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Study on Effect of Adding Booster Runner in Conical Basin: Gravitational Water Vortex Power Plant: A Numerical and Experimental Approach

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Abstract

Gravitational water vortex power plant is an ultra-low head hydropower technology, in which a free formed – free surface water vortex rotates a prime mover thereby generating electricity. Previous researchers concluded that gravitational water vortex power plant with conical basin is superior to conventional cylindrical type basin with regards to power production. In this study, we present effect of adding an additional runner, booster runner lower in position from the main runner coupled in the same shaft, aimed at increasing the power output. Three different booster runners have been designed considering different parameter of the runner design like inlet and outlet blade angle, impact angle, the number of blades, the height of runner, taper angle, bottom outlet diameter and number of blade tested by numerical modeling followed experimental verification. For numerical modeling, flow domain is modeled in 3D CAD software, CATIA followed by domain discretization and solution in ANSYS. The solution procedure is based on 3-D steady state simulations. Individual and coupled performance of runner(s) has been done and finally compared. At optimum condition, an increase in 6% in the efficiency can be obtained from the use of booster runner.

Keywords

Gravitational Water Vortex Power Plant (GWVPP) – water vortex – runner – booster runner – flow domain

1. Introduction

Anthropogenic climate change presents a serious threat to the health, prosperity, and stability of human communities, to the stability and existence of non-human species and ecosystems, and to international political and military stability [1]. The present world consumption pattern shows fossil fuel is the major source of energy in the world [2]. Due to the negative effects of fossil fuel and carbon emission, people are being led to the use of renewable and pollution free source of energy. The quest for clean, economic and environmentally friendly source of energy has concluded low head turbines provide electricity to the off-grid remote and isolated region without affecting the environment around it. Hydropower technology being renewable and pollution free source of energy is developing rapidly and contribute 2.2% of global energy consumption [2].

In developing countries like Nepal, the development of small and micro hydropower is must to electrify rural and isolated communities. In fact, it is one of the most prospective renewable energy sources that have received considerable attention because of its potential to generate green energy ranging from 1 kW to 500 kW but the development of this kind of energy is very low due to comparatively higher civil works cost per unit power production. The micro hydro project in the hilly regions have enough head to generate power but water at places with the low head such as the Terai region of our country is being wasted due to lack of proper technology to tap the energy [3].

Among the different hydropower system, GWVPP is an emerging concept and showing its future possibility in power production by utilizing low head. It was invented by an Austrian Engineer, Franz Zotlöterer. This type of plant requires very small head and very less civil structures. Not only does this power plant produce a useful output of electricity, it also aerates the water in a gentle way. [4] The water passes through a straight inlet into a round basin tangentially which then forms a vortex [5]. An impeller placed coaxially with the so formed vortex extracts the water power due to dynamic force of the vortex [4].

The basin geometry depends on the discharge supplied. Under sufficient flow condition, vortex minimum diameter is at the bottom level and is always smaller than the exit hole [6]. The important parameters which can determine the water free vortex kinetic energy and vortex configuration 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 [7, 8]. Wanchat et al [9] investigated parameters which affect the velocity vector field for GWVPP which include outlet diameter at the bottom center of the basin, gravitational vortex head and flow rate.

Optimum vortex strength occurs within the range of orifice diameter to tank diameter ratios (d/D) of 14–18% for low and high head sites, respectively. Thus, for a cylindrical basin, to maximize the power output, the range of orifice diameter to basin diameter ratios lies within 14–18% [10]. The different geometrical parameters that can be varied of conical basin are: (i) basin opening (ii) basin diameter (iii) notch length (iv) Canal Height and (v) Cone Angle. Among these parameters for a given basin diameter, all other parameters have significant contribution to the change in velocity except notch angle [11]. Kueh et al also tried to investigate conditions of formation of water vortex using Xflow, a commercialize CFD code based on Lagrangian approach [12].

Experimental tests have been carried out to compare the performance of the system with the conical basin with that of the system with cylindrical basin. Due to the increase in the value of velocity head with the increase in depth and greater vortex strength, turbine efficiency was greater in the conical basin compared to the cylindrical basin[13, 6]. Dhakal et al [14] 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. In the same research, the conical basin is optimized for maximum exit velocity of swirling flow. Sapkota et al [15] have shown 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.

The Reynolds Stress Model is the most suitable amongst those tested for analyzing strong air-core water vortices in a multiphase flow model because the model accounts for streamline curvature and anisotropic turbulence. Although the Shear Stress Transport k-ω model with curvature correction offers an improved solution over the standard Shear Stress Transport k-ω model, the Reynolds Stress approach still renders better accuracies. Mesh sensitivity analysis indicated that an unstructured mesh is unsuitable for vortex flow due to excessive numerical (false) diffusion and a finely structured radial grid is required [16].

So, in order to harness the energy from the fast swirling exit water, a runner has been designed and tested to know the performance characteristics. The runners were tested alone and combined with other runner is cascade form. The runners used near the exit hole had low efficiency of their own but increased(boosted) the power output when combined with main runners. Thus the name '**BOOSTER**' runner.

2. Concept of Booster Runner

The runners are designed on the basis of impulse turbine like cross flow. The water entering from the notch of the canal flow around the basin and drop to the certain height. This potential energy is converted to the kinetic energy as water swirls around an empty core of decreasing radius. If there is more height for fall of water, then there is high kinetic energy. The runner is placed concentric to the basin and empty core then the water strikes the runner.

In a turbine, when water jet travels from the inlet to outlet of the blade, the outlet velocity, and direction of water jet changes from that of the inlet. The change in velocity and direction changes the momentum of the water jet, and this change in momentum is absorbed by the main runner to rotate. After that water again fall

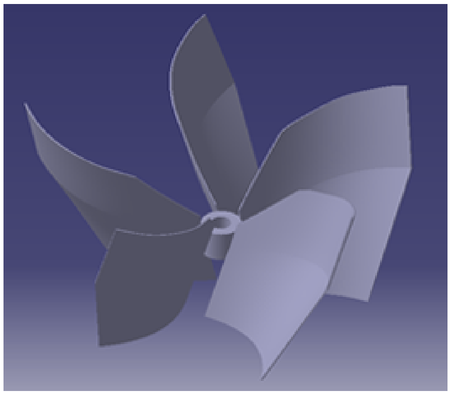

Figure 1: Booster Runner Model

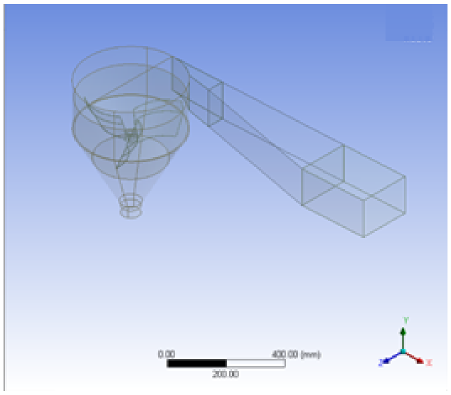

Figure 2: Basin Model

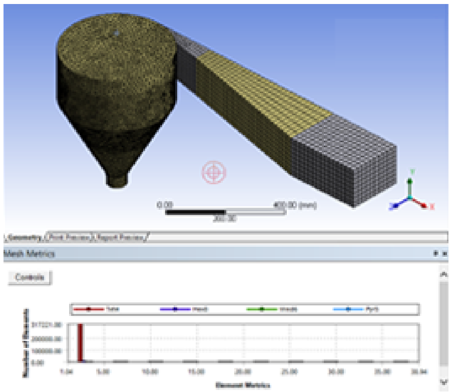

Figure 3: Meshing of Flow Domain

to a certain height and this energy is again absorbed by booster runner. There is a certain gap between the main runner and booster runner so that water can swirl in the gap.

There are different parameters considered during the design of the main runner in order to extract the maximum power from the water in a conical basin. The impact angle, the height of the blade, the taper angle of the blade, inlet and outlet blade angle in both horizontal and vertical plane, top and bottom cut portion, the number of blades of runner and bottom outer diameter was taken into consideration in order to transfer the impulse force from water to runner.

As the main runner disturbs the vortex motion of the water, the tangential velocity of water decreases and vertical velocity becomes high due to which the impact angle of the booster runner blade becomes high. The outer diameter of the runner was adjusted to that the inner diameter of the conical basin at the designed position of the booster runner. The profile and the number of blades of the booster runner ware designed by considering the positive effect on extraction of energy and the negative impact of the drag loss associated with it. During the process of analysis, the dimension of the basin, canal, shaft, and hub were taken constant.

3. Numerical Model Development

The purpose of the simulation is to determine the torque developed by the runner in the given setup at a given flow rate and angular velocity. This helps us to calculate power produced by the runner which in turn helps us in determining the efficiency. For the purpose of simulation, the different runners designed and the fluid flow domain was modeled as shown in figure 1 and 2 respectively using 3D CAD software, CATIA.

The modeling and meshing of the proposed model is done using ICEM CFD for FLUENT analysis. The model was divided into 5 different parts to provide different mesh size and different cell zone conditions as per the requirement. The metrics like aspect ratio, orthogonal quality, etc. were continuously monitored to achieve better mesh and thus a better solution. After assigning necessary boundary conditions, the solution procedure involved assigning water as the fluid in all the domain (single phase modeling). Based on the concept of single rotating frame motion, various angular velocity was input for multiple results.

The governing equations are discretized by the finite volume method (FVM) using the commercial CFD package ANSYS FLUENT 16.2. To solve the discretized equation, steady state pressure based segregated solver with double precision and the implicit scheme was used. The second order method is used for the interpolation of field variables, Green-Gauss Cell-Based for interpolation of solution variables and Standard scheme for interpolation of cell-face pressure. The SIMPLE method was used to solve the pressure-velocity coupled equations.

For mesh independent solution (grid convergence), the solution becomes independent of the number of divisions of the fluid domain. The grid convergence graph for simulation of the conical basin is shown in figure 4. As per the grid convergence analysis, the number of nodes for all the consecutive analysis was set to be around

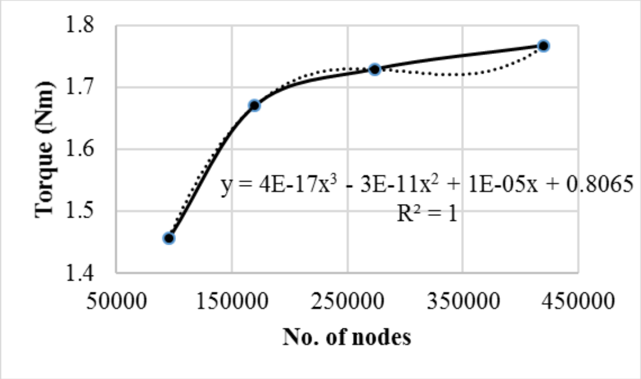

Figure 4: Grid Convergence Criteria for Torque Analysis

300000. The initial velocity was set to 0.25m/s which was determined using the current meter.

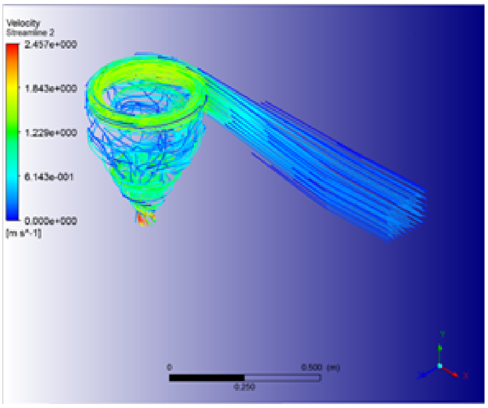

Figure 5: Velocity Contour

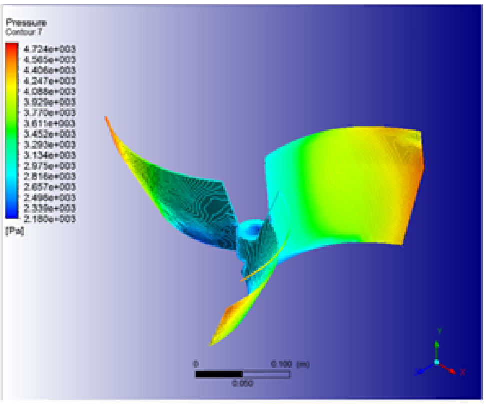

Figure 6: Pressure Contour

4. Experimental Setup

The test rig shown in figure 7 consists of a basin of diameter 400mm, canal height of 200mm, notch angle of approx. 10° and cone angle of approx. 28° has a total height of 0.6m. The runner(s) are assembled with the shaft, coupled with a pulley and supported by bearings. For the purpose of torque measurement, a brake drum dynamo-meter is fabricated and used. A digital tachometer is used for the purpose of rotational speed measurement. A current meter is used for measuring the flow velocity of water in inlet canal which was in turn used for the calculation of flow rate. A Vee notch is also used for the purpose of redundancy in flow measurement.

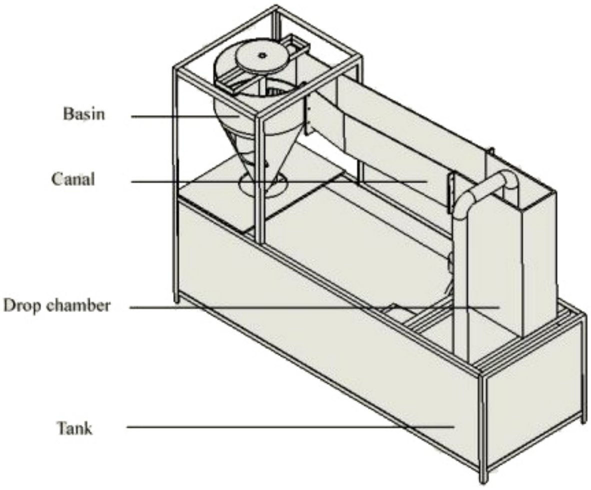

Figure 7: Experimental Test Bench

Among all of the booster runner, two of them have 3 blades and one has 6 blades. The main runner consists of 5 blades. The position of the runner was at the possibly lowest position as suggested by previous researchers. The speed of the runner was increased by decreasing the load and vice versa, by a pulley attached to the shaft of runner. The data taken from the spring balance was used to measure the torque on the shaft of the runner and finally used to calculate the shaft power of the turbine. The data are presented in the form of efficiency after necessary calculations.

Figure 8: Booster Runners

5. Results and Discussion

The results obtained from numerical modelling can be seen in figure 9 and figure 10.

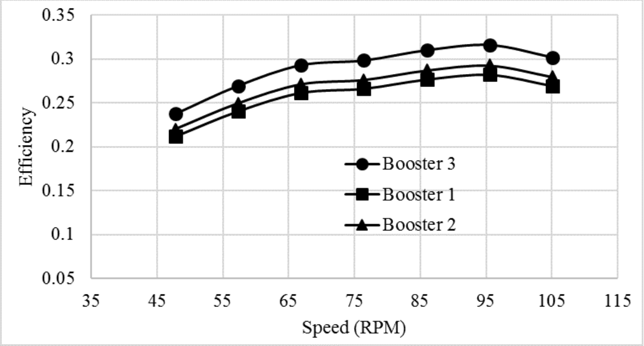

Figure 9: Computational Performance of Booster Runners

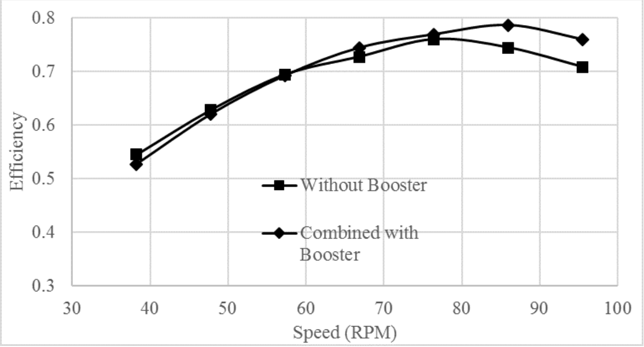

Figure 10: Computational Performance of Booster Runner with Main Runner

The plant without booster has a max efficiency of 76.03%. At optimum conditions of individual runners, booster runners 1,2 and 3 have max efficiency of 28.22%, 29.27%, and 31.61% respectively. Maximum efficiency of 78.65% is obtained when the main runner is coupled with booster runner 3. The nature of curve of all runner systems is almost similar. The efficiency of the turbine increases on increasing speed and becomes maximum at a certain speed and then on increasing speed the efficiency starts to drop.

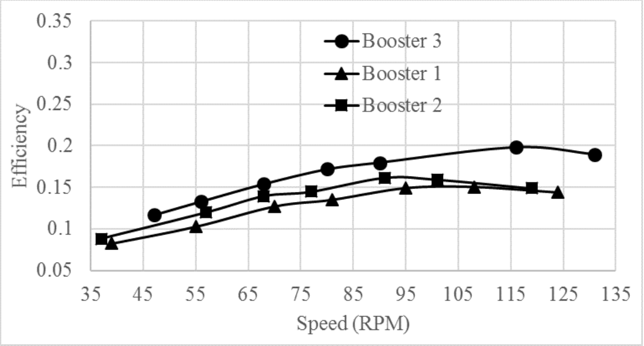

Figure 11: Experimental Performance of Booster Runners

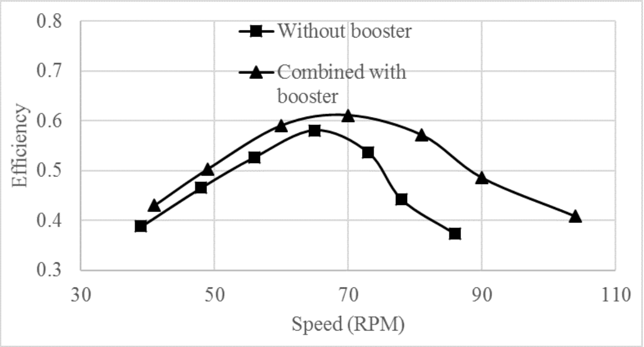

Figure 12: Experimental Performance of Booster Runner with Main Runner

At low speed, the system without booster has greater efficiency than the coupled system (fig 10) but at high speed, the efficiency of coupled system is more. At low speed of the system, water cannot swirl properly after striking the main runner. Water falls vertically and is unable to give proper impact to the booster runner. Nonetheless, some energy is wasted to overcome the drag force of the booster runner. But at high speed, the effect reverses and the impact on the booster runner is sufficient to overcome the drag force due to the booster runner blades. Overall the effect of adding booster comes to be useful to increase the performance of the turbine.

6. Conclusion

In this research, the potential of using small hydropower, Gravitational Water Vortex Power Plant with maximum energy extraction from swirling water was featured. The numerical solution and experimentation of the same verified that output power and efficiency of the system increases by assembling booster runner with a single main runner for all similar inlet condition. The energy of water that falls to certain height after leaving the main runner was harvested by designing suitable booster runner that meet the necessary condition. The increase in efficiency is about 6% more than that of a single main runner. Although there are some operational and manufacturing challenges, comparatively low initial investment makes GWVPP an excellent choice for power generation in the remote villages that are isolated where grid line supply is not sufficient or unavailable. Developing countries like Nepal can address the scattered low-income consumers fulfilling their demands, which could result in the improvement of the rural electrification.

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References

[1] Richard Heede and Naomi Oreskes. Potential emissions of {CO2} and methane from proved reserves of fossil fuels: An alternative analysis. *Global Environmental Change*, 36:12 – 20, 2016.

[2] International Energy Agency. Key world energy statistics. Technical report, International Energy Agency, 2016.

[3] Tri Ratna Bajracharya and Raj Kumar Chaulagain. Developing innovative low head water turbine for free-flowing streams suitable for micro-hydro power in flat (terai) region in nepal. Master's thesis, Center for Energy Studies, Institute of Engineering, Tribhuvan University, 2013.

[4] Frank Zotloeterer. Hydroelectric power plant, Jul 2004. Patent.

[5] Sean Mulligan and John Casserly. The hydraulic design and optimization of a free water vortex for the purpose of power extraction. Master's thesis, 2010. Final Year Project Report.

[6] Tri Ratna Bajracharya and Raj Kumar Chaulagain. Development and Testing of Gravitational Water Vortex Turbine. Master's thesis, Center for Energy Studies, Institute of Engineering, Tribhuvan University, 2012.

[7] Sujate Wanchat and Ratchaphon Suntivarakorn. Preliminary Design of a Vortex Pool for Electrical Generation. *Advanced Science Letters*, 13(1):173–177, 2012.

[8] Sujate Wanchat and Ratchaphon Suntivarakorn. Preliminary Design of a Vortex Pool for Electrical Generation. *Journal of Computational and Theoretical Nanoscience*, 13(1), 2011.

[9] Sujate Wanchat, Ratchaphon Suntivarakorn, Sujin Wanchat, Kitipong Tonmit, and Pongpun Kayanyiem. A Parametric Study of a Gravitation Vortex Power Plant. In *Energy and Power Technology*, volume 805 of *Advanced Materials Research*, pages 811–817. Trans Tech Publications, December 2013.

[10] Sean Mulligan and John Casserly. The Hydraulic Design and Optimisation of a Free Water Vortex for the Purpose of Power Extraction. Final year civil engineering project, 2010.

[11] Sagar Dhakal, Ashesh Babu Timilsina, Rabin Dhakal, Dinesh Fuyal, Tri Ratna Bajracharya, and Hari P. Pandit. Effect of dominant parameters for conical basin: Gravitational water vortex power plant. *IOE Graduate Conference*, 5(2):111 – 115, 2015.

[12] Tze Cheng Kueh, Shiao Lin Beh, Dirk Rilling, and Yongson Ooi. Numerical analysis of water vortex formation for the water vortex power plant. *International Journal of Innovation, Management and Technology*, 2:380–386, October 2014.

[13] Sagar Dhakal, Ashesh B. Timilsina, Rabin Dhakal, Dinesh Fuyal, Tri R. Bajracharya, Hari P. Pandit, Nagendra Amatya, and Amrit M. Nakarmi. Comparison

of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant. *Renewable and Sustainable Energy Reviews*, 48:662 – 669, 2015.

[14] Sagar Dhakal, Ashesh B. Timilsina, Rabin Dhakal, Dinesh Fuyal, Tri R. Bajracharya, and Hari P. Pandit. Design optimization of basin and testing of runner for gravitational water vortex power plant. Technical report, 2014. Final Year Project Report.

[15] Anil Sapkota, Ankit Gautam, Jhalak Dhakal, Subash Neupane, and Shreeraj Shakya. Design Study of Runner for Gravitational Water Vortex Power Plant with Conical Basin. Technical report, Department of Mechanical Engineering, Institute of Engineering, Tribhuvan University, 2016. Final Year Project Report.

[16] Sean Mulligan, John Casserly, and Richard Sherlock. Hydrodynamic investigation of free-surface turbulent vortex flows with strong circulation in a vortex chamber. *5th IAHR International Junior Researcher and Engineer Workshop on Hydraulic Structures*.