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Development of Screw Type Runner for Conical Basin of Gravitational Water Vortex Power Plant

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Abstract

The gravitational water vortex power plant (GWVPP) is an emergent type of hydropower plant which utilizes energy created by water vortex to generate electricity. It is very efficient in ultra-low head range (0.7-2 m). This research was conducted to develop and optimize a screw type runner, which was a new type of runner for GWVPP, considering top surface of GWVPP open to atmosphere. After the CFD based optimization, the optimum dimension of the runner was determined to have 100 mm radius of curvature, 100 mm pitch, 180 mm radius, 1 number of blade, 318 mm height and was positioned at 240 mm below the top surface of GWVPP. The maximum efficiency was found to be 13.99%. Similarly, previous type runner having similar surface area and same radius of curvature with that of the optimized screw type runner was found to have a maximum efficiency of 7.03% under same boundary conditions.

Keywords

Gravitational Water Vortex Power Plant (GWVPP), Computational Fluid Dynamics (CFD), Screw Type Runner, Conical Vertical Archimedes Screw Runner, Conical Runner, Open Channel Flow, Two Phase Modeling

1. Introduction

With rapid growth in world population, energy consumption is also increasing rapidly. Among different forms of energy, electrical energy is one of most commonly used forms of energy and its production has not been sufficient for the world. There are about 940 million people in the world who don't have access to electricity and most of them belong to rural areas. Despite the fact that access to electricity has been increasing worldwide in recent decades, this is not sufficient. The current trends show that 660 million of people will still lack access to electricity in 2030 [1]. Hence, it is important to enhance the electricity production especially in rural areas. Among different sources of electricity production, hydropower is one of the main source. Particularly, in rural areas which are mostly isolated communities [2], hydropower like micro and pico hydropower plants are mostly viable option for supplying electricity in those communities. Micro hydropower plants ranges from 5 kW to 100kW , whereas pico hydropower plants are below 5 kW generation [3].

In developing countries like Nepal, where geographical terrain are so unfavorable that access to national grid line does not seem viable in many cases for rural communities. In these circumstances, low head micro and pico hydropower provide good alternative. Moreover, these kind of hydropower are economical as they don't require construction of large dams.

Among different types of low head power plant, Gravitational water vortex power plant is one of the most efficient. It is ultra-low head turbine which operates in the range of 0.7 to 2 m [4]. In this type of power plant, the water passes through a large, straight inlet, which then passes tangentially into a round basin as shown in Figure 1. The water will then form a powerful vortex, which exits from the outlet at the centre bottom of the shallow basin. A vertical axis turbine is placed at the center of vortex which withdraws rotational energy from gravitational vortex. The turbine does not work on pressure differential but on the dynamic force of the vortex. This type of power generation system is suitable in areas with low velocity water flow such as small rivers and existing agricultural irrigation canals [4, 5].

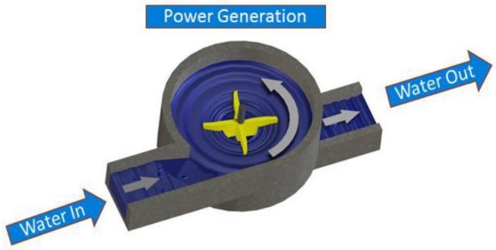

Figure 1: Schematic presentation of gravitational vortex power plant [6]

1.1 Problem Statement

GWVPP is a new type of technology. So the researches in this field is less in comparison to other conventional hydropower plants. The past researches mainly focused on the study of different parameters like basin geometry, notch angle, cone angle and length of the GWVPP canal and optimizing these parameters to achieve maximum efficiency [5]. Besides, as turbine is a paramount component of the power plant, its optimization is essential to achieve maximum efficiency. So, many researches have been concerned to optimize the runner. The runner optimization mainly focused on position of runner, number of blades, size of blades and blade inlet angle. Both experimental and numerical simulation methods are used for the optimization of the vortex power plant.

However, in one hand, the past researches focused just on optimizing the runner with reference to blade angle, number of blades, position of runner etc. without much exploration of different types of runner that could be more suitable for vortex power plant [5]. In other hand, they assumed the GWVPP top surface, which is actually open to the atmosphere, as a wall considering GWVPP canal as a casing or a closed channel during numerical simulation and consequently using only water as a fluid. In actual GWVPP, the top surface is open and there is interaction of air and water [7, 8, 2]. Therefore, the numerical simulation also needs to consider these facts.

Thus, to address these shortcomings of past researches, this study focuses on developing a new type of runner considering the top surface open and two phase modeling of air and water.

1.2 Related Researches

An experimental study performed by Chaulagain et al. [9] was focused on developing low head water turbine for micro-hydropower power plants in Terai region of Nepal. The study concluded that for a fixed discharge condition, the height of a cylindrical basin, diameter and bottom exit hole are fixed. The study further suggests that the vortex minimum diameter is at the bottom level and is smaller than the exit hole. Similarly, Dhakal et al. [10] performed a numerical and experimental study on comparison of cylindrical and conical basin of GWVPP and found that conical basin produces more power and efficiency than cylindrical basin. Further, they concluded that maximum power can be extracted at 65-70% of the total height of basin from top surface of the power plant with maximum efficiency of 36.84%. Similarly, Gautam et al. [2] studied effect of adding booster runner lower in position to main runner in order to enhance power output and efficiency. The maximum efficiency of 78.65% was obtained when the main runner is coupled with booster runner which is 6% more than that of single main runner. Besides, Regmi et al. [7] performed a CFD analysis considering top surface of GWVPP open where tapered ratios of the basin were varied with and without changing the exit hole and corresponding variations in flow parameters were observed. It was found to have a maximum efficiency of 7.93% for a baseline basin geometry of existing runner.

Similarly, Khan et al. [11] numerically studied optimization of runner blades considering open channel flow and maximum efficiency was found to be 12.08%. Acharya et al. [12] studied variation of inlet angle of attack,α and radius of curvature and found that the maximum torque was obtained at an angle of 18° and around radius of curvature 285 mm. CFD analysis on three different designs of runner with straight, twisted and curved blade profile were carried out by Dhakal et al. [3] and found that the curved blade profile had higher efficiency with peak efficiency of 82.4% compared to 46.31% for the straight blade runner and 63.54% for twisted blade profile. Bajracharya et al. [8] studied the effect of seven different geometric parameters on system efficiency and found that runner height is the most significant parameter to be considered in the design of a turbine runner. The maximum efficiency of 47.85% was obtained from the experiments. Besides, Rahman et al. [5] published a review paper on GWVPP which suggested that there are lot of rooms for maximizing efficiency of GWVPP runner. In order to achieve maximum efficiency, a suitable turbine should be explored and selected first followed by optimization of shape and blade profile. Thus, with an aim of exploring different type of runner that has not been used in GWVPP, this study focuses on developing a screw type runner which is a modification of general type of Archimedes screw runner shown in Figure 2.

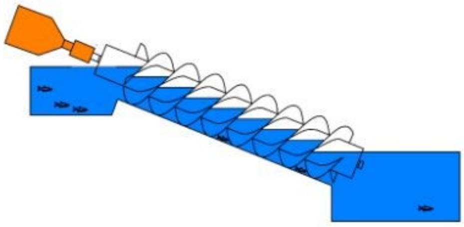

Figure 2: General Archimedes screw hydro power plant [13]

2. Methodology

2.1 Design

2.1.1 Gravitational water vortex power plant canal with conical basin

Its dimension, shown in Figure 3, is taken from past research [7]. It is taken as a reference for the design of screw type runner. Its CAD modeling is done in SOLIDWORKS.

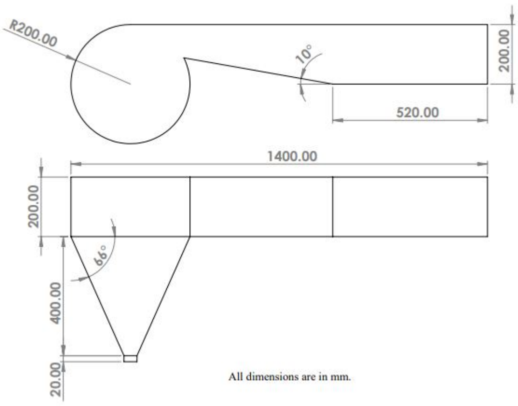

Figure 3: Dimension of GWVPP with conical basin

2.1.2 Conical screw type runner

Conical screw type runner is designed based on a design principle of Archimedes screw turbine [13]. Figure 4 shows a typical Archimedes screw configured as a hydropower plant and the most important dimensions and parameters required to define the Archimedes screw are given in Table 1.

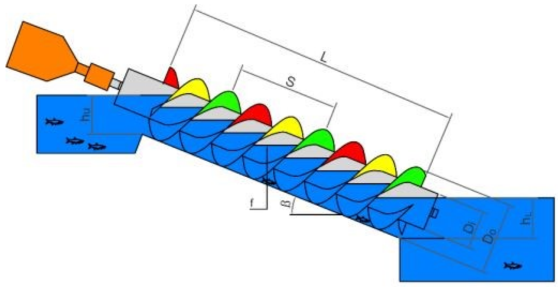

Figure 4: Archimedes screw geometry and parameters [13]

Table 1: Parameters required to define Archimedes screw [13]

β:	Screw inclination angle
D_o:	Outer diameter of screw
S:	Pitch length of screw
D_i:	Inner diameter of screw or shaft diameter
L:	Total screw length
f:	Bucket fill height
G_w:	Gap between trough and screw
h_u:	Water level at upper position (inlet)
h_L:	Water level at lower position (outlet)
N:	Number of helical planed surfaces

At first, β = 90° for vertical axis screw turbine.

Then, runner was positioned at 240 mm below the top surface of GWVPP so that the runner was submerged at 66% of the total height in order to achieve maximum vortex strength according to past research [10].

Outer diameter was selected based on the dimension of conical basin. So,

$$\text{Outer diameter of top surface of runner}(D_{ot}) = 360\,mm$$

$$\text{Outer diameter of bottom surface of runner}(D_{ob}) = 80\,mm$$

$$\text{Outer diameter of runner}(D_o) = \frac{D_{ob}+D_{ot}}{2} = 220\,mm$$

$$\text{Pitch length of screw }(S) = 1.4D_o = 308\,mm$$

So 300 mm was used in order to make it easier for CAD modeling.

$$\text{Inner diameter}(D_i) = \frac{D_o}{4.5} = 48\,mm$$

So 40 mm diameter of shaft was used.

Length or height of the screw runner was selected as per the site condition. The available height available in the conical basin was 360 mm. So, 320 mm height was selected as it gives:

$$\frac{L}{D_o} = 1.45 = \text{lies between 2 and 1.25}$$

If L/D_o was below 1.25, the screw would be too short for its diameter and as it was less than 2, efficiency decreased slightly [13]. Later, reducing 1 mm on both ends for easier CAD modeling and ANSYS simulation, 318 mm was used as the height of the runner.

Parameters viz. bucket fill height, water level at upper position (inlet), water level at lower position (outlet) and gap between trough and screw were irrelevant during the design of conical screw type runner.

Moreover, since there was no relation that determines radius of curvature for screw type runner, it was determined based on past research. In past research by [12], radius of curvature for maximum efficiency was 285 mm. So near to that value, initially 235 mm of radius of curvature was selected.

Lastly, since there was no specific relation to determine number of helical planed surfaces or blade number (N), initially it was taken as 2 blade number.

After determining all required dimensions, its CAD modeling was done in SOLIDWORKS. Initial proposed screw type runner is shown in Figure 5.

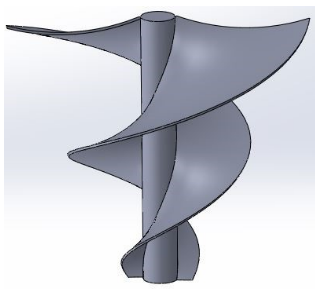

Figure 5: Initial proposed screw type runner

2.2 Numerical Model Development

The numerical simulation was done to determine the torque developed by the runner and discharge flow rate at a given angular velocity of the runner. Once the values of torque developed and discharge flow rate were known, power produced by the runner were calculated. Consequently, efficiency was determined [2].

Numerical simulation software, ANSYS 2019 R2 version, was used for simulations and SOLIDWORKS was used as a CAD modeling software. The CAD models which were created in SOLIDWORKS were converted into parasolid format and imported into ANSYS CFX for CFD analysis. For meshing, ANSYS AUTODYN was used. The mesh metrics like skewness, orthogonal quality, element quality, etc. were monitored to get better mesh quality and consequently, an accurate solution. The model was divided into two different parts which were stationary domain and rotary domain. [3, 2].

2.3 Physics Setup

The analysis was based on two phase modeling of air and water. So, multiphase Eulerian fluid approach was used. The temperature and reference pressure of the domain were set to 25°C and 1 atm respectively. The buoyancy reference density of 1.2 kg/m^3 was used.

Properties of air and water were used as given in the ANSYS software. In the production of air-core vortices, the buoyancy plays a vital role, therefore, buoyancy was also included in the analysis. SST turbulence model was used. The boundary conditions [11, 7, 14] used for CFD analysis were shown in Figure 6. The model included advection scheme as "High Resolution" and turbulence numeric was "High Resolution". Timescale was set to "Auto Timescale". The number of iterations was set to 2000 with a residual target of 0.0001 [7, 11].

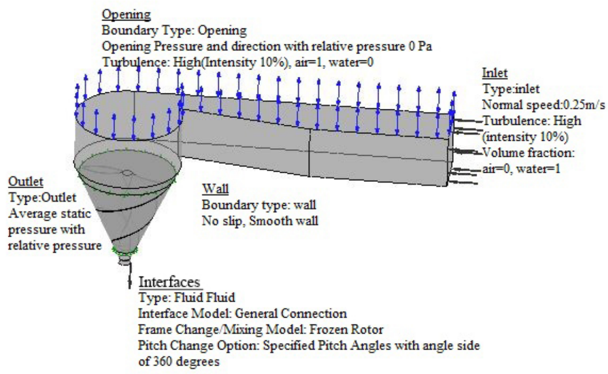

Figure 6: Boundary Conditions

2.4 Mesh Independence Test

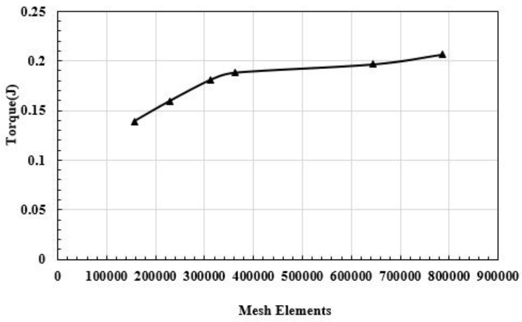

Figure 7: Mesh Independent Test

In mesh independence test, six different mesh sizes with the number of elements varying from 156807 to 785246 were used as shown in Figure 7. As shown in Figure 7, when the number of elements were higher than 363366, the torque on the screw type runner changed slightly. The difference in torque between 785246 elements i.e. 0.206 J and 363366 elements i.e. 0.188 J was within 9.57% which was considerable. So, 363366 number of elements was used in order to trade-off between accuracy and time for completion of simulation.

3. Results and Discussion

3.1 Optimizing the Screw Type Runner by Varying Different Parameters

For optimizing the initial assumed screw type runner, different CAD models were simulated at steady state conditions at 70 rpm. From the simulations, values of discharge flow rate at outlet and torque were obtained. From the obtained values, input power, output power and efficiency were calculated. Power developed at the runner is calculated as:

$$\text{Power developed at runner} = T \times \omega$$

where,

T= Torque=$torque\_y()@Turbine$ Nm

ω= Angular velocity= $2\pi\frac{N}{60}$ rad/s

Input power is calculated as:

$$\text{Input power} = \rho g Q H$$

where,

ρ= Density of water= 998 kg/m^3

g= Acceleration due to gravity= 9.81 m/s

Q= Discharge flow rate= $\frac{massFlow()@Outlet}{998}$ m^3/s

H= Head upto runner mean height [7]= 0.399 m for screw-type runner

Efficiency is calculated as:

$$\text{Efficiency} = \frac{\text{Power developed at the runner}}{\text{Input power}} \times 100\%$$

In optimization, different parameters viz. number of blades, pitch, length, radius of curvature, radius, position of runner and edge deflection angle of the runner [5, 15] were successively analyzed by varying their numbers and subsequently analyzing torques, discharge flow rates, powers and efficiencies obtained. Then, the corresponding values of the parameters giving maximum efficiencies were chosen. At first, number of blades of initial proposed screw type runner were varied maintaining all other parameters constant. Then, the most efficient number of blade was chosen. Similarly other parameters were also varied successively and their corresponding values producing maximum efficiency were chosen.

3.1.1 Different number of blade with other parameters constant

At first, CFD analysis of the screw type runner at steady state conditions of 70 rpm was performed by varying number of blades from 1 to 7 maintaining constant radius of curvature of 235 mm and pitch of 300 mm. From the analysis, it was found that as the number of blade increased, power developed in the runner decreased. So, the screw type runner having 1 number of blade with 235 mm radius of curvature and 300 mm pitch length developed maximum power of 1.41 watt, discharge flow rate of 0.0046 m^3/s and efficiency of 7.76%. So, 1 blade number was selected.

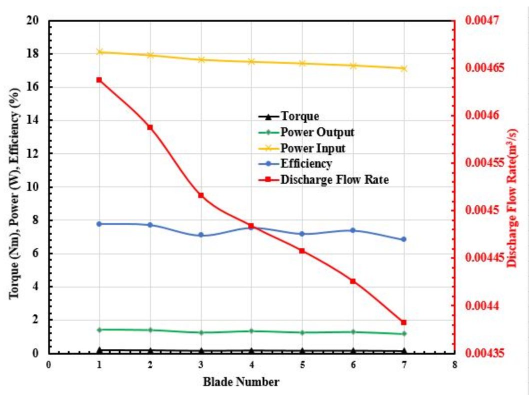

Figure 8: Variations of torque, discharge, power and efficiency with blade number

3.1.2 Different number of pitch with other parameters constant

Similarly, pitch of the runner was varied from 25 mm to 1000 mm. The simulation results showed that as the pitch length was decreased, the power developed by the runner increased, reached optimum value and then gradually decreased. The runner having 100 pitch length with 1 number of blade and 235 mm radius of curvature developed maximum power of 1.80 watt and efficiency of 11.53% with discharge flow rate of 0.0040 m^3/s. So, 100 mm pitch was selected.

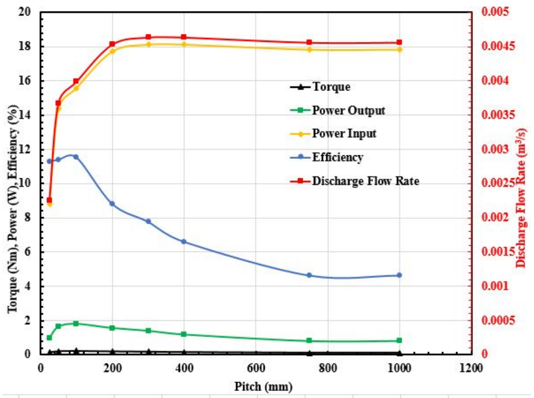

Figure 9: Variations of torque, discharge, power and efficiency with pitch

3.1.3 Different number of length with other parameters constant

Besides, length was varied maintaining all other parameters constant. The results obtained from the simulations showed that as the length of the runner increased, the power output increased. The runner with 318 mm of length developed maximum efficiency of 11.53% and power of 1.80 watt with 0.0040 m^3/s discharge flow rate. So, 318 mm length was selected.

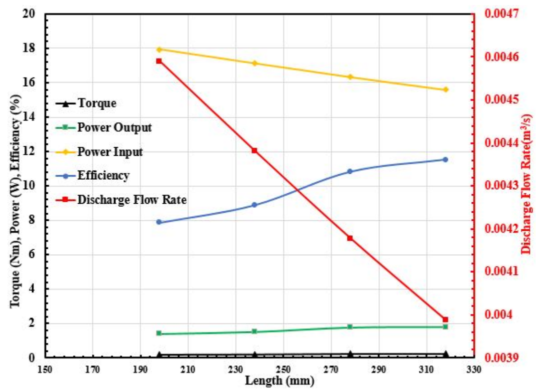

Figure 10: Variations of torque, discharge, power and efficiency with length

3.1.4 Different radius of curvature with other parameters constant

Moreover, radius of curvature was varied maintaining all other parameters constant. The results obtained showed that as the radius of curvature decreased, the power developed and efficiency of the runner also increased, reached its maximum value and then decreased. The runner with 100 mm radius of curvature with 1 blade number, 318 mm of length and 100 mm pitch length developed a maximum power of 1.89 watt, discharge flow rate of 0.0039 m^3/s and efficiency of 12.48%. So, 100 mm radius of curvature was selected.

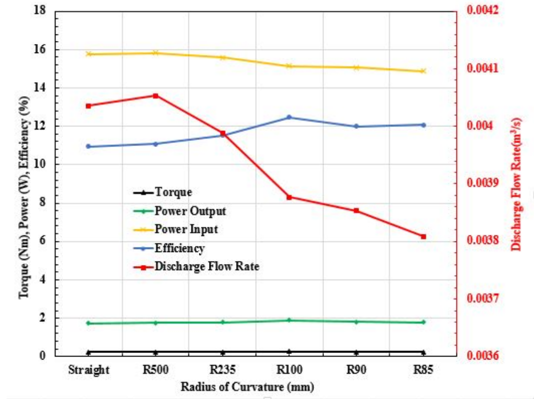

Figure 11: Variations of torque, discharge, power and efficiency with radius of curvature

3.1.5 Different radius with other parameters constant

Similarly, radius was varied maintaining all other parameters constant.

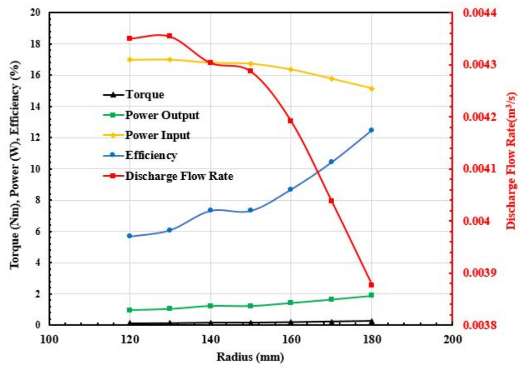

Figure 12: Variations of torque, discharge, power and efficiency with radius

The results obtained from simulations showed that the power and efficiency increases as radius increased. The runner having 180 mm radius with 100 mm radius of curvature, 1 blade number, 318 mm of length and 100 mm pitch length developed a maximum power of 1.89 watt, efficiency of 12.48% at discharge flow rate of 0.0039 m^3/s.

3.1.6 Different positions of the runner

Similarly, the runner's position, which was a distance between top surfaces of GWVPP and the runner, was varied maintaining optimized values of all other parameters constant. The power produced by the runner increased as the position increased from 150 mm to 240 mm. The maximum power of 1.89 watt and efficiency of 12.48% at discharge flow rate of 0.0039 m^3/s were produced at 240 mm which is actually 66% of the total height considering the height between top surface and runner mean height.

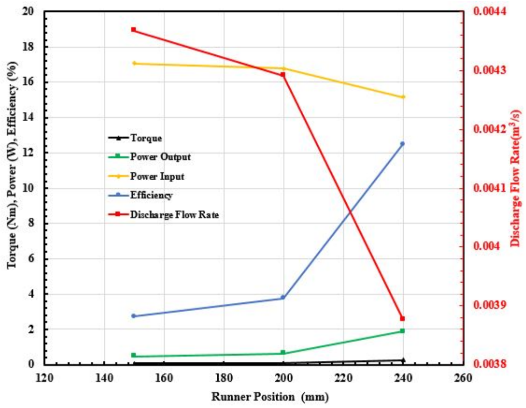

Figure 13: Variations of torque, discharge, power and efficiency with runner position

3.1.7 Different edge deflection angle of runner

Similarly, edge deflection angle was varied above and below 147.67° keeping all other parameters constant. 147.67° was the angle made by simplified straight of 100 mm radius of curvature with respect to the center of the 100 mm radius of curvature as shown in Figure 14. The results obtained from simulations showed that the runner with 147.67° developed maximum power of 1.86 watt, discharge flow rate of 0.0039 m^3/s and efficiency of 12.05%. But slightly lower than the previously optimized screw type runner with 100 mm radius of curvature. So the runner with curved surface having 100 mm radius of curvature without straight edge deflection angle was selected. Thus, the maximum efficiency obtained at 70 rpm was 12.48% and the final optimized runner is shown in Figure 16 and its dimension is given in Table 2.

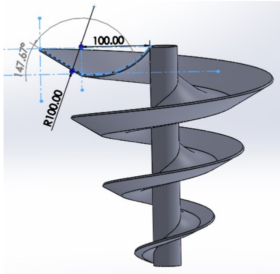

Figure 14: Edge deflection angle of 147.67° of screw type runner

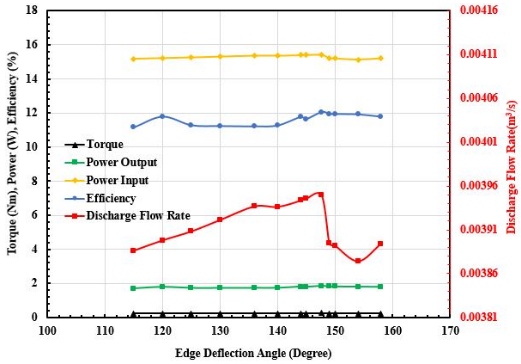

Figure 15: Variations of torque, discharge, power and efficiency with edge deflection angle

Figure 16: Optimized screw type runner

Table 2: Dimensions of optimized screw type runner

Descriptions	Dimensions
Pitch Length	100 mm
Radius of Curvature	100 mm
Blade thickness	3 mm
Blade number	1
Length	318 mm
Radius	180 mm
Position of runner from top surface	240 mm

3.2 Performance Analysis

3.2.1 Optimized screw type runner

The optimized screw type runner was performed a steady state CFD analysis at different speed to determine the maximum power developed and efficiency. The results obtained showed that the optimized runner developed a maximum power of 2.16 watt and efficiency of 13.99% with discharge flow rate of 0.0040 m^3/s at 100 rpm.

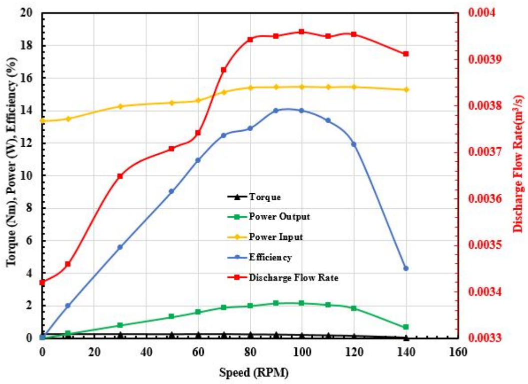

Figure 17: Variations of torque, discharge, power and efficiency with speed of optimized screw type runner

3.2.2 Mesh independence test of results obtained

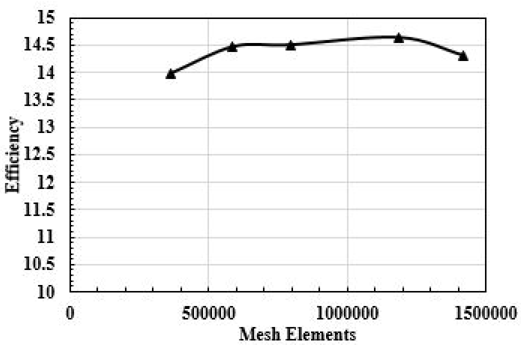

Figure 18: Mesh independence test of obtained results

For mesh independence test, maximum efficiency of the optimized screw type runner was taken for analysis. As shown in Figure 18, the number of elements were varied from 364581 to 1421229. When the number of elements were higher than 364581, efficiency of the runner changed slightly. The difference in efficiency between 1421229 and 364581 mesh elements, which were 14.31% and 13.99% respectively, was within 2.31%. Thus, in this study, results obtained by using mesh elements of 364581 numbers were close to accuracy.

3.2.3 Previous type runner

The CAD modeling of previous type runner used in GWVPP was done in SOLIDWORKS which is shown in Figure 19. The runner had similar surface area to the optimized screw type runner and same radius of curvature both horizontally and vertically. The dimensions of optimized screw type runner and previous runner is given in Table 3. Here, mean head upto the runner was taken as 0.35 mm. The results obtained from CFD analysis showed that the maximum power developed and efficiency were found to be 1.08 watt and 7.03% at 45 rpm respectively with discharge flow rate of 0.0045 m^3/s.

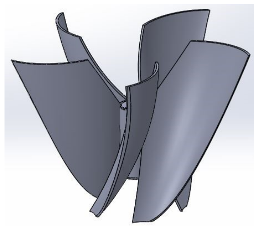

Figure 19: Previous type runner

Table 3: Dimensions of optimized screw type runner and previous type runner

Description	Previous type runner	Optimized screw type runner
Surface area of runner (mm^2)	322693	320408.76
Length (mm)	230	318
Blade number	5	1
Radius (mm)	180	180
Inclination Angle (degree)	168 (from vertical)	
Radius of Curvature (mm)	100	100

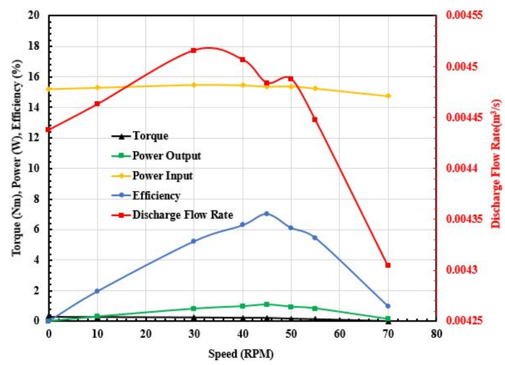

Figure 20: Variations of torque, discharge, power and efficiency with speed of previous type runner

With the same dimension of the GWVPP canal and boundary conditions, past study by [7] had obtained the maximum efficiency of 7.93% with maximum output power of 2.373 watt at 68 rpm which was similar to the efficiency of this study. So, CFD analysis of this study was validated.

4. Conclusions and Recommendations

In this research, a screw type runner is optimized with the help of CFD analysis. The optimum dimension of the runner is 100 mm radius of curvature, 100 mm pitch, 180 mm radius, 1 number of blade, 318 mm height and was positioned at 240 mm below the top surface of GWVPP. The maximum efficiency is found to be 13.99% with maximum power output of 2.16 watt at 100 rpm. Similarly, previous type of runner with similar surface area and same radius of curvature under same conditions is found to have a maximum efficiency of 7.03% with maximum power output of 1.08 watt at 45 rpm.

This study can be further extended by considering the top surface closed and water as the only fluid in the domain like many of the past researches. The results obtained from those studies can be compared with the past researches and analysis of efficiency and power can be done. Besides, further analysis can be done varying the pitch length between 50 mm and 100 mm with narrow margin which can further increase efficiency. Moreover, the results can be validated from experimental analysis of the runner.

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