COMPUTATIONAL AND EXPERIMENTAL STUDY OF THE EFFECT OF SOLIDITY AND ASPECT RATIO OF A HELICAL TURBINE FOR ENERGY GENERATION IN A MODEL GRAVITATIONAL WATER VORTEX POWER PLANT

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Abstract

Gravitational Water Vortex power plant is a relatively new plant used to generate hydropower from low head rivers and canals. There has been an increase in research in the field of runner design and canal design for GWVPPs throughout the world. As no definite equations are formulated in case of runners used in a GWVPP, they are currently produced by hit and trial method. This research focuses on studying about the use of a pure reaction turbine, Gorlov turbine, to generate power from a GWVPP. ANSYS Fluent was used to perform computational study while the experimental study was done using helical turbine blades fabricated using a 3-D printer. The energy generated is very low compared to the impulse turbines. Both the computational and experimental study shows that when increasing the aspect ratio of the turbine but keeping the solidity same, the efficiency is increased significantly. However, the studies also show that on increasing the solidity, the efficiency seems to decrease. All the turbines used submerged to 3 different depts and all the results show that increasing the submergence increased the efficiency.

Keywords: GWVPP, solidity, aspect ratio, depth, efficiency

1.   Introduction

The total energy consumption of Nepal in year 2014/2015 was 500 million GJ; among which, bio-mass fuel is the largest energy resources occupying about 77.63% of the total energy demand. Government has been involved in developing policies that push its citizens to use more of the clean energy sources like electricity. Despite a huge potential for hydro-electricity, Nepal hasn't been able to fully utilize its water resources for energy generation purpose. As a result, the electricity is available to only 70% of the total population. Construction of large hydropower system is time consuming and needs a huge capital investment. Micro and pico-hydropowers are can be constructed in places where electricity cannot be easily provided but that have water resources like canals and rivers.

GWVPP is a technology that falls in the category of micro hydro power plant because the maximum reported power generation had not exceeded 100kW. The main advantage of this technology is that it requires ultra-low head of about 0.7- 3 m [1] and it is environment friendly too. Austrian Engineer, Franz Zotloterer is the one who discovered this ultra-low head power plant. Water is passed through a long & straight channel with small notch at the inlet, which then passes tangentially into a conical basin and forms a powerful vortex. A runner is placed at the center of the vortex which is brought in rotational motion by the dynamic force of the vortex. The water is passed out through the outlet at the bottom of the basin.

Although, GWVPP is one of the new low-head hydropower technologies, there has been many researches going on parallelly throughout the world. Dhakal et al. [2] conducted experimental investigation of the GWVPP using turbine models of 3, 6 and 12 conical blades to find the optimum number of blades for the plant. The efficiency decreased with increase in number of blades since they caused a greater distortion in the vortex. The efficiency also decreases with increase in radii of the blades since the water velocities at radii far away from the core are lower.

Dahal et. al. [3] tested 5 different kinds of boosters with the optimum runners used by the Gautam et. al. to test the effect of a booster in the efficiency. They found that, while the standalone main runner had an efficiency of 64.05%, the boosters they used increased the efficiency to 75.36 to 84.058 %.

Khan. H. [4] found that maximum efficiency occurred when blades used in the runner were in the shape of the cross-flow blades which causes a lesser distortion in the vortex profile and extracts maximum kinetic energy of the flowing water.

All of these researches use impulse turbines to extract energy in a GWVPP. Research is yet to be done to test the effect of using reaction turbines in a GWVPP. One of such reaction turbines is the Gorlov Turbine shown in figure 1. Gorlov's turbine, inspired by the Darrieus rotor of 1931, extracts up to 35% of the kinetic energy of moving water, even with a flow rate of as little as 1.5 meters per second and in only a meter of water. Gorlov turbine uses helical blades which provide a good self-starting ability while used in free-stream of water.

Fig 1: Gorlov Turbine

The major installer of the Gorlovturine is Lucid Energy Technologies, LLP (Lucid), formerly GCK Technologies (where "G" stood for Gorlov), and succeeded with several small scale installations over the years. Lucid/GCK also provided two prototypes to the Korean Ocean Research and Development Institute (KORDI) for testing in the Uldolmok Tidal Strait (GCK Technologies, 2002-2006). Based on the experience with the Lucid/GCKGHTs, in 2009, KORDI completed their Uldolmok Tidal Current Power Plant, a full scale test project rated at 1MW.

Following are some of the parameters that effect the efficiency of a Gorlov Turbine.

Blade Profile

Blade profile shape can have a significant impact on performance due to the pressure forces that develop when subjected to an incident flow. Traditionally, vertical axis turbine blades have been designed with the common NACA 4-digit series symmetrical profiles due to the availability of the lift and 35 drag data for a large range of Reynolds numbers. Durability is also a consideration in selecting a blade shape. As the blades are being used for water and we are fabricating a model using 3D printer, using a cambered profile would result in low strength. Thus, a symmetric profile of NACA 0018 is used in our study.

Solidity Ratio

$$Solidity\ ratio\ (\sigma) = \frac{BC}{\pi D}$$

Where, B = Number of Blades

C = Chord Length

D = Diameter of Turbine

A high solidity device (e.g., σ>0.3) will more easily self-start but will operate at a lower tip speed ratio, whereas a low solidity device (e.g., σ< 0.15) may be more difficult to self-start but operates at a higher tip speed ratio [5].

Aspect Ratio

Aspect ratio $= \frac{H}{D}$

Where, H = Height of the Turbine

D = Diameter of the Turbine

Using a double multiple stream-tube modeling method for a Darrieus turbine, Chu et. al [6], determined that coefficient of performance increased with aspect ratio. However, starting torque coefficient was inversely proportional to the aspect ratio.

Helical Pitch Angle

Helical pitch angle (δ) for a vertical axis turbine refers to the pitch angle that the blade makes with a horizontal plane. For this analysis, only constant pitch angles are considered, though it is possible for the pitch angle to vary along the blade length. Experiments concluded that as helical pitch angle increased, performance of the turbine improved, up through a 90-degree pitch angle (which is equivalent to a straight-bladed Darrieus turbine) [7]. But, as we are using Gorlov turbine for our analysis, there is a pitch angle associated with the runner blades.

Blade Wrap

Blade wrap is a term in helical turbine geometry referring to the percent of radial circumference that the blades span. A blade wrap ratio can be defined by considering turbine height, Number of blades, turbine diameter with the helical pitch angle (δ):

$$w = \frac{B \times H}{\pi \times D \times tan(\delta)}$$

A turbine with a blade wrap ratio of 1, for example, will contain no circumferential void space between the end of one blade and the beginning of another. For our analysis, we will have a blade wrap of 1 for all the turbines to be formulated.
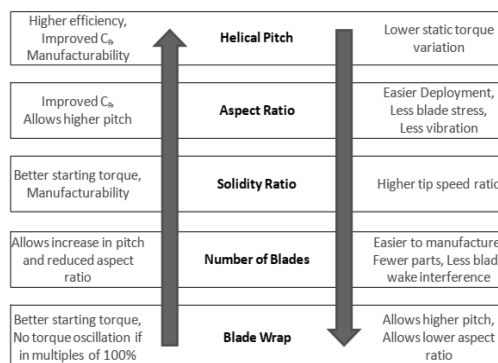

Fig 2: Trade off for a helical turbine design parameter [8]

Simulation of the model using ANSYS Fluent

By using ANSYS Fluent as a simulation tool, the turbine and basin are imported in the software to analyze various parameters. First of all, all the existing parameters of the turbine, water flow conditions and basin are input in the system to properly model the system. After that, the operating conditions are changed to find the best possible flow condition values for the designed model. Firstly, only the basin was modeled to get the flow of water without any turbine interference. After that, the turbine was put into place and the effect of the turbine on vortex was seen.

The turbine models prepared in SOLIDWORKS were encased within a turbine domain and the assembly of turbine domain along with basin is imported into the ANSYS design modeler. The turbine blades were cut out from the turbine domain and the turbine domain was again cut from the basin so that the domain can rotate inside the basin. The assembly is shown below
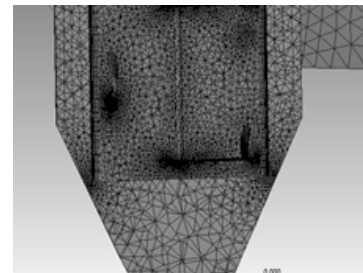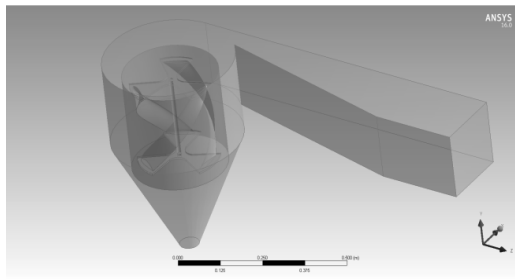
The model was then imported to the built-in meshing software in ANSYS (ICEMCFD) and automatic generation of meshes was done with slight tweaking of maximum and minimum mesh sizes. The mesh used in this way was unstructured and can be seen in the above figure. Torque in the turbine blades was taken as the output from these simulations.

Calculation of efficiency

After processing, by going through the report section of post processing, we found out the total amount of torque about (0,1,0) in the turbine blade surfaces and found the resulting power in those surfaces using following formula:

$$P_e = T \times \omega$$

Where,
P_e = Power extracted, W
T = Torque, Nm
ω = angular velocity, rad/s
This was repeated for all the angular speeds that we set in the processing part.
Theoretical power for the turbine is calculated as:

$$P = \rho \times g \times h \times Q$$

Where,
ρ = density of water, 998 kg/m^3
g = acceleration due to gravity, 9.81 m/s^2
h = height of the basin, 610 mm
Q = flow rate of water, 0.01 m^3/s
Using

$\eta = \frac{P_e}{P}$ efficiency is calculated for various turbine profiles and working conditions.

Model Fabrication and Experimental Testing

Different runner profiles were formulated to find the effect of changing solidity and aspect ratio on the efficiency of the turbine. Due to the limitation of the physical dimensions of the turbine basin, the size of the turbine could not be varied much and following different profiles were created using SOLIDWORKS and imported in the ANSYS workbench to find the trend on efficiency while using different solidities and Aspect ratio.

Due to the limitation of budget, only the turbine 2,3 and 5 were fabricated using a 3D printer. These were tested extensively in the conical basin at Himalaya College of Engineering to validate the results obtained from simulations.

Table 1: Design parameters of Helical Turbine with twist angle 120^0 and aspect ratio 1

SN.	Solidity	Blade Wrap (%)	Helical Twist (^{0})	Blade Profile	Aspect Ratio	Number of Blades
1	0.2	100	120	NACA 0018	1	3
2	0.3	100	120	NACA 0018	1	3
3	0.4	100	120	NACA 0018	1	3
4	0.2	100	120	NACA 0018	1.25	3
5	0.3	100	120	NACA 0018	1.25	3
6	0.4	100	120	NACA 0018	1.25	3

Fig 3: Runner profiles tested experimentally. From left, profiles 5, 2 and 3

In the setup, a submersible type centrifugal pump of discharge 40 m3/hrat the rated head of 15 m is used to pump water from the sump to drop chamber. The canal is 0.88 m long, and of square cross section (0.2 m * 0.2 m) delivers water to the basin of diameter 0.4 m, height 0.61 m in which the top part is cyldindrical with diamter 0.4m and height 250mm while the lower part is conical with taper angle 280 and height 0.36m . The basin opening is 0.060 m which was calculated using the existing literature (*). The water passing through the canal is directed into the drop chamber using a tapering canal of taper angle 100.

Measurement of the torque was done using a brake dynamometer which was formed using two spring balances and a rope with high friction coefficient. Measurement of rotational velocity of the turbine was done using a digital tachometer. Measurement of flow rate was done using the inbuilt V-notch in the chamber and using following formula:

Q = 1.36 H2.5. (Pritchard, 2010)

Results, Discussion and Conclusion

The 3 different turbines that were fabricated were tested at different submergence level, which was measured from the upper bearing of the shaft. The experimental results at different submergence level are tabulated below:

Turbine	Flow rate (m3/s)	Head (m)	Available Power (W)	Submergence (m)	Force 1 (kg)	Force 2 ((kg)	Speed (rad/s)	Braking Power (W)	Efficiency
Turbine 2	0.01	0.061	59.84	0.07	0.250	0.000	2.9906	0.29	0.49%
Turbine 2	0.01	0.061	59.84	0.10	0.280	0.000	3.059	0.34	0.56%
Turbine 2	0.01	0.061	59.84	0.12	0.225	0.000	2.9559	0.26	0.44%
Turbine 3	0.01	0.061	59.84	0.07	0.190	0.000	2.2226	0.17	0.28%
Turbine 3	0.01	0.061	59.84	0.10	0.220	0.000	2.3556	0.20	0.34%
Turbine 3	0.01	0.061	59.84	0.12	0.200	0.000	2.3533	0.18	0.29%
Turbine 5	0.01	0.061	59.84	0.07	0.120	0.000	3.1505	0.15	0.25%
Turbine 5	0.01	0.061	59.84	0.10	0.150	0.000	3.0087	0.18	0.30%
Turbine 5	0.01	0.061	59.84	0.12	0.120	0.000	2.8163	0.13	0.22%
Turbine 5	0.01	0.061	59.84	0.15	0.080	0.000	2.8638	0.09	0.15%
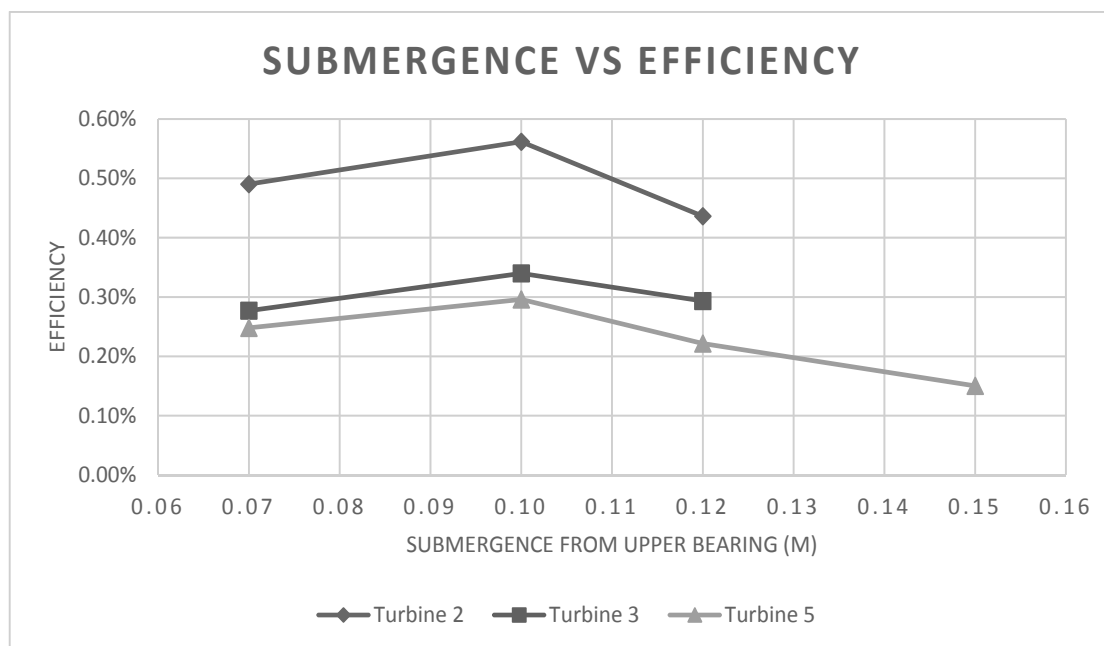
As seen from above table and figure, there is a trend of increasing and then decreasing efficiency as we increase the submergence of the turbine in the basin. Turbine 2 with a solidity of 0.3 and aspect ratio of 1 has the highest efficiency in the submergence of 0.10. This is same as shown from the computational results too. Turbine 3 and turbine 5 are comparable in their efficiencies. Data from our computational studies also shows the increase in solidity in the turbines with Aspect Ratio 1 causes a decrease in efficiency from 3 to 4, which can also be seen from above figure. Also, for a solidty of 0.3, the efficiency was less for AR 1.24 than that of AR 1 which can also be seen from above.

Therefore, the results from the simulations are validated by the experiments too. Thus, as seen from the computational results, we can see that increasing the flow rate will increase the turbine efficiency by a lot. But, as seen from the experiments too, using helical turbines in GWVPP is very inefficient and would result in production of very less power for a considerable amount of investment. Production of the turbines requires fabrication of complex helical blades which prove to be expensive too.

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