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Design Study of Runner for Gravitational Water Vortex Power Plant with Conical Basin

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Abstract

Among the different hydropower system, GWVPP is an emerging concept and showing its future possibility in power production by utilizing low head. It is an ultra-low head turbine which can operate in a low head range of 0.7 to 2 m, which is often seen as too low for conventional hydro turbines, and has a similar yield to conventional hydroelectric turbines. There of number of parameters associated with basin and turbine geometry which affect the efficiency of GWVPP. Altering some parameters among them changes the efficiency of the system. However these research conducted are based on hit and trial method followed by experimentation. No particular analytical calculation has been done. So, this work is intended to optimize the runner of Gravitational Water Vortex Power Plant. Among different parameters affecting torque, power and efficiency two parameters inlet jet angle and radius of curvature of turbine blade are considered for this study. These two parameters are computed from analytical analysis and verified using 3-d simulation.The maximum torque at impact jet angle 18°, radius of curvature 285mm was found to be 0.413 Nm with the deviation of 2.37% between analytical and numerical analysis.

Keywords

GWVPP (Gravitational Water Vortex Power Plant)

1. Introduction

The gravitational water vortex power plant (GWVPP) is an economic and clean energy system allowing for the conversion of the low-head potential energy into kinetic energy to drive power turbines by means of a gravitation vortex pool. In developing countries like Nepal, the development of small and micro hydropower is must to electrify rural and isolated communities. It can operate in a low head range of 0.7 to 2 m, which is often seen as too low for conventional hydro turbines, and has a similar yield to conventional hydroelectric turbines.In addition, there is positive environmental effect on the river as water passing through the turbine is aerated [1].

A majority of runner used in GWVPP turbine is in rectangular shape which converts the kinetic energy of water into electricity. The design is widely celebrated due to its simplistic yet effective approach. Some of the researcher have done experiments to increase the performance of turbine by changing the angle, size and curvature of rectangular runner. However these research conducted are based on hit and trial method followed by experimentation. No particular analytical calculation has been done. Now, this area of development is demanding research in field of runner and its optimization.

Vortices are formed at the intake of hydraulic structures due to a design flaw, where a large amount of water is drained into the intake. This flow into the intake causes a vortex to initiate at the free surface due to the Coriolis force. This vortex gradually intensifies, causes the water rotation to speed up and in turn causes the pressure in the center of the vortex to decrease. This pressure gradually decreases to an extent that ultimately it reduces below the atmospheric pressure and sucks the air into the intake and forms an air core. The radius of the air core gradually reduces while moving from the free surface to the intake [2]. Wanchat studied the effect of basin structure in formation of water vortex stream. This study indicates the important parameters which can determine the water free vortex kinetic energy and vortex configuration and they include the height of water, the orifice diameter, conditions at the inlet and the basin configuration. It was found that a cylindrical tank with an orifice at the bottom center with the incoming flow guided by a plate is the most suitable configuration to create the kinetic energy water vortex [3]. Dhakal, et al have shown that the conical structure of basin is more suited since vortex strength is found to be more that of a cylindrical structured basin [4]. In the same research, the conical basin is optimized for maximum exit velocity of swirling flow. For a given flow and head the different geometrical parameters that can be varied of conical basin for gravitational water vortex power plant are: (i) basin opening, (ii) basin diameter (iii) notch length iv) Canal Height and v) Cone Angle and among these parameters ; among these parameters for a given basin diameter all other parameters had significant contribution for the change in velocity except notch angle [5]. Although the objective of study with Pandit,et.al is different with similar principle , their study also suggests us that the geometry of hydro-cyclones is very sensitive to its hydraulic and particle removal capability [6].Much attention has been paid to the design of the turbine blades in cylindrical basin systems, with the aim of increasing the efficiency of energy conversion. Variations in width, height, shape, curvature and the number of blades have been investigated, but the simple design remains the most common in use and easiest to manufacture. The positioning of the blades in the vortex has also been considered. Dhakal, et al, proposed that the optimum position of runner in the vortex plant is 65% from the top of vortex, since this is the point where maximum velocities can be achieved [4]. Dhakal, et al, also investigated three different runner with straight, twisted and curved blade profile of rectangular blade and conclude that curved blade profile is suitable for GWVPP [7]. The efficiency has been shown to decrease with an increase in the number of blades since they cause 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 [8] . Pongsakorn et al, have shown that 5 baffle plates with propeller area of 50% gave the highest degree of torque. The result showed that the propeller with a 50% baffle plate proportion helped to increase the torque at an average of 10.25% and with an average of overall efficiency of 4.12% [9]. Gautam et al have studied effect of addition of booster runner by adding booster runner at the bottom of the basin which shows the increase in efficiency of the system by around 6% [10].

This research is intended to optimize runner profile for Low Head Gravitational Water Vortex Power Plant using analytical (empirical) method and numerical simulation.

2. Methodology

2.1 1-D calculation

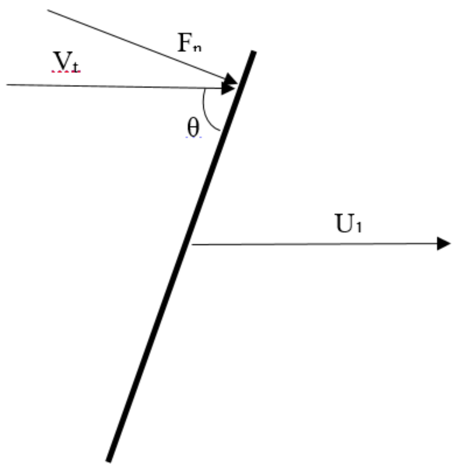

Figure 1: Velocity triangle for 1-Dimensional inclined straight line

The basic formula for the 1-dimensional blade profile is derived using the impulse momentum principle for the water jet and the 1-d blade profile. At the beginning the profile of blade is considered as a straight rectangular for simplicity hence 1-dimensional representation can be done using a straight line. The work done and efficiency are:

$$Workdone = \rho a(V_t - U_1)^2(sin\theta)^2 U_1$$

$$\eta = \frac{2U_1(V_t - U_1)^2(sin\theta)^2}{(V_t)^3} \tag{1}$$

2.2 2-D calculation

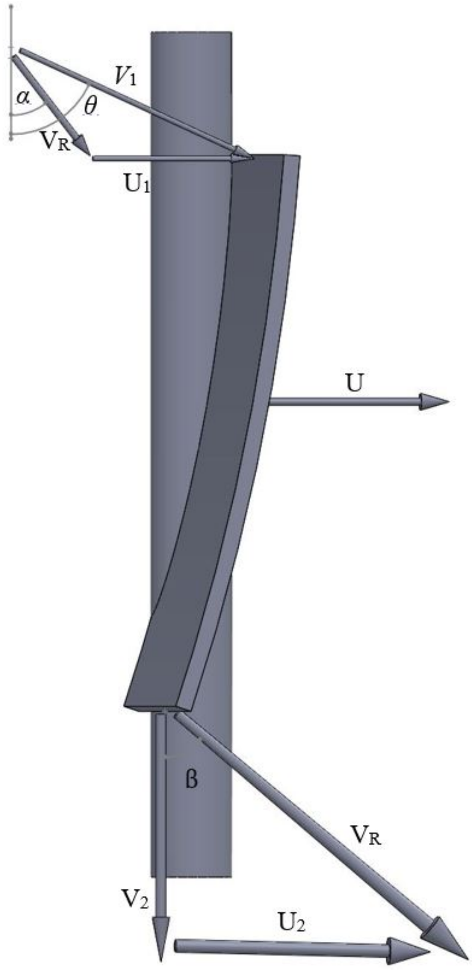

Figure 2: Velocity Triangle for 2-Dimensional analysis

The efficiency for 2-d calculation is:

$$\eta = \frac{2(sin\alpha)}{V_1} \tag{2}$$

2.3 3-D analysis

A model for the analysis was created using SOLIDWORKS as a CAD tool. Following basic dimension were used to construct the geometry for preliminary analysis.

Table 1: Canal Dimension

SN	Parameters	Dimensions
1	Length	800mm
2	Depth	200mm
3	Width	200mm
4	Notch angle	10°
5	Notch angle starts from	200mm

Table 2: Basin Dimension

SN	Parameters	Dimension
1	Diameter	400mm
2	Outlet diameter	40mm
3	Total Height	610mm
4	Conical Height	410mm

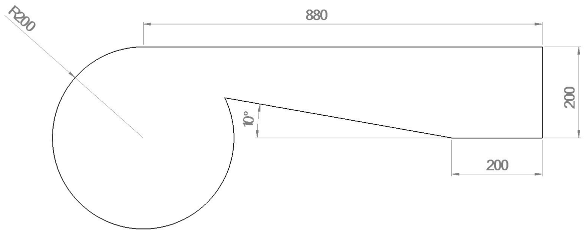

Figure 3: Top view of basin

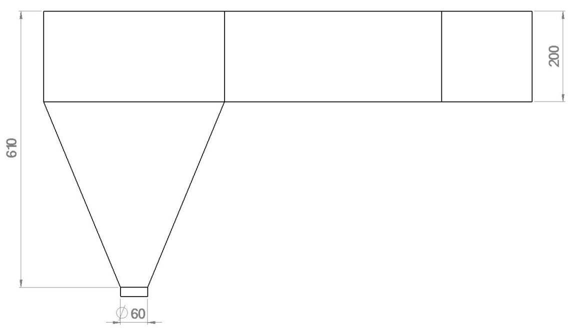

Figure 4: Front view of basin

Table 3: Turbine parameters Dimensions

SN	Parameters	Dimensions
1	Diameter of Turbine	250mm
2	Height of Blade	210mm
3	Inlet angle of jet	17°
4	Radius of curvature	285

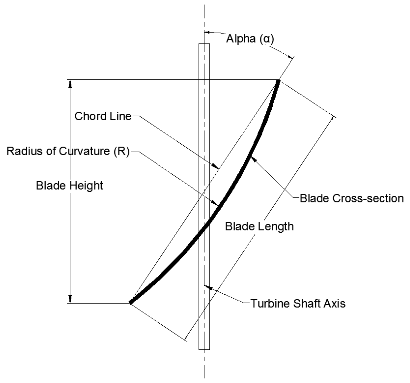

Figure 5: Nomenclature of turbine

2.3.1 Mesh Independent Test

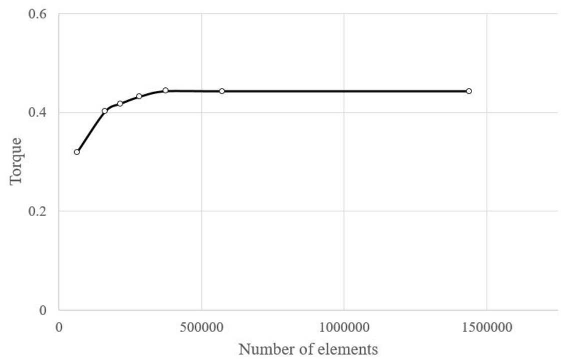

Figure 6: Mesh Independent Test

7 iterations with different number of mesh elements for same turbine was done. It was found that upto 283230 number of elements the value of torque was varied and after that it was found nearly same. So the simulation was done with mesh element 374226.

2.3.2 Physics Setup

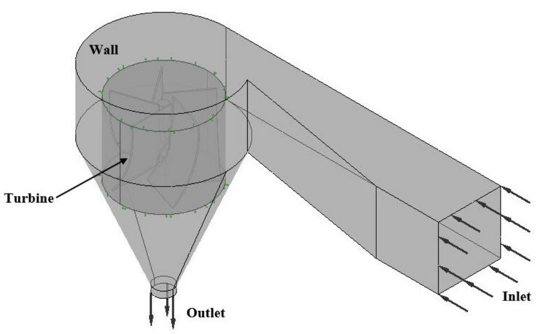

Figure 7: Solid Domain for Test rig

Table 4: Turbine parameters Dimensions

SN	Name	Boundary condition	Boundary value
1	Inlet	Speed	0.25 m/s
2	Outlet	Avg. static Pressure	0 Pa
3	Wall	No slip wall	Smooth wall
4	Turbine	No Slip Wall	Smooth wall

3. Results and Discussion

3.1 1-Dimensional Results and analysis

As per as the methodology the first step of the research was to calculate the 1-Dimensional power output and efficiency of the turbine. The plot for different cases were plotted to see the trend and relation between different parameters.

3.1.1 Outer Radius Vs Power

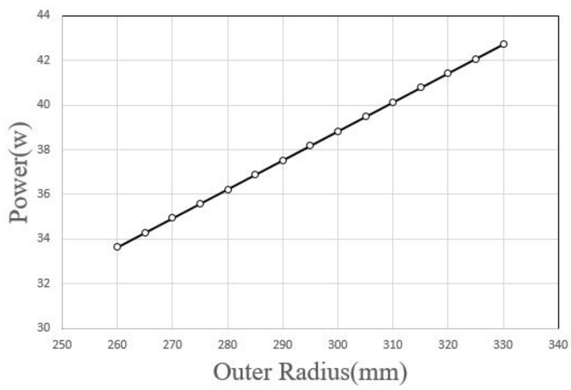

Figure 8: Outer radius vs Power

Graph shows relation between the outer diameter of the turbine and power output. As shown in graph the power output increases as the diameter of the turbine increases. The obtained linear relation between power and outer radius is due to the fact that 1-dimensional analysis does not consider the mass of the turbine and opposite reaction of water which decreases the power when outer diameter of turbine is increased considerably.

3.1.2 Angular Velocity Vs Power

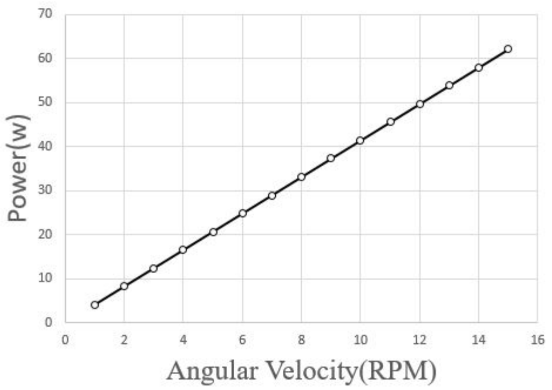

Figure 9: Angular velocity vs Power

Figure shows relation between Angular Velocity Vs Power. As seen in the figure the obtained power increases as the angular speed of the runner increases. Same as in the outer diameter vs power curve it has linear relationship between power and angular velocity. It does not consider the fact that power drop after certain rise in angular velocity due to high friction and opposite reaction of water flow.

3.1.3 Jet angle Vs Efficiency

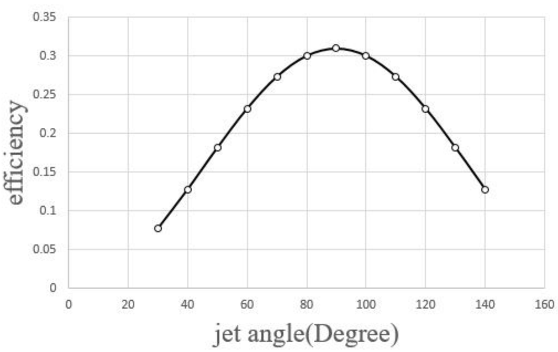

Figure 10: Jet angle vs Efficiency

Figure shows the graph between the jet angle Vs Efficiency of the turbine. Efficiency of the turbine increases when the angle of impact of jet with turbine increases and decreases after a certain value. The efficiency is maximum when jet impacts with turbine perpendicularly. So the turbine should be placed in such angle that it impacts with jet perpendicularly so that maximum efficiency can be obtained.

3.1.4 Turbine speed vs Efficiency

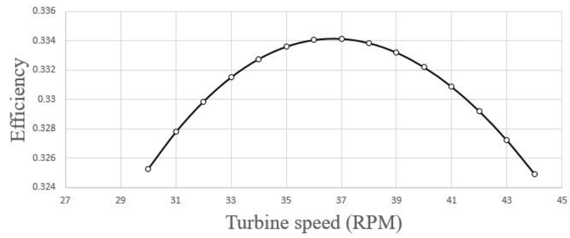

Figure 11: Turbine speed Vs Efficiency

Figure shows the graph between turbine speed and efficiency for a designed diameter of the turbine. As shown in the figure efficiency increases as the turbine speed increases and decreases after a certain value. The decrease in efficiency after certain speed is due to the fact that for a certain diameter of a turbine the maximum turbine speed is fixed and after that speed, efficiency decreases considerably.

3.2 2-Dimensional Results and analysis

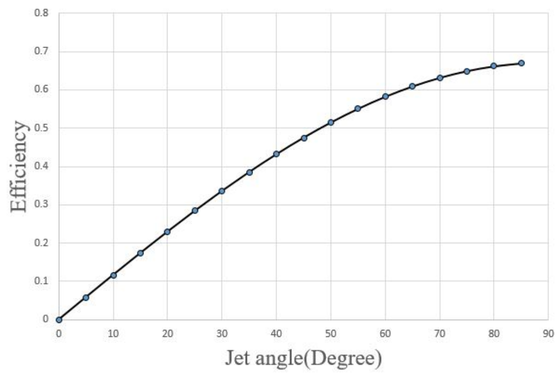

Figure 12: Jet angle Vs Efficiency

Figure shows the graph between Jet angle and efficiency of the turbine. As the angle of jet increases, efficiency of the turbine also increases. For the maximum efficiency of the turbine the jet should strike turbine blade perpendicularly. So the study will focus on to achieve the required angle to maximize efficiency of the turbine.

3.3 3-Dimensional Results and analysis

To obtain maximum efficiency from a turbine, jet must impact the turbine blade at an angle of 90°. This angle can be obtained when the incident angle $\alpha = 17°$. So number of simulation was done to test the validity and to find the best radius of curvature of turbine blade.

3.3.1 For Inlet jet angle $\alpha = 15°$

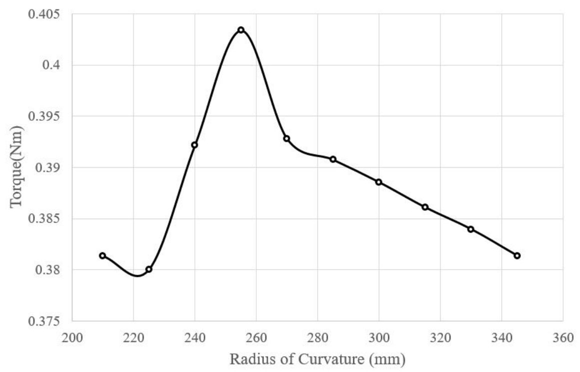

Figure 13: Torque Vs Radius of Curvature of inlet jet angle 15°

Figure shows the graph between Torque and Radius of curvature of turbine. At low radius of curvature the torque obtained is low, increases at increasing radius of curvature and decreases after certain value. In case of 15° inlet jet angle the maximum torque is obtained at around radius of curvature 260 mm.

3.3.2 For Inlet jet angle $\alpha = 16°$

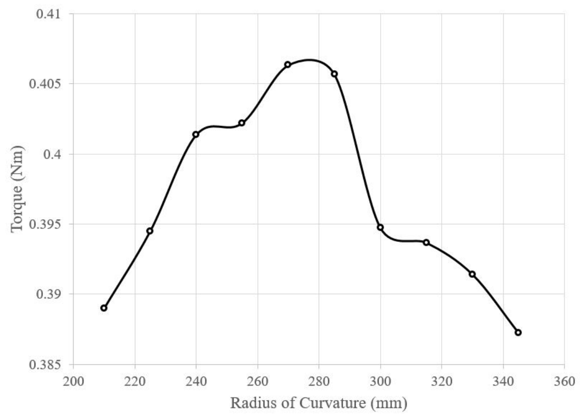

Figure 14: Torque Vs Radius of Curvature of inlet jet angle 16°

Figure shows the plot of torque vs radius of curvature for inlet jet angle 16°. At low radius of curvature the torque obtained is low, increases at increasing radius of curvature and decreases after certain value. In case of 16° the maximum torque is obtained around radius of curvature 280mm.

3.3.3 For Inlet jet angle $\alpha = 17°$

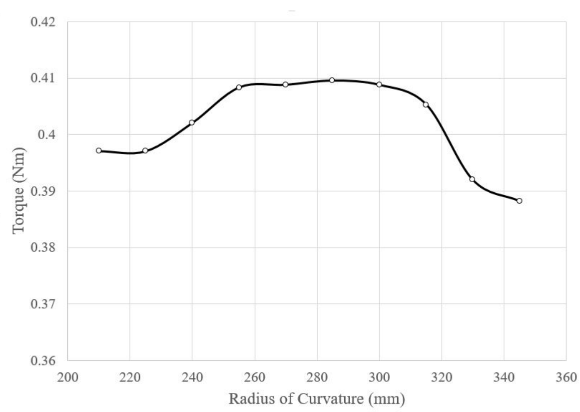

Figure 15: Torque Vs Radius of Curvature of inlet jet angle C

Figure shows the plot of torque vs radius of curvature for inlet jet angle 17°. There is no significant difference in torque in the given compared area. So in case of 17° there is large range of radius of curvature to get maximum torque.

3.3.4 For Inlet jet angle $\alpha = 18°$

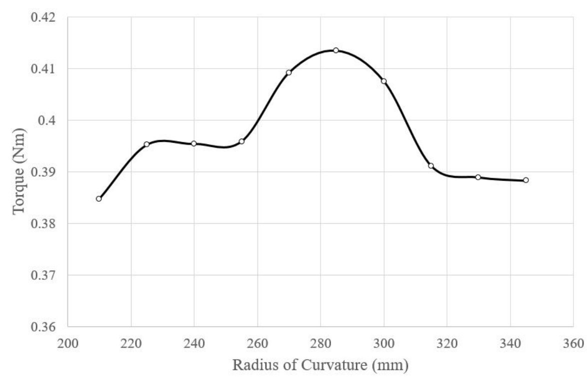

Figure 16: Torque Vs Radius of Curvature of inlet jet angle18°

Figure shows the plot of torque vs radius of curvature for inlet jet angle 18°. There is no significant difference in torque in the certain compared area . So in case of 18° there is large range of radius of curvature to get maximum torque.

3.3.5 For Inlet jet angle $\alpha = 19°$

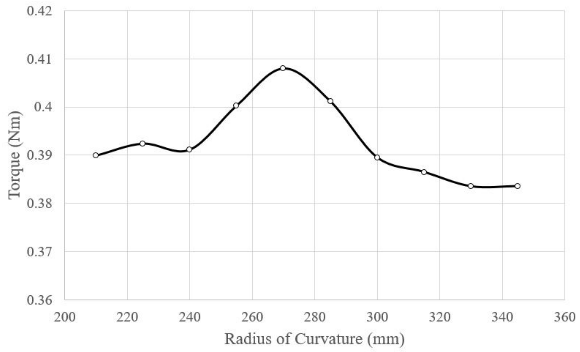

Figure 17: Torque Vs Radius of Curvature of inlet jet angle 19°

Figure shows the plot of torque vs radius of curvature for inlet jet angle 19°. At low radius of curvature the torque obtained is low, increases at increasing radius of curvature and decreases after certain value. In case of 19° the maximum torque is obtained around radius of curvature 250mm.

4. Conclusion

Different parameters associated with basin and turbine can be changed to increase the torque of the GWVPP. So, in this study inlet angle of attack α and radius of curvature R is changed and computed using analytical and Numerical simulation. This study has determined the range up to which each parameter can be varied keeping all other parameters constant so that torque obtained can be maximized. The maximum torque is obtained at an angle 18° and around radius of curvature 285mm.

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