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Performance Analysis of Booster based Gravitational Water Vortex Power Plant

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Abstract:
Gravitational Water Vortex Power Plant (GWVPP) is a power generation system that suits for ultralow head streams of water with low flow rate. Due to the simple design, compact structure, and the possibility of local fabrication, it can benefit rural areas for off-grid supply. The purpose of this research is to study the potential of booster based GWVPP. Previous researches concluded the best position of turbine in GWVPP is actually not the maximum head position which eventually does not extract all possible head. This research explores the possibility of adding an extra runner (booster runner) below the main runner in the existing set up for additional power generation. The performance of the booster runner, modelled in CATIA V5R21 was studied computationally using ANSYS 18.1 FLUENT for various boosters with varieties of number of blades, blade inclination angle, height of booster, rotational speed and the blade profile so as to obtain the most suitable design of the booster runner, which was then verified experimentally in a model set up using four different booster runners. The research showed an increase of 3.84W in the miniaturized model which corresponds to the increase in efficiency of 20.4% from a total of 63.55% by main runner alone. This implies that the power generation can be increased by the addition of the booster runner in the existing set up.

Keywords: Gravitational Water Vortex Power Plant, Booster Runner, Main Runner, Blade Inclination Angle, Height of Booster, Rotational Speed, Blade Profile, Power

1 Introduction

Around 1.2 billion people in the world lack the access to electricity and 85% of those people are from rural areas [1,2]. Those people in those regions are still waiting for expansion of national grid so that they can use electricity for their everyday operations. In this context, low head turbines provide an effective alternative which can run off grid without consuming much resources and with no imparting bad effects on environment.

In countries like Nepal, these low head power plant possesses even more significance due to geographical structure and isolated communities. Low head power plant is in most cases run-off river without any dam and one of the most cost-effective renewable energy technologies for rural electrification. These types of turbines can extract the energy of water at very low head condition to electrified isolated small villages and communities without needing the connection to the national grid. Therefore, various low head power plants being developed. Among those low head power plant, Gravitational Water Vortex Power Plant is a promising one due to the fact that it can utilize very low head of water, environment friendly and doesn't need heavy constructions for operations.

1.1 Gravitational Water Vortex Power Plant

Gravitational water vortex turbine is an ultra-low head turbine which can operate in as low head as 0.7m with similar yield as conventional hydroelectric turbines used for production of renewable energy characterized with positive environmental yield [3]. It was invented by an Austrian Engineer, Franz Zotlöterer. In this power plant water enters tangentially into the basin through the channel and due to its inertia and gravitational pull, it forms a powerful vortex, where its potential energy is converted into kinetic energy. A runner is placed at the center core of the vortex which is rotated by rotational kinetic energy of the vortex when water strikes with runner blades. The water is passed out through the outlet at the bottom of the basin.

There are have been a number of researches on GWVPP for the optimization of basin structure, runner, inlet and outlet configurations. Wanchat et al [4,5] indicate the important parameters which can determine the water free vortex energy and vortex configuration are height of water

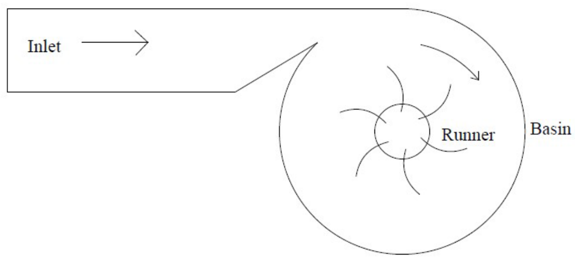

Figure 1: Working of a GWVPP

in canal, the orifice diameter, the condition of inlet and basin configuration. They proposed a cylindrical tank with the incoming flow guided by a plate as a suitable configuration to create the kinetic energy water vortex and an orifice at the bottom center as the optimum design. A research has found that the vortex formed inside round basin is proportional with the rotational speed without the presence of turbine in the system but, when the turbine is installed then the vortex height changes significantly along with the efficiency [6]. Mulligan et al [7] suggested that optimum vortex strength occurs within the range of orifice diameter to tank diameter ratios (d/D) of 14–18% to maximize the output power for cylindrical basin. Wanchat et al [4] concluded that the cylindrical basin with inlet guide has the best flow fluid among cylindrical basin with central outlet, rectangular basin with pre-rotation and cylindrical basin with inlet guide.

A team from Pulchowk Campus, Dhakal et al [8] compared the strength between the vortex formed with conical and cylindrical basins which showed that vortex formation was aided by conical basin. Use of conical basin created a significant increase in vortex strength due to which increases in efficiency of power plant. Dhakal et al [9,10] suggested that notch inlet width to be as small as possible and cone height to be as high as possible to maximize the performance of conical basin. Dhakal et al [8] found that as the number of blades of turbine increased from six to twelve, the efficiency of the GWVPP reduced and maximum efficiency obtained with five blades. The outlet is usually at the center of basin and this outlet diameter has considerable effect on vortex strength as well as efficiency of vortex turbine [11]. A study was carried out to find better design of runner for GWVPP with conical basin where 22 different runners were designed and found the model 21 to be optimum which had five number of blades with concave blade profile [12]. Dhakal et al [1] performed analysis for three different runner blade profiles showed that a curved blade profile is most suitable for the GWVPP with blade inclination angle 19° with hub.

1.1.1 Booster Runner

Booster runner is an additional runner in series with main runner near to the exit hole to extract the additional power. Booster runner is smaller than the main runner to account for the decreasing cross section of the basin. Dhakal et al [13] showed that the position for maximum efficiency of impulse based runner is not at the bottom of the basin but somewhere in between top open channel and the exit drain. This suggested that water current possesses significant amount of energy even after energy extraction by main runner. Gautam et al [14] studied the effect of adding booster runner in conical basin of GWVPP along with a numerical and experimental approach concluding that addition of booster runner increases significance amount of power, which increases efficiency from 76.03% to 78.85%.

1.2 Computational Fluid Dynamics

To simulate a flow problem, it have to use mathematical physical and programming tools to solve the problem then data is generated and analyzed. Fluid (gas and liquid) flows are governed by partial differential equations which represent conservation laws for the mass, momentum, and energy. Computational Fluid Dynamics (CFD) is the art of replacing such Partial Differential Equation systems by a set of algebraic equations which can be solved using digital computers.

All CFD packages contain 3 main elements: (i) a pre-processor, (ii) a solver and (iii) a post processor [15].

The continuity and Navier-Stokes equation in cylindrical coordinates are described below:

$$\frac{\partial V_r}{\partial r}+\frac{\partial V_z}{\partial z}+\frac{V_r}{r}=0$$

$$\mathrm{V_r}\frac{\partial \mathrm{V_\theta}}{\partial \mathrm{r}}+\mathrm{V_z}\frac{\partial \mathrm{V_\theta}}{\partial \mathrm{z}}-\frac{\mathrm{V_r V_\theta}}{\mathrm{r}}=\mathrm{v}\left(\frac{\partial^2 \mathrm{V_\theta}}{\partial \mathrm{r}^2}+\mathrm{V_z}\frac{\partial \mathrm{V_\theta}}{\mathrm{r}\partial \mathrm{r}}-\frac{\mathrm{V_\theta}}{\mathrm{r}^2}+\frac{\partial^2 \mathrm{V_\theta}}{\partial \mathrm{z}^2}\right)$$

$$\mathrm{V_r}\frac{\partial \mathrm{V_r}}{\partial \mathrm{r}}+\mathrm{V_z}\frac{\mathrm{V_r}}{\partial \mathrm{z}}-\frac{\mathrm{V\theta}^2}{\mathrm{r}}+\frac{\partial \rho}{\rho \partial \mathrm{r}}=\mathrm{v}\left(\frac{\partial^2 \mathrm{V_r}}{\partial \mathrm{r}^2}+\frac{\partial \mathrm{V_r}}{\mathrm{r}\partial \mathrm{r}}-\frac{\mathrm{V_r}}{\mathrm{r}^2}+\frac{\partial^2 \mathrm{V_r}}{\partial \mathrm{z}^2}\right)$$

$$\frac{V_r\,\partial \mathrm{V_z}}{\partial \mathrm{r}}+\frac{V_z\,\partial \mathrm{V_z}}{\partial \mathrm{z}}+\frac{\partial \rho}{\rho\,\partial \mathrm{z}}=\mathrm{v}\left(\frac{\partial^2 V_z}{\partial \mathrm{r}^2}+\frac{\partial \mathrm{V_z}}{r\,\partial \mathrm{r}}+\frac{\partial^2 V_r}{\partial \mathrm{z}^2}\right)$$

Where, V_θ, V_r and V_z are tangential, radial and axial velocity components respectively, ρ is fluid density, g is gravitational acceleration and ν is kinematic viscosity. Due to the complexity of the equations, it's extremely difficult to get an analytical solution directly [16].

2 Booster Runner Design

As the flow is distorted due to main runner, the flow conditions for booster runner is not same as that for main runner. Tangential velocity of water decreases and inlet tip angle becomes high due to which the impact angle of the booster runner blade needs to be higher. Some clearance has to be provided between the main runner and booster runner for the water to gain swirl. Thus, there're various parameters considered during the design of the booster runner in order to extract the maximum power. It includes number of blades, blade inclination angle with the hub axis, rotational speed, blade profile, height of blade, inlet and outlet tip angle of the blade. During analysis of booster runner, the dimension of the main runner, basin, canal, shaft, and hub were taken constant.

2.1 Design parameter analysis

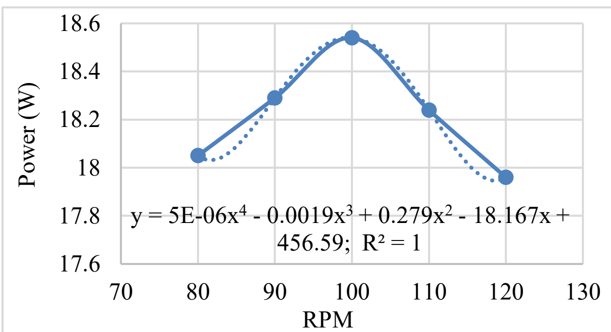

Figure 2: Output power vs rotating speed (RPM)

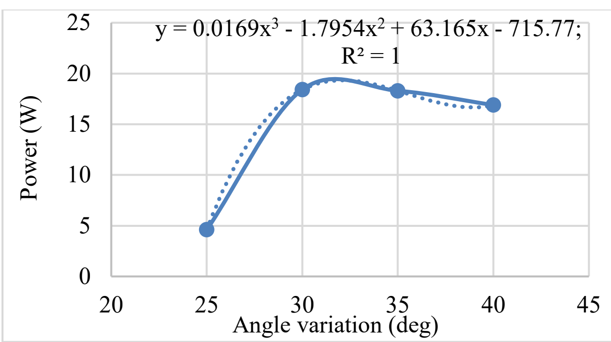

Figure 3: Output power vs blade inclination angle

The power output was found to be varying with rotational speed. At around the speed of 100 rpm, power output was maximum as evident in the Figure 2. Any speed more than or less than this was marked by decrease in output power. Output power was found to be increasing with increase in inclination angle till just above 32 degrees. Beyond that, output power decreased with increase in angle of attack. Number of blades contribute to both, contact surface area for water and the overall mass of the runner. In addition to 3these, increase in number of blades would also mean increase in interference between incoming and deflected currents of water. Output power was found to be increasing with increase in number of blades till 5 and beyond 5, it decreased with increase in number of blades.

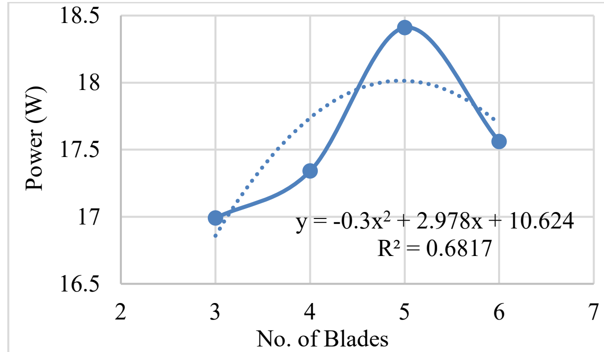

Figure 4: Output power vs number of blades

2.2 Theoretical Design of Booster runner

For Preliminary design

Let, Outer Radius (r_1) =0.07 m

Inner Radius (r_2) =0.02m

From Streamlines Visualization,

β_1=35° (Approx.),

β_2=90° (Assume that no outlet whirl velocity)

Velocity at booster height, V_1 =1.8 m/s (Approx.)

From velocity triangle analysis,

$V_{w1}=V_1 * \cos\beta_1$=1.47 m/s

$V_{f1}=V_1 * \sin\beta_1$=1.03 m/s

$U_1=\omega * r_1$=0.8 m/s

$\alpha_1= \tan^{-1}\{V_{f1}/(V_{w1}-U_1)\}$ =56.95°

(Chosen 55 degree for fabrication)

As it difficult to fabricate the unsymmetrical types of runner profile due to small in size, tip angle at both inlet and outlet are assumed to be same. ($\alpha_1 = \alpha_2$).

3 Numerical Model Development

The purpose of the computational study was to determine torque develop by the different runners in different rotational speed, blade inclination angle, angle of impact and number of blades. Main runner, booster runners and test rig were modelled in 3D CAD software, CATIA V5R21. Computational study was performed in ANSYS 18.1 FLUENT and experimental verification was performed in a miniaturized test bench model. The model was divided into 5 domains to provide different mesh size at runner zone, booster zone, mid-section between runner and booster zone, inlet (canal) zone and outlet zone as shown in figure 6. The metrics like aspect ratio, element quality, skewness, orthogonal quality, etc. were continuously monitored to keep those within the permissible value which would give better mesh and thus a better solution.

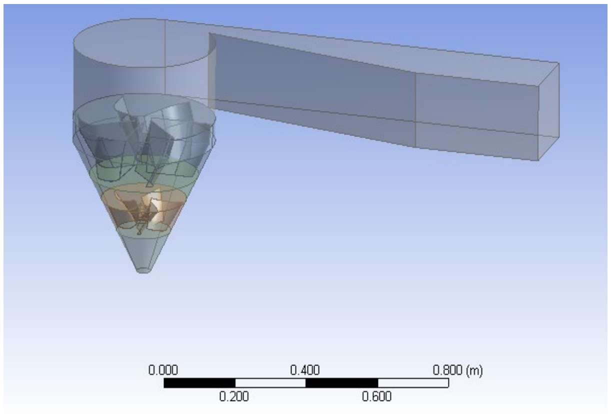

Figure 5: Design modeling of runner and booster

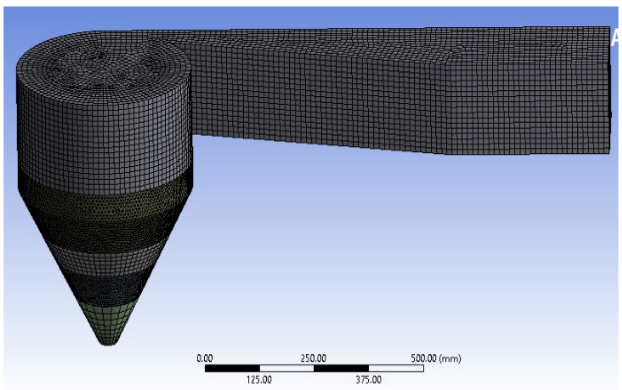

Figure 6: Meshed basin geometry

Based on the concept of single rotating frame motion, angular velocity was provided same for both main runner domain and booster runner domain keeping the main runner and booster runner fixed. The governing equations are discretized by the finite volume method using the commercial CFD package ANSYS 18.1 FLUENT. Discretized equation was solved on steady state pressure based segregated solver with double precision and the implicit scheme conditions. The SIMPLE scheme with Green Gauss Cell Based and second order upwind were used for pressure, momentum, turbulent kinetic energy and specific dissipation rate. Viscous model k-omega SST model with curvature correction used for pressure-based condition.

Streamlines were observed to find out the angle of strike of water on the blades of turbines. Figure 7 shows the streamline flow of water in the stationary domain after adding runner. The streamlines were found to deviate significantly after striking on the runner blades. The flow was mainly axial with lesser vortex strength and this assisted the design of booster runner.

Table 1: Mesh properties

SN	Mesh Metrics	Min.	Max.	Avg.	S.D.
1	Aspect Ratio	1.0021	17.194	1.8148	0.7033
2	Element Quality	7.8903e-002	1	0.8321	0.1463
3	Orthogonal Quality	5.3586e-002	1	0.8560	0.1451
4	Skewness	1.3057e-010	0.9464	0.1743	0.1409

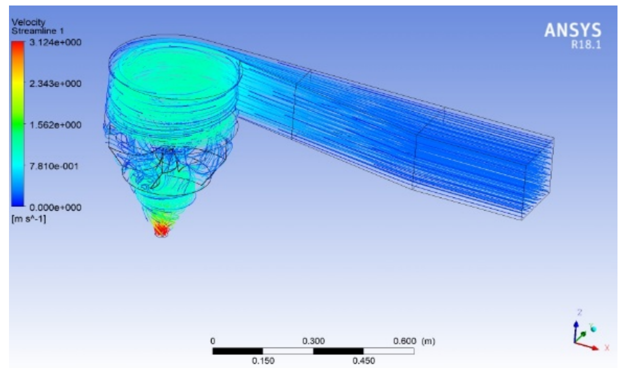

Figure 7: Streamline visualization (Velocity contour)

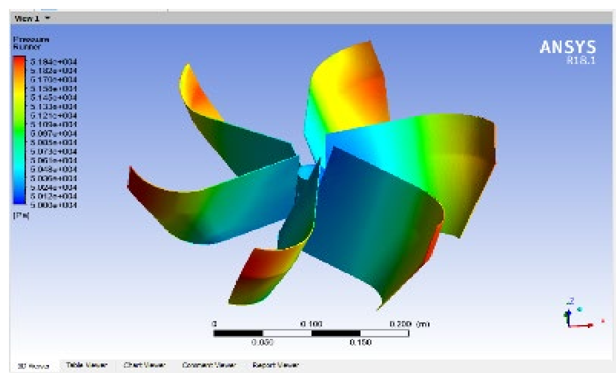

Figure 8: Pressure contour of main runner

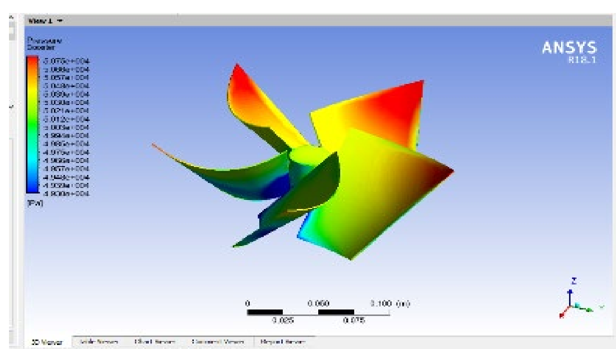

Figure 9: Pressure contour (Booster runner)

As evidenced by the pressure contour of both main runner and booster runner, pressure is maximum at the outer region of the blades as shown in figure 8 and figure 9. It is due to the fact that velocity of water stream increases with increase in distance from central axis i.e. velocity is higher near the wall of basin. This high velocity is responsible for higher pressure on the outer region of both main runner blades and booster runner blades.

4 Experimental Setup

Figure 10: Experimental test bench

Figure 11: Fabricated main runner

The test rig consists of a basin with upper cylindrical part of diameter 400mm and lower conical section of cone angle of 28^0 and total height of 0.6m. Canal height is 200mm, notch angle of 11^0. Runners are assembled with the shaft having diameter of 20 mm, coupled with a pulley and supported by bearings. For the measurement of torque, a brake drum dynamo-meter was fabricated and used. A digital tachometer is used for measurement of the rotational speed of shaft. The test rig that was used for experimental testing is shown in figure 10.

Main runner consists of 6 blades while each booster runner had 5 blades. Main runner was placed above booster runner at the optimum position.

Model 1

Model 2

Model 3

Model 4

Figure 12: Fabricated booster runners

Figure 13: Main runner and booster runner assembly

The top view of a main runner and four booster runners are shown in figure 11 and figure 12, respectively. The booster runner is combined with main runner just below the optimum position of main runner suggested by previous researchers as shown in figure 13. Certain space is maintained between main runner and booster runner so that water flow can regain some of vortex energy as it is distorted after interaction with main runner blades.

The whole test rig set up was fixed to the ground so as to provide firm support and prevent from vibration during operation.

5 Results and Discussion

The computational and experimental results corresponding to the power outputs obtained for main runner alone and after addition of each of the booster runners with the main runner are as shown in figure 14. A total of four models of booster runners were tested successively and the corresponding power outputs were noted.

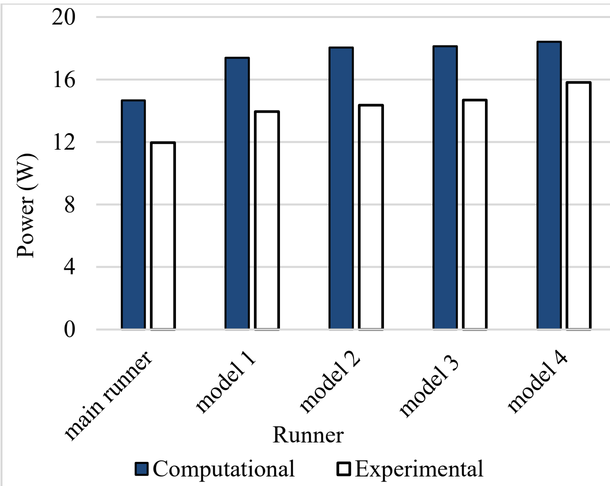

Figure 14: Computational and experimental data comparison

When operated without booster runner, output power was found to be 14.66 W and 11.96 W in computational and experimental analysis respectively which corresponds to the efficiency of 77.91% computationally and 63.55% experimentally. On addition of booster runner, output power was found to be greater for each model of runner for both computational and experimental analysis. However, the increase in power was found to be maximum for model 4 (symmetrically curve blade), from 14.66 W to 18.41 W computationally and from 11.96 W to 15.81 W experimentally and least for model 1 (Straight blade), from 14.66 W to 17.39 W computationally and from 11.96 W to 13.95 W experimentally. This Both computational results and experimental results were found to be in agreement with this result. The deviations between computational and experimental results were found to be constant. The reasons for the deviations could be vibration, friction and various kinds of other losses which couldn't be taken into account for computational analysis.

6 Conclusion

In this research, the potential of maximum energy extraction from Gravitational Water Vortex Power Plant by adding an extra runner i.e. booster runner just below the main runner was studied. Various parameters like number of blades, blade inclination angle with hub axis, height of booster, rotational speed and the blade profile were varied and analyzed in order to obtain the most suitable design of the booster runner. The computational and experimental results verified that the output power and efficiency of the system increases considerably by addition of booster runner to the main runner for all similar inlet conditions. In total, four booster runner models were tested and model 4 was found to be the best model with the increase of 3.84W in the miniaturized model which corresponds to the increase of 20.4% more than that of a single main runner. Although, there was considerable difference between computational analysis and experimental testing results, it was in acceptable range and was mainly attributed to leakage and mechanical losses.

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