be placed at 65 % -75 % from the top position to increase overall performance (Dhakal *et al*., 2015b). Further investigated numerically that the strength and shape of the vortex by changing different parameters such as basin inlet and outlet diameter, upper channel height, width and length, basin cone angle, and upper channel UC deflector angle (Dhakal *et al*., 2014). A study was performed by changing the material of the vortex turbines from mild steel to aluminium and compared their efficiencies. The results showed that aluminium-made turbine material showed greater efficiency than turbine made from mild steel (Sritram *et al*., 2015). A detailed experimental analysis was performed on GWVT to improve the efficiency of GWVT (Saleem *et al*., 2020). Moreover, a study was performed on a multi-stage GWVT assembled in conical shape basin with an independent shaft to maximize the power out of the plant. The numerical analysis was also carried out on both basin and turbine of Gravitational water vortex turbine (Ullah *et al*., 2020). A two-phase flow analysis was performed based on the CFD approach on various basin parameters to select the best basin design configuration (Khan *et al*., 2018). A extra booster runner was added in same shaft to extract the vortex energy at various heights in the shape of a conical basin and observed a 6 % increase in efficiency. The weight of the existing runner's shaft increases with

Links Researchers

the addition of a booster rotor, requiring the need of a stronger vortex to rotate the turbine (Gautam *et al*., 2016).

Apart from experimental and numerical studies, researchers also performed analytical results on GWVT. They work analytically both on single-stage and multi-stages GWVT. A relation was observed for calculating the force on each blade (Power *et al*., 2016). A relation was shown for calculating the specific speed and nominal speed, a flow rate of water, and angular velocity of the turbine. Moreover, the brake torque and output power of multi-stages GWVT assembled in a conical basin are also calculated through a relation (Marian *et al*., 2013).

To the best of our knowledge, different researcher has made numerous effort to examine various aspects of GWVT (Marian *et al*., 2013; Gautam *et al*., 2016). However, limited research has been performed on maximizing vortex energy utilization in the conical basin of the single-stage GWVT. Moreover, few researchers used direct water pumping for vortex formation in a cylindrical or conical basin in earlier investigations, resulting in a vortex turbine that performs similar to a pressure-driven turbine. However, evaluating the GWVTs performance on different water inlet heads and flow rates generating natural vortex formation is yet not to be found. Therefore, the performance parameters such as vortex formation, vortex height, vortex shape, and rotational speed rpm of a runner by varying water head, and flow rates in a basin of the conical shape of single-stage GWVT are yet to be investigated. Moreover, the influence of vortex height, vortex formation on rpm of single-stage GWVT is also yet not to be explored. This gap motivated the authors to conduct the present investigations and work on a single-stage GWVT considering different output parameters such as vortex height, vortex shape, vortex formation, and rpm of GWVT. Therefore, the current work is described by novelty and originality in the analysis of maximum utilization of vortex energy as well as the performance evaluation in terms of rpm and their effect on vortex formation, vortex shape, and vortex height. Furthermore, the outlook of this study also comprises fabrication of a complete experimental test rig, fabrication of conical basin and runner, experimental and statistical analysis of single-stage GWVT. The objective of the current study is to analyze the influence of inlet head and flow rates on vortex formation, vortex shape, vortex height, and rotational speed of a runner of a single-stage GWVT. Moreover, the effect of vortex height, vortex shape, and vortex formation on runner rotational speed rpm is also investigated in the current study to know the performance predication of single-stage GWVT.

Materials and Methods

GWVT mainly consists of basin and turbine. A massive basin of water-primarily comprising of conical and cylindrical cross-section is known as the basin, which gives rise to an artificial gravitational water vortex. Further, the turbine used in this setup might have multiple or single stages of runners. A conical basin CB and a single-stage turbine setup are used in the present study.

Modeling of gravitational water vortex turbine

Conical basin: The parameters design for the optimized conical basin CB are top diameter D, orifice diameter d, and vertical height Hc of the conical basin. The upper diameter of a basin is 400 mm, and basin outlet diameter is taken as 57 mm for stable vortex formation; as for the small GWVT, the basin inlet diameter to basin outlet diameter is taken as 0.14 both for the cylindrical and conical basin. The conical basin has a cone angle of 23°. The upstream channel (UC) through which the water enters into the basin is an open rectangular cross-section channel with a deflector at one end to ensure that the water enters the conical basin in a tangential manner. The design parameters for the conical basin as shown in Figure 1 with conical basin top diameter 400 mm, basin height 610 mm, cone angle 23°, upstream channel length 880 mm, upstream channel height 200 mm, upstream channel width 200 mm, notch angle 10°, upstream channel notch length 480 mm and basin outlet 57 mm. The mild steel has been used to fabricate conical basin CB and upper channel UC .

Gravitational water vortex turbine (GWVT)

The runner of GWVT has a diameter of 200 mm, height 70 mm, hub diameter of 30 mm, and shaft diameter 12.5 mm placed at 65 % -75 % from the top position of the conical basin as shown in Figure 2. The GWVT has been assembled in a conical basin consisting of a runner having five blades, a shaft, and a runner hub. The pulley is mounted on the shaft of GWVT, measuring the brake force through the prony brake mechanism.

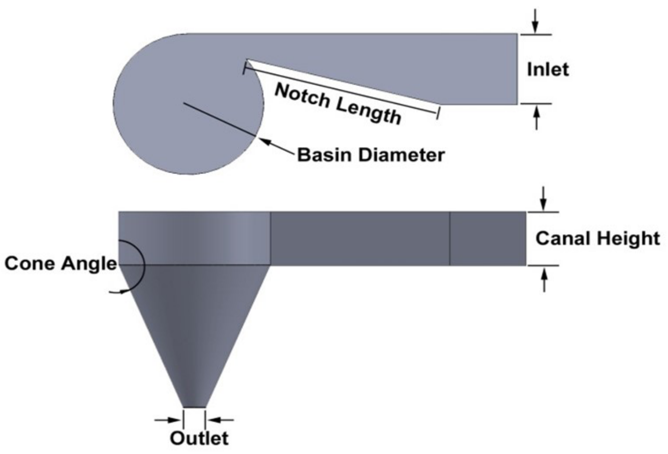

Figure 1: *Top and side view of conical basin.*

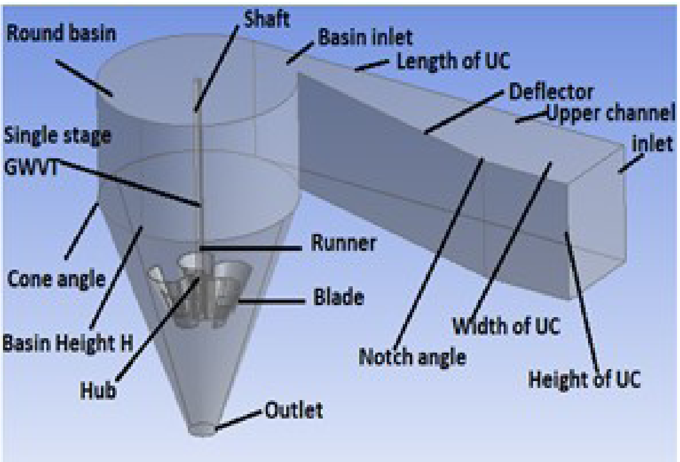

Figure 2: *Cad modelling of gravitational water vortex turbine.*

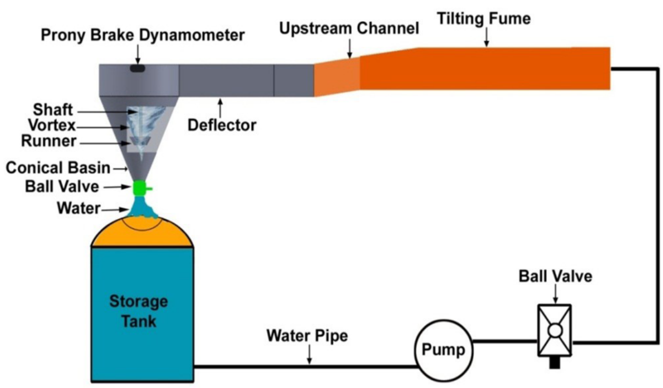

Figure 3: *Schematic of single- stage GWVT set up.*

In the current work, UC of the single-stage GWVT is settled at various water head levels along the height of the conical basin (CB), as shown in Figure 4. The input parameters of the current study are water inlet head, water flow rates while the output parameters are vortex formation, vortex shape, vortex height, and rotational speed. A total of 25 different experiments were conducted having two factors and five-level to check the GWVT performance by changing water flow rates and inlet head levels to investigate the vortex formation, vortex height, vortex shape and the runner's rotational speed, and their influence on GWVT peformance.

Figure 4: *Experimental set up of GWVT.*

Experimental set up

In the present study, the schematic and the actual experimental setup were used to investigate the evaluation of GWVT are shown in Figures 3 and 4. The overall setup comprises a GWVT assembly with a conical basin, a prony brake dynamometer, water flow meter, water storage tank 3000 L, overhead water titling fume, and a centrifugal pump. The water undergoes over an open channel and entered tangentially into the conical basin; the potential energy of water changed into kinetic energy, enhancing the runner rotation of GWVT. The ball valves restrain the fluctuation of the inlet flow rate. A two-ball valve is connected, one is located at the basin outlet, and the other is located at the inlet of the titling fume. The pre-existing water from the basin outlet is conveyed to the water storage tank and then recycled with the help of a centrifugal pump. The experimental setup consists of two main parts: the static basin and upper channel, and the other is the dynamic turbine part. The shaft is connected with a runner and has been supported by ball bearings to make sure the decrease in uncertainty and human error during measurements of net forces and rotational speeds. The flow rates of water Q have been measured with the help of a digital flow meter with an accuracy of ±0.02. The digital tachometer (Lotron DT-2236B, Accuracy: ±0.05% + 1 digit) was used to measure the rpm on various head and flow rate conditions. The height of the vortex produced is measured with measuring tape mounted on the inner surface of a conical basin. The following equations were used to measure the various input and output parameters during the experimental analysis of the single-stage of GWVT.

If N is the rotational speed in revolution per minute rpm. The angular velocity ω can be determined as:

$$\text{Angularvelocity } (\omega) = 2\times\pi\times N/60 \quad \ldots (1)$$

The torque T can be calculated for measuring power output.

$$\text{Torque} = T = rF \ (2)$$

r is the radius of the pulley and F is the net load applied on the turbine shaft

While the input power and output power can be observed as

$$\text{Input power } P_{in} = \gamma Q = \rho g Q H \text{ where } \gamma = \rho g \quad \ldots(3)$$
$$\text{Brake horse power} = \text{Output power} = T\times\omega \quad \ldots(4)$$
$$\text{Efficiency based on vortex height} = \eta = BHP/P_{in}\times 100 \ (5)$$

All experiments were carried out three times and then an average value of each experiment is recorded for further evaluation. The reading of each experiment was recorded at the steady-state condition after runner rotation. According to Moffat uncertainty analysis (Moffat, 1988), a comprehensive precise error in the range of 0.03% to ±0.08% has resulted during experimentations, as shown in Table 1.

Table 1: *GWVT performance parameters and output range with uncertainties.*

Parameters	Output-range	Uncertainty
Mass (kg)	0.40-4.80	0.03%
Force (N)	6.0-20.50	0.03%
Vortex height (m)	0.15-0.60	0.04%
Rotational-speed (rpm)	45-172	±0.05%

As shown in Figures 5 and 6, a valuable shape vortex with a fully developed air-core observed through increasing head from 0.60 to 0.70 m. It is cleared from Figures 5 and 6 that the shape of the vortex depends upon flow rates. A good shape, strong vortex and worst shape weak vortex generates by varying the water flow rates level. Increasing the flow level from 0.002 m^3/s to 0.004 m^3/s enhances to increase the vortex height. The maximum flow rates level of 0.005 m^3/s and 0.006 m^3/s slightly decreased the vortex height of the GWVT due to excessive water pressure embed on runner blades. The higher flow level effect the vortex formation which enhances to produce worst shape vortex with the creation of less developed air-core formation which affected and reduced the overall performance of GWVT.

Figure 5: *Vortex height and vortex formation at 0.7 m head.*

Figure 6: *Vortex height and vortex formation at 0.004 m^3/s.*

Results and Discussion

Effect of flow-rates through different head on vortex formation and vortex-height

The water vortex shape and vortex formation are the important parameters in designing a GWVT (Wanchat and Suntivarakorn, 2012). The GWVT overall performance is based upon the vortex height (Chattha *et al*., 2017). In the current study, flow rates with a different head level on vortex formation and vortex height are investigated. According to Table 2, both water flow rates and water inlet head have five different levels of 0.002, 0.003, 0.004, 0.005 and 0.006 m^3/s and 0.6, 0.65, 0.70, 0.75 and 0.80

Links Researchers

m head, respectively. As the flow rates level rises from 0.002 m^3/s to 0.004 m^3/s and head level from 0.60 to 0.70 m, the corresponding vortex height of GWVT increased. In addition to this, a stable vortex formation with a fully developed air core also exists. The worst form of the vortex with less developed air-core and a reduction in the vortex height occurred at maximum flow rates and water inlet head level of 0.005, 0.006 m^3/s and 0.75, 0.80 m, respectively. The worst vortex formation and reduction in a height of the vortex is due to the malformation of the vortex. The higher flow rates distorted the formation of the water vortex, which generates weak vortex formation. Similarly, as shown in Figure 7, the vortex height of GWVT increases within increases in flow rates and inlet head up to specific limit then decrease significantly at maximum flow rates and water inlet head level. A decrease in vortex height at head 0.8 m and 0.004 m^3/s is due to beyond water falling from the water channel into a CB which enhanced to decrease the vortex height. A maximum vortex height with good shape formation achieved at optimum flow rates of 0.004 m^3/s and median head level of 0.70 m, enhancing the overall performance of the GWVT. The flow rates and head levels below from 0.004 m^3/s and 0.70 m head and above from 0.004 m^3/s and 0.70 m, respectively minimize the vortex height and generate less air developed core vortex formation.

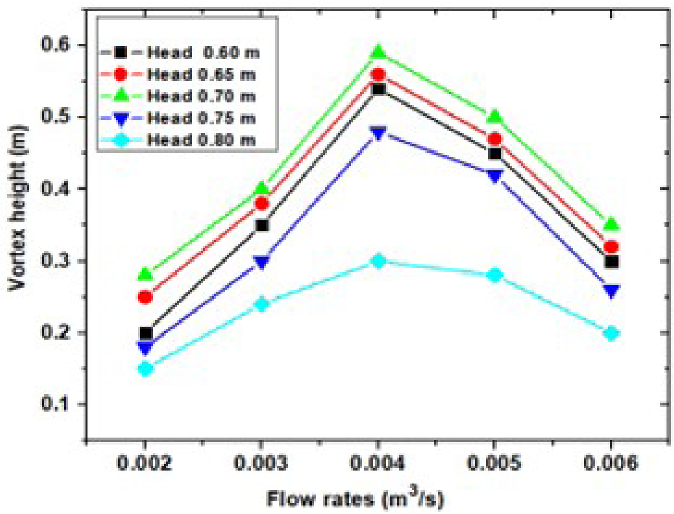

Figure 7: *Variation of flow-rates vs vortex-height at different head.*

Effect of head at different flow-rates on vortex-height

The vortex formation and vortex height of the GWVT are the major parameters in deciding the GWVT performance in terms of rpm, power output, and mechanical efficiency (Shabara *et al.*, 2015). A good shape vortex with a fully developed air-core having maximum vortex height generates maximum output power and efficiency (Nishi and Inagaki, 2017a). In this section, the vortex height of GWVT is investigated by varying water inlet head level. As shown in Figure 8, increasing flow level from 0.002 m^3/s to 0.004 m^3/s and head level from 0.6 to 0.7, respectively resultant increases in vortex height of the GWVT occurred. A significant reduction in the height of a vortex occurred at a maximum head and water flow level as shown in Figure 8. The maximum head level decreases the vortex height of GWVT and develops less air core with a weak vortex formation. The reduction in vortex height at the maximum head and flow rates is due to distortion of the water, which disturbed the formation of the vortex to produce bad shape vortex formation resultant little bit decreased in vortex height. Therefore, the generation of vortex height at 0.004 m^3/s is more significant than at 0.006 m^3/s. In addition to this, stable, good shape, and strong vortex formation occurred at an optimum head level, which maximizes the height of a vortex and helps in blade rotation of the turbine to move more fastly.

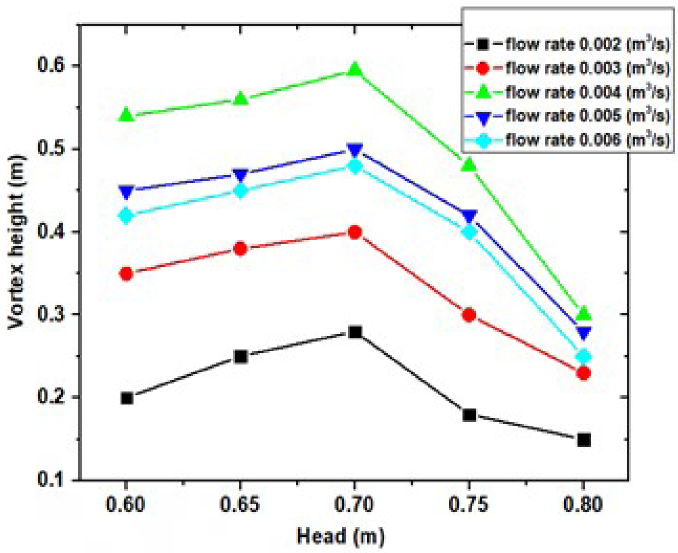

Figure 8: *Variation of head vs vortex-height at different flow rates.*

Effect of head through different flow-rates on rotational-speed

The runner rotational speed (rpm) enhances the overall output performance of the GWVT (Dhakal *et al.*, 2017). The efficiency of the turbine depends upon the rotational speed (rpm) of the runner. The lower and higher rpm produced minimum and maximum efficiency of the GWVT (Kueh *et al.*, 2017). The output power of the GWVT can be determined by enhancing the rotational speed rpm of the runner by varying the inlet head. The influences of the inlet head-on runner rotational speed of the GWVT through various flow rates are investigated in the current study. Increasing the inlet head and flow rates up to a certain limit increases the runner rotational speed rpm. However, the runner rotational speed was reduced at a higher water head and flow rate level. The vortex height of the GWVT increases with increasing inlet head from 0.60 to 0.70 m and flow rates from 0.002 to 0.004 m^3/s, respectively, which enhance to increase runner rotational speed. The reduction in runner rotational speed is because of reduction in vortex height at the maximum head and flow rates. Figure 9 shows that maximum rotational speed rpm observed at 0.70 m head and 0.004 m^3/s, and lower rpm exist at 0.80 m head and 0.006 m^3/s, respectively, which affected the GWVT output performance.

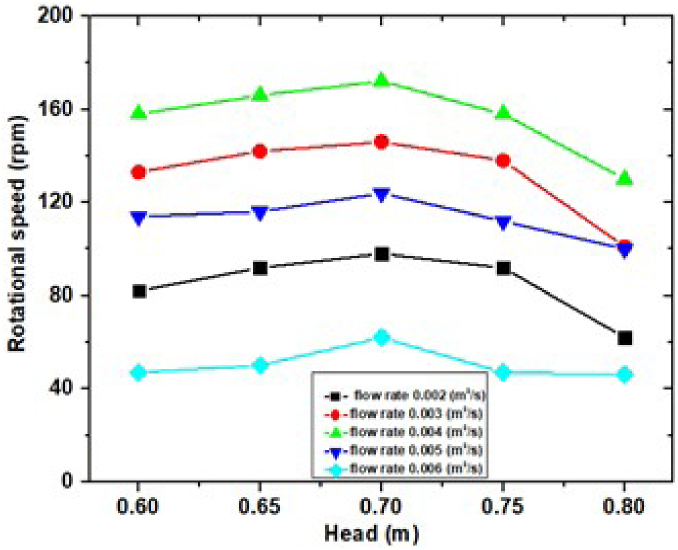

Figure 9: *Variation of head vs rpm at different flow rates.*

Effect of flow-rates on rotational-speed at different head

The efficiency of the GWVT depends upon both rotational speed and torque inserted on the shaft through a pulley. Both optimum torque and rotational speed produced maximum efficiency (Kueh *et al*., 2017). Moreover, the efficiency of the GWVT becomes reduced at greater torque which generates low rotational speed (Khan, 2016). The runner rotational speed rpm increases with increasing flow rates from 0.002 to 0.004 m^3/s and increases inlet head level from 0.60 to 0.70 m. A rotational speed rpm becomes reduced at maximal head and water flow rates. The runner rotational speed becomes minimum due to the maximum load insert on the blades, creating greater torque on the turbine shaft. This greater torque reduced the rotational speed of the runner. The reduction in runner rotational speed rpm occurred at higher flow rates of 0.005, 0.006 m^3/s and maximal head level of 0.75 and 0.80 m, respectively. The decrease in rpm is due to maximum water pressure embedded on blade which enhanced to produce maximum load on the GWVT blades. Another reason is the maximum load inserted on the runner shaft which creates maximum torque on the runner shaft. As shown in the Figure 10, the optimum flow rates in which the runner rotational speed becomes maximum at all head levels is 0.004 m^3/s. The level above and below from 0.004 m^3/s generates lower runner rotational speed.

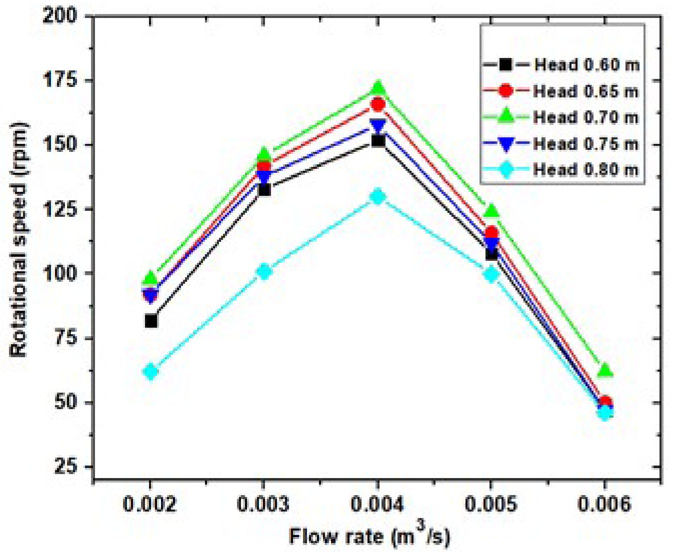

Figure 10: *Variation of flow-rates vs rpm at different head.*

Effect of vortex-height on rotational-speed through different head

The performance of the GWVT depends on vortex height. The runner rpm is dependent on vortex height (Gupta *et al*., 2021). The vortex and runner rotational speed are the two key parameters by determining and maximizing the output and efficiency of the GWVT (Huwae *et al*., 2020). The increase or decrease in rotational speed is due to an increase or decrease in the vortex height of the GWVT. However, the runner rotational speed little bit reduced at maximum vortex height. Moreover, the shape of the vortex formation also affected the runner rotational speed rpm. The strong and best shape water vortex formation maximizes the runner rotational speed, while the weak and worst shape vortex formation reduced the GWVT rotational speed. The water inlet head of 0.70 m has maximum rotational speed at all vortex height. However, the rotational speed of the runner is minimum at 0.80 m head level at all vortex heights. Figure 11 showed that increasing vortex height through varying head level increases the runner rotational speed up to a specific limit and then reduced at maximum water head level. A reduction

Links Researchers

in rotational speed at maximal head level is due to a little bit decrease in vortex height, which minimizes the rotational speed.

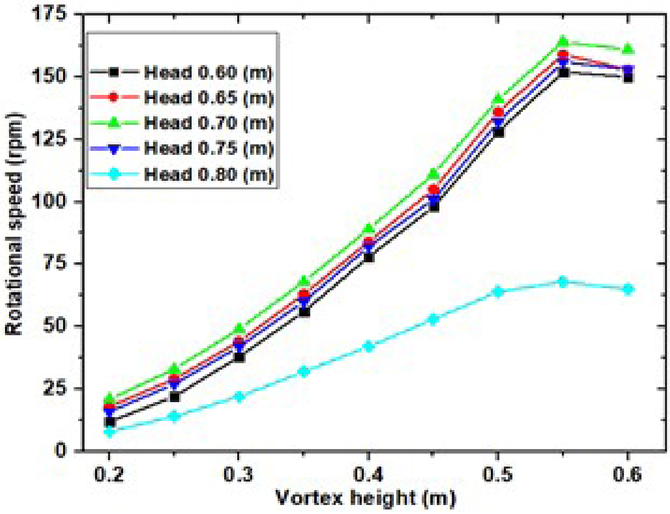

Figure 11: *Variation of vortex-height vs rpm at different head.*

ANOVA analysis

Analysis of Variance (ANOVA) is a statistical technique used to analyze recorded data (Habib *et al*., 2021; Sharif, 2022). It's a method of predicting the influence of input factors and their interactions on the response (Habib *et al*., 2022; Hussain *et al*., 2022). In this work, ANOVA is used to find the factors that affect response variables significantly with a 95 % confidence level. By providing a range around measured values, a confidence level shows that how exact or accurate the estimated statistics are measured (Montgomery, 2017). P and F-values are used to find the significances of input variables and also their percentage contribution (Pietraszek *et al*., 2016). If the P-value of any input factors or their interactions on the response is greater than 0.05, then they are considered insignificant. A 95 % confidence level indicates that there is only a 5 % probability of the wrong estimation. Therefore, P-values are used to check the influences of input factors on the response (Neseli, 2014). Moreover, the percentage contribution indicated how much each input factors influence the response (Hussain *et al*., 2022). In this study, inlet head and water flow rates were the input factor whereas rpm, the height of the water vortex were the response.

ANOVA for vortex-height

To evaluate the performance evaluation of the GWVT, both input factor water flow rates, and head were investigated on the response variable, i.e., vortex height of the GWVT. Figure 12 shows that both head and flow rates have a dominant effect on the vortex height of the GWVT. The main effect plot for means as shown in Figure 12 showed that a minimum vortex height was observed at 0.80 m head, and maximum vortex height is found at 0.70 m head. Same the minimum and maximum vortex height were observed at 0.002 m^3/s and 0.004 m^3/s, flow rates, respectively. Moreover, P-value as shown in Table 2 shows that both head and flow rates have a highly significant effect on the vortex height of the GWVT. However, in Table 2, the effect of flow rates affecting the vortex height is higher than the head with a percentage contribution of 63.30%. Further, it is observed that both input factor head and flow rates have a high influence on the vortex height of the GWVT developed in a conical basin.

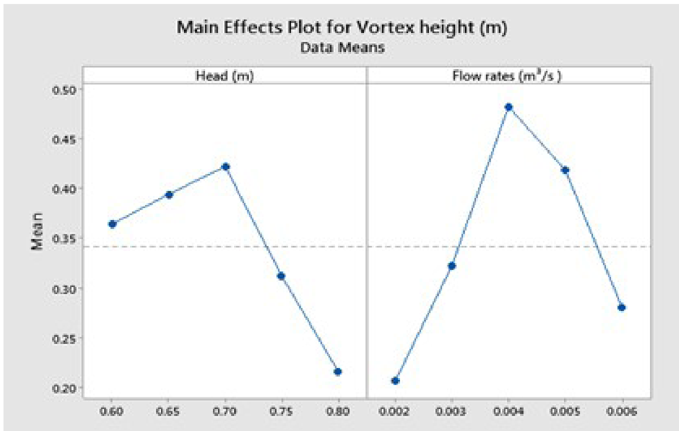

Figure 12: *Main effects plot for vortex height (m).*

Table 2: *ANOVA for Vortex height.*

Source	DF	Seq-SS	Contribution	Adj-SS	Adj-MS	F-value	P-value
Model	4	0.3724	98.00 %	0.3724	0.093098	49.12 %	0.002
Linear	4	0.3724	98.00 %	0.3724	0.093098	49.12 %	0.002
Head (m)	2	0.13182	34.70 %	0.13182	0.032954	34.82	0.002
Flow rates (m^3/s)	2	0.24058	63.30 %	0.24058	0.060144	63.54	0.001
Error	4	0.01514	2 %	0.01514	0.000947		
Total	16	0.38754					

Table 3: *ANOVA for rotational speed.*

Source	DF	Seq-SS	Contribution	Adj-SS	Adj-MS	F-Value	P-value
Model	4	0.79648	96.5 %	0.79648	0.881	45.30	0.003
Linear	4	0.79648	96.5 %	0.79648	0.881	45.30	0.003
Head (m)	2	0.4938	26.00 %	0.4938	0.1243	26.09	0.003
Flow rates (m^3/s)	2	.30268	70.50 %	0.30268	0.7567	70.91	0.002
Error	4	983.4	3.5 %	983.4	61.46		
Total	16	36190.2					

ANOVA for rotational-speed

In order to evaluate the experimental performance, the response variable, i.e., rotational speed rpm was analyzed. The response variable shows that both head and flow rates have high effects on rotational speed rpm. As shown in Figure 13, the main effects plot for means analyzed the minimum value of rotational speed at 0.8 m head and maximum value at 0.7 m head contradicting the value of flow rates which shows the maximum value at 0.004 m^3/s and minimum value at 0.006 m^3/s. P-value in Table 3 reveals that the effect of flow levels and head on the GWVT rpm is highly significant. The level above or below forms the optimum level reduced the rotational speed (rpm) of the single-stage GWVT. Moreover, from ANOVA table 3 it is observed that flow rates have a more significant effect on rpm than inlet head.

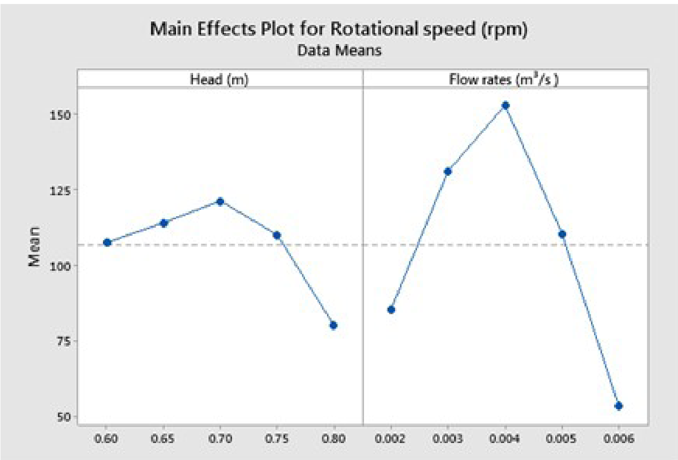

Figure 13: *Main effects plot for rotational speed.*

Suggestion

The overall performance in terms of output power and efficiency of single-stage GWVT can be improved by generating good shape strong vortex created by optimum water inlet head and flow rates.

An advantage of varying flow rate and head of GWVT with conical basin improves the performance parameters. It increases the water inlet head and flow rates at optimum position strengthening the vortex formation, which further increases the rotational speed, thereby increasing the output power and efficiency of GWVT.

Conclusions and Recommendations

The current study was conducted on a single-stage (GWVT) with a curved blade configuration inside in a conical basin. The performance parameters such as vortex formation, shape, height, and rotational speed have been investigated under various water flow and water head conditions. The above study has been concerned that the performance of GWVT depends upon vortex height and vortex shape. A strong and fully developed air-core vortex shape with the maximum vortex height is the key parameters in determining the GWVT performance. The following investigations are outlined as follows.

A strong and fully developed air-core vortex was formed in the conical basin at median head of 0.7 m, and flow rate of 0.004 m^3/s. However, the maximal head and flow rates of 0.8 m, and 0.006 m^3/s, respectively, yield worst shape vortex formation and reduced vortex height in a conical basin.

Similarly, the optimal performance of single-stage GWVT is achieved at 0.7 m head and 0.004 m^3/s flow rate in terms of rotational speed. Overall, 0.7 m head and 0.004 m^3/s developed a strong vortex with a rotational speed of 172 rpm and vortex height of 0.59 m.

The GWVT rotational speed increased with increasing vortex height, although at the peak of vortex height, the runner rotational speed little decreased which results small decrease in the overall performance of GWVT.

Links Researchers

Novelty Statement

The performance of a single-stage gravitational water vortex turbine with a curved blade is thoroughly examined in this study, which also examines the effects of input variables like water head and flow rate on vortex formation, vortex height, and rotational speed. The results show that a strong and completely developed air core is achieved with a rotational speed of 172 rpm and a vortex height of 0.59 m, which are the ideal operating parameters for maximum efficiency and power output. With insights into the variables that affect their performance, this study demonstrates the promise of gravitational water vortex turbines as a reasonably priced and environmentally responsible micro hydro-power technology.

Author's Contribution

Riaz Muhammad: Conceptualization, methodology, supervision, review and editing.
Aamer Sharif: Conceptualization, methodology, experimentation, investigation, writing.
Muftooh Ur Rehman Siddiqi: Conceptualization, review and editing, supervision.

Conflict of interest
The authors have declared no conflict of interest.

References

Abbasi, T., Abbasi, S.J.R. and Reviews, S.E., 2011. Small hydro and the environmental implications of its extensive utilization. Renew. Sustain. Energ. Rev., 15: 2134-2143. https://doi.org/10.1016/j.rser.2010.11.050

Campbell, R.J, 2010. Small hydro and low-head hydro power technologies and prospects.

Chattha, J.A., Cheema, T.A. and Khan, N.H., 2017. Numerical investigation of basin geometries for vortex generation in a gravitational water vortex power plant. 8th International Renewable Energy Congress (IREC), 2017. IEEE, pp. 1-5. https://doi.org/10.1109/IREC.2017.7926028

Dhakal, R., Bajracharya, T., Shakya, S., Kumal, B., Kathmandu, N., Khanal, K., Kavre, N., Williamson, S., Gautam, S. and Ghale, D., 2017. Computational and experimental investigation of runner for gravitational water vortex power plant. Proc. Meet. Held, pp. 8. https://doi.org/10.1109/ICRERA.2017.8191087

Dhakal, R., Nepal, A., Acharya, A., Kumal, B., Aryal, T., Williamson, S., Khanal, K. and Devkota, L., 2016. Technical and economic prospects for the site implementation of a gravitational water vortex power plant in Nepal. 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), 2016. IEEE, 1001-1006. https://doi.org/10.1109/ICRERA.2016.7884485

Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R. and Pandit, H.P., 2014. Effect of dominant parameters for conical basin: Gravitational water vortex power plant. Proc. IOE Graduate Conf., 2014: 381.

Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P. and Amatya, N., 2015a. Mathematical modeling, design optimization and experimental verification of conical basin: Gravitational water vortex power plant. Dalam World Largest Hydro Conference.

Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P., Amatya, N., Nakarmi, A.M. J.R. and Reviews, S.E. 2015b. Comparison of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant. Renew. Sustain. Energ. Rev., 48: 662-669. https://doi.org/10.1016/j.rser.2015.04.030

Gautam, A., Sapkota, A., Neupane, S., Dhakal, J., Timilsina, A.B. and Shakya, S., 2016. Study on effect of adding booster runner in conical basin: Gravitational water vortex power plant: A numerical and experimental approach. Proc. IOE Graduate Conf., 2016: 107-113.

Gheorghe-Marius, M. and Tudor, S.M., 2013. Energy capture in the gravitational vortex water flow. J. Marine Technol. Environ., 1: 89-96.

Gupta, A., Prakash, A., Singh, G.K. and Tripathi, H., 2021. Design of a micro hydro power plant based on the vortex flow of water. Parameters, 5. https://doi.org/10.48175/IJARSCT-1149

Guzmán, V.J.A., Glasscock, J.A., 2021. Analytical solution for a strong free-surface water vortex describing flow in a full-scale gravitational vortex hydropower system. Water Sci. Engin., 14: 72-79.

Habib, N., Sharif, A., Hussain, A., Aamir, M., Giasin, K. and Pimenov, D.Y., 2022. Assessment of hole quality, thermal analysis, and chip formation during dry drilling process of gray

Links Researchers

cast iron ASTM A48. Eng, 3: 301-310. https://doi.org/10.3390/eng3030022

Habib, N., Sharif, A., Hussain, A., Aamir, M., Giasin, K., Pimenov, D.Y. and Ali, U., 2021. Analysis of hole quality and chips formation in the dry drilling process of Al7075-T6. Metals, 11: 891. https://doi.org/10.3390/met11060891

Hamududu, B. and Killingtveit, A.J.E., 2012. Assessing climate change impacts on global hydropower. Energies 5: 305-322. https://doi.org/10.3390/en5020305

Hoseinzadeh, S., Ghasemi, M.H. and Heyns, S.J.R.E., 2020a. Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems. Renew. Energy, 160: 323-332. https://doi.org/10.1016/j.renene.2020.06.149

Hoseinzadeh, S., Sohani, A., Samiezadeh, S., Kariman, H. and Ghasemi, M.H., 2020b. Using computational fluid dynamics for different alternatives water flow path in a thermal photovoltaic (PVT) system. Int. J. Numer. Meth. Heat Fluid Flow, https://doi.org/10.1108/HFF-02-2020-0085

Hussain, A., Sharif, A., Habib, N., Ali, S., Akhtar, K., Ahmad, F., Salman, M., Ahmad, W., Ullah, I. and Ishaq, M., 2021. Effect of drilling process parameters on brass alloy 272 through experimental techniques. J. Mechan. Engin. Res. Develop., 44: 222-234.

Huwae, R., Sudibyo, H., Subekti, R.A., Susatyo, A. and Khaerudini, D.S., 2020. A review: Gravitational water vortex power plant. International conference on sustainable energy engineering and application (ICSEEA), 2020. IEEE, 1-7. https://doi.org/10.1109/ICSEEA50711.2020.9306140

Khan, N.H., 2016. Blade optimization of gravitational water vortex turbine. PhD diss., Tesis MT, Teknik Mesin, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology.

Khan, N.H., Cheema, T.A., Chattha, J.A. and Park, C.W., 2018. Effective basin-blade configurations of a gravitational water vortex turbine for microhydropower generation. J. Energy Engin., 144: 04018042. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000558

Kueh, T.C., Beh, S., Ooi, Y. and Rilling, D., 2017. Experimental study to the influences of rotational speed and blade shape on water vortex turbine performance. J. Phys. Conf. Ser., IOP Publ., 012066. https://doi.org/10.1088/1742-6596/822/1/012066

Marian, M.G., Sajin, T. and Azzouz, A., 2013. Study of micro hydropower plant operating in gravitational vortex flow mode. Appl. Mech. Mater., Trans. Tech. Publ., pp. 601-605. https://doi.org/10.4028/www.scientific.net/AMM.371.601

Moffat, R.J., 1988. Describing the uncertainties in experimental results. Exp. Thermal Fluid Sci., 1: 3-17. https://doi.org/10.1016/0894-1777(88)90043-X

Montgomery, D.C., 2017. Design and analysis of experiments, John wiley and sons.

Mulligan, S. and Casserly, J., 2010. The hydraulic design and optimisation of a free water vortex for the purpose of power extraction. BE Project Report Institute of Technology, Sligo, 2010.

Mulligan, S. and Hull, P., 2010. Design and optimisation of a water vortex hydropower plant. IT Sligo Research.

Neseli, S., 2014. Optimization of process parameters with minimum thrust force and torque in drilling operation using Taguchi method. Adv. Mech. Eng., 6: 925382. https://doi.org/10.1155/2014/925382

Nishi, Y. and Inagaki, T., 2017a. Performance and flow field of a gravitation vortex type water turbine. Int. J. Rotat. Mach., Pages 11. https://doi.org/10.1155/2017/2610508

Nishi, Y. and Inagaki, T., 2017b. Performance and flow field of a gravitation vortex type water turbine. Int. J. Rotat. Machin., 2017: Article ID 2610508

Pietraszek, J., Kołomycki, M., Szczotok, A. and Dwornicka, R., 2016. The fuzzy approach to assessment of ANOVA results. Int. Conf. Comp. Collect. Intell., Springer, pp. 260-268. https://doi.org/10.1007/978-3-319-45243-2_24

Power, C., Mcnabola, A. and Coughlan, P., 2016. A parametric experimental investigation of the operating conditions of gravitational vortex hydropower (GVHP). J. Clean Energy Technol., 4: 112-119. https://doi.org/10.7763/JOCET.2016.V4.263

Saleem, A.S., Cheema, T.A., Ullah, R., Ahmad, S.M., Chattha, J.A., Akbar, B. and Park, C.W.J.E., 2020. Parametric study of single-stage gravitational water vortex turbine with cylindrical basin. Renew. Energy, 145: 117464. https://doi.org/10.1016/j.energy.2020.117464

Shabara, H.M., Yaakob, O.B., Ahmed, Y.M. and Elbatran, A.H., 2015. CFD simulation of water gravitation vortex pool flow for mini hydropower plants. J. Teknol., 74. https://doi.org/10.11113/jt.v74.4645

Sharif, A., 2022. Study on burr formation, tool wear and surface quality in machining Al6063. J. Mater. Manufact., 1: 1-9.

Sharif, A., Siddiqi, M. and Muhammad, R., 2020. Novel runner configuration of a gravitational water vortex power plant for micro hydropower generation. J. Eng. Appl. Sci., 39: 87-93. https://doi.org/10.17582/journal.jeas/39.1.87.93

Sharif, A., Siddiqi, M.U.R., Tahir, M., Ullah, U., Aslam, A., Tipu, A.K., Arif, M. and Sheikh, N.A., 2021. Investigating the effect of inlet head and water pressure on the performance of single stage gravitational water vortex turbine. J. Mechan. Engin. Res. Develop., 44: 156-168.

Sharif, A., Tipu, J.A.K., Arif, M., Abbasi, M.S., Jabbar, A.U., Noon, A.A. and Siddiqi, M.U.R., 2022. Performance evaluation of a multi-stage gravitational water vortex turbine with optimum number of blades. J. Mechan. Engin. Res. Develop., 45: 35-43.

Shoukat, A.A., Noon, A.A., Anwar, M., Ahmed, H.W., Khan, T.I., Koten, H., Siddiqie, M.U.R. and Sharif, A., 2021. Blades optimization for maximum power output of vertical axis wind turbine. Int. J. Renew. Energy Develop., 10: 585-595. https://doi.org/10.14710/ijred.2021.35530

Sritram, P., Treedet, W. and Suntivarakorn, R., 2015. Effect of turbine materials on power generation efficiency from free water vortex hydro power plant. IOP conference series: Materials science and engineering, 2015. IOP Publishing, 012018. https://doi.org/10.1088/1757-899X/103/1/012018

Tipu, A.K., Arif, M., Sharif, A. and Siddiqi, M.U.R., 2021. Implementing truss elements for ensuring structural integrity on the blade of up-scaled gravitational water vortex turbine. J. Mechan. Engin. Res. Develop., 44: 115-122

Ullah, I. and Sharif, A., 2022. Novel blade design and performance evaluation of a single-stage savanious horizontal water turbine. J. Technol. Innov. Energy, 1: 42-50. https://doi.org/10.56556/jtie.v1i4.394

Ullah, I., Siddiqi, M.U.R., Tahir, M., Sharif, A., Noon, A.A., Tipu, J.A.K., Arif, M., Jabbar, A.U., Siddiqi, S.M. and Ullah, N., 2022. Performance investigation of a single-stage savanious horizontal water turbine with optimum number of blades. J. Mechan. Engin. Res. Develop., 45: 29-42.

Ullah, R., Cheema, T.A., Saleem, A.S., Ahmad, S.M., Chattha, J.A. and Park, C.W., 2020. Preliminary experimental study on multi-stage gravitational water vortex turbine in a conical basin. Renew. Energy, 145: 2516-2529. https://doi.org/10.1016/j.renene.2019.07.128

Venukumar, A., 2013. Artificial vortex (ArVo) power generation. An innovative micro hydroelectric power generation scheme. 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS), 2013. IEEE, 53-57. https://doi.org/10.1109/GHTC-SAS.2013.6629888

Wanchat, S., and Suntivarakorn, R., 2012. Preliminary design of a vortex pool for electrical generation. Adv. Sci. Lett., 13: 173-177. https://doi.org/10.1166/asl.2012.3855

Zotlöterer, F.J.W., 2008. Hydroelectric power station.