JREE: Vol. 9, No. 2, (Spring 2022) 75-81

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Materials and Energy Research Center
MERC

Research Article

CFD Analysis of the Most Favorable Gap Between the Main Runner and Booster Runner of Gravitational Water Vortex Turbine

Bharosh Kumar Yadav[a*], Amit Chandra Jyoti[a], Pintu Kr. Rajak[a], Ramesh Kr. Mahato[a], Deelip Kr. Chaudhary[a], Mehdi Jahangiri[b], Ram Dayal Yadav[a]

[a] *Department of Mechanical Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Dharan-08, Nepal.*
[b] *Department of Mechanical Engineering, Shahrekord Branch, Islamic Azad University, Shahrekord, Iran.*

P A P E R I N F O

Paper history:
Received 20 September 2021
Revised in revised form: 05 January 2022
Scientific Accepted: 23 November 2021
Published: 19 April 2022

Keywords:
Low Head MHP,
Computational Fluid Dynamic (CFD),
Vortex Turbine,
Booster Runner,
Main Runner

A B S T R A C T

The Gravitational Water Vortex Power Plant (GWVPP) is a power generation system designed for ultralow head and low flow water streams. Energy supply to rural areas using off-grid models is simple in design and structure and sustainable to promote electricity access through renewable energy sources in the villages of Nepal. The objective of this study is to determine the most favorable gap between the booster and main runners of a Gravitational Water Vortex Turbine (GWVT) to ensure maximum power output of the GWVPP. CFD analysis was used to evaluate the 30 mm gap between the main and booster runners, which was the most favorable gap for enhancing the plant's power. In this study, the optimum power and economic analysis of the entire plant was conducted in the case of mass flow rates of 4 kg/s, 6 kg/s, and 8 kg/s. The system was modeled in SolidWorks V2016 and its Computational Fluid Dynamic (CFD) analysis was performed utilizing ANSYS R2 2020 with varying multiple gaps between the main and booster runners to determine the most favorable gap of the plant's runner. This research concluded that optimum power could be achieved if the distance of the main runner's bottom position be fixed at 16.72 %, i.e., the distance between the top position of the conical basin and the top position of the booster runner. At a mass flow rate of 8 kg/s, the plant generated maximum electric energy (3,998,719.6 kWh) comparatively and economically contributed 268,870.10 USD on an annual basis.

https://doi.org/10.30501/jree.2022.298216.1237

1. INTRODUCTION

Water is a clean, inexpensive source of energy through which an environmentally benign generation of power can be ensured, and this is is of utmost importance for a sustainable future. Nevertheless, much of water energy remains underutilized [1]. The Gravitational Water Vortex Power Plant (GWVPP) uses a hydrokinetic technique to extract energy, in which case the kinetic energy of flowing water is immediately transformed into electricity by a turbine with low or no head [2]. The GWVT is a type of low-head turbine that can operate at 0.7-3.0 m head, which is conventional for the production of renewable energy and such hydro turbines have a positive impact on the environment. The GWVT turbine rotates in a co-axial manner and is a strike on its overall circumference. Water enters the cannel by a huge, straight intake and then, flows tangentially over the circular basin forming a vortex. Due to the dynamic force between the turbine and flowing water fluid, a vortex emerges that passes through the bottom of the basin, which is intentionally structured to maintain pressure differences. It not only provides electricity for households but also aerates the flow of water. Dhakal et al. performed a computational and experimental analysis for GWVPP with cylindrical and conical basins to determine the optimum position of the runner. They demonstrated that the power and efficiency were higher 65-75 % in the conical basin, compared to the cylindrical basin [3, 4]. The GWVT is beneficial for a variety of uses in human civilization and industry, e.g., it can be used in load-setting situations to light up home, community, run modest fans, etc. It can also be used for irrigation as a water delivery system with a motorized fountain spray. In industries, it is more useful to light up bulbs and preserve energy grids [5]. The concentration of dissolved oxygen may increase upon the formation of a vortex. It is more advantageous in geographical places such as mountain steep areas where transmission lines are not properly accessible.

Mulligan et al. adjusted the ratio of orifice diameter and tank diameter (d/D) in the range of 14-18 % for both in low-head and high-head locations and found the vortex power optimum [6]. Nepal is a landlocked country and 17 % of the total land is flat, known as Terai Madhesh Region (TMR). Tri Ratna Bajracharya et al. studied the free-flowing low-head water

*Corresponding Author's Email: bharosh@ioepc.edu.np (B. Kumar Yadav)
URL: https://www.jree.ir/article_148440.html

Please cite this article as: Kumar Yadav, B., Chandra Jyoti, A., Rajak, P.Kr., Mahato, R.Kr., Chaudhary, D.Kr., Jahangiri, M. and Dayal Yadav, R., "CFD analysis of the most favorable gap between the main runner and booster runner of gravitational water vortex turbine", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 9, No. 2, (2022), 75-81. (https://doi.org/10.30501/jree.2022.298216.1237).

turbine of TMR, the condition of discharge, and length of the basin diameter, and they found that the vortex was minimum at the bottom level depending on the geometry of the basin's supply of discharge [7]. Wanchat et al. investigated the formation of a vortex in/of the water stream and found that the kinetic energy of the vortex of the water stream was the characteristic of the water height, diameter of the orifice, and basin of the structure. They also employed numerical and experimental analyses to evaluate the produced electric power of 60 W, which achieved 30 % efficiency for the plant [8, 9]. Rabin Dhakal et al. investigated the design method of the GWVPP runner and found the efficiency of the curved blade to be greater than a straight or twisted blade profile [10]. Manil Kayastha et al. suggested that the shifting of the runner downwards would increase the efficiency of the plant [11]. R. Ullah et al. conducted a performance analysis on multi-stage GWVT and found that the performance of the GWVPP could be increased using multistage, implying that the alignment manner of the two runners should be the same rotor to a basin with an identical diameter. He further analyzed experimentally the effect of the ratios of rotor diameter to basin diameter on multistage GWVPP with a conical basin of the plant for adequate power and efficiency [12, 13].

As a result of the literate review, some relevant research gaps have been identified. None of the scientific literature studies has focused on the measurement of the most favorable gap between the main and booster runners of the GWVPP plant. CFD analysis evaluated which gap between the main and booster runner would be the most favorable one to cover so as to enhance the plant's power. In this study, the optimum power and economic analysis of the entire plant was evaluated at mass flow rates of 4 kg/s, 6 kg/s, and 8 kg/s. Therefore, the present research work aims to bridge the research gap for ensuring reliable and sustainable energy in the installation of cum production in the GWVPP plant.

2. METHODOLOGY

In this work, a holistic approach was used for the analysis of two-stage GWVPP, as shown in Figure 1. In today's world where global warming is one of the greatest human challenges, sustainable energy generation is becoming increasingly relevant. The use of green and clean energy sources is the best way to minimize hazardous gases and other emissions of conventional energy usage.

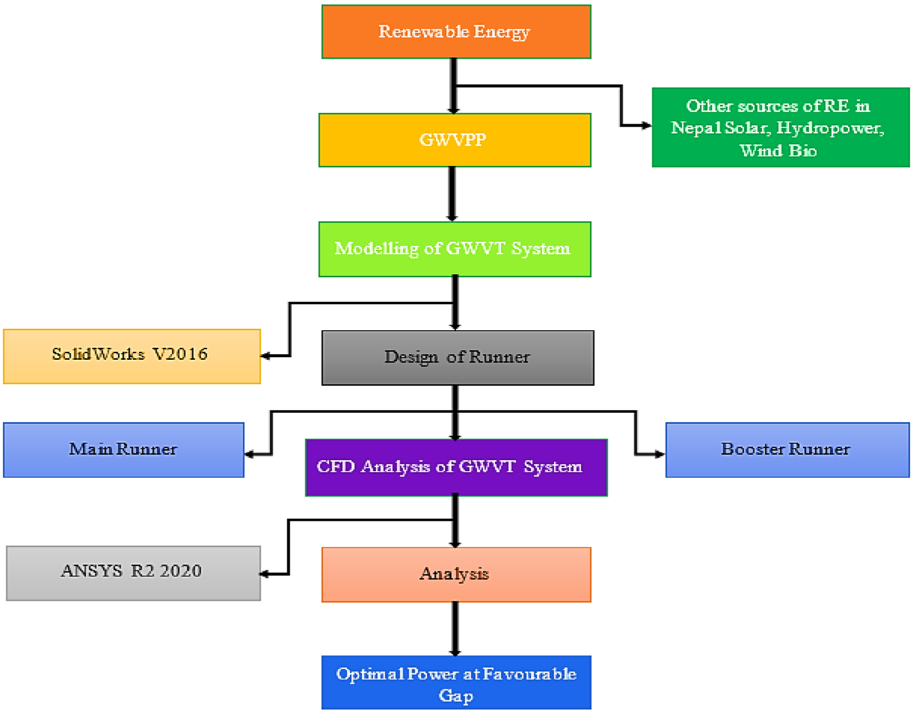


Figure 1. Flowchart describing the methodology of the study

The gravitational water vortex power plant is a form of micro-hydropower system that converts the energy of flowing fluid into rotational energy with a head between 0.7-3.0 meters. The GWVPP system is built with a circular/conical basin in which water creates a vortex above the drain used to drive a water turbine. By using the Navier-Strokes equation and the continuity equations, cylindrical coordinates can be described taking the assumption of steady, incompressible, and axis-symmetric flows as follows [14]:

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} + \frac{V_r}{r} = 0 \tag{1}$$

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

$$V_r\frac{\partial V_r}{\partial r} + V_z\frac{\partial V_r}{\partial z} - \frac{{V_\theta}^2}{r} + \frac{\partial \rho}{\rho \partial r} = \nu\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{\partial V_r}{r\,\partial r} - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial z^2}\right) \tag{3}$$

$$V_r\frac{\partial V_z}{\partial r} + V_z\frac{\partial V_z}{\partial z} + \frac{\partial \rho}{\rho\,\partial z} = g + \nu\left(\frac{\partial^2 V_z}{\partial r^2} + \frac{\partial V_z}{r\,\partial r} + \frac{\partial^2 V_z}{\partial z^2}\right) \tag{4}$$

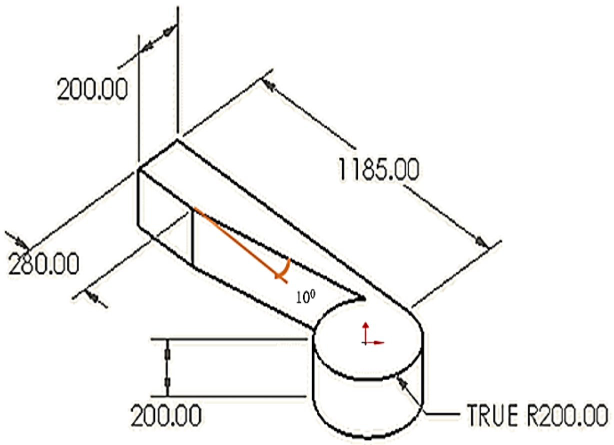
where V_θ = tangential velocity, V_r = radial velocity, V_z = axial velocity, ρ = density of fluid, g = gravitational acceleration, and ν = kinematic viscosity.

3. NUMERICAL SIMULATIONS

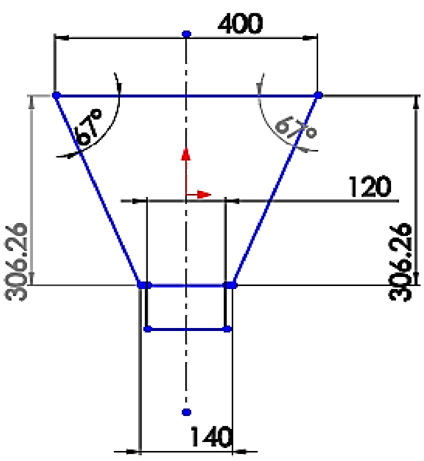
A numerical simulation as a computer-based calculation uses a program to implement a mathematical model of a physical system [15]. Most nonlinear systems require numerical simulations to analyze their behavior because their mathematical models are too complex to provide analytical answers [16]. Computational fluid dynamics is a branch of fluid mechanics used for the analysis of and solution to the problem corresponding to the fluid flow involving data structures and the numerical analysis [17]. The calculations that are essential to the model with a free fluid stream and the interaction of the fluid with its surface area are defined by boundary conditions that can be solved using computers [18]. The SolidWorks V2016 was utilized for modeling the GWVPP system, and different gaps were provided such as 10mm, 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm in between the main runner and booster runner of the GWVT. Finally, simulation results were analyzed using ANSYS R2 2020 and used to customize the favorable gap of the runners of the GWVPT for optimal power of the plants.

3.1. 3D modeling of runner

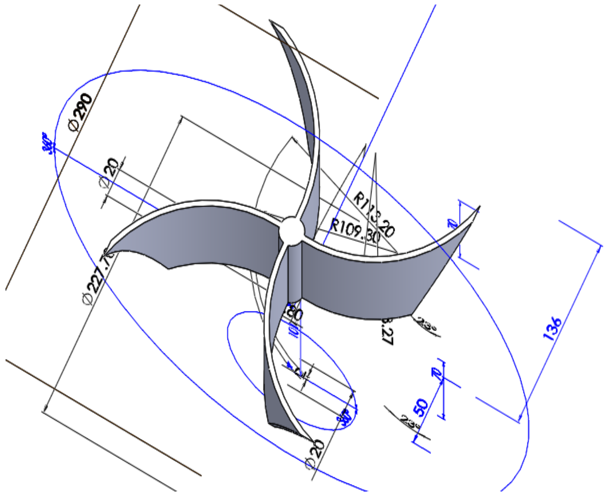
The 3D modeling of the GWVPP structure was performed using SolidWorks and various sections of GWVT such as canal, basin, and runners aligned together, as shown in Figure 2. In the design process, the booster runner was kept fixed at about 70 % of the total height of GWVT from the top position of the conical basin and, simultaneously, the main runner varied at different gaps such as 10 mm, 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm to achieve optimum and sustainable power of the plant.



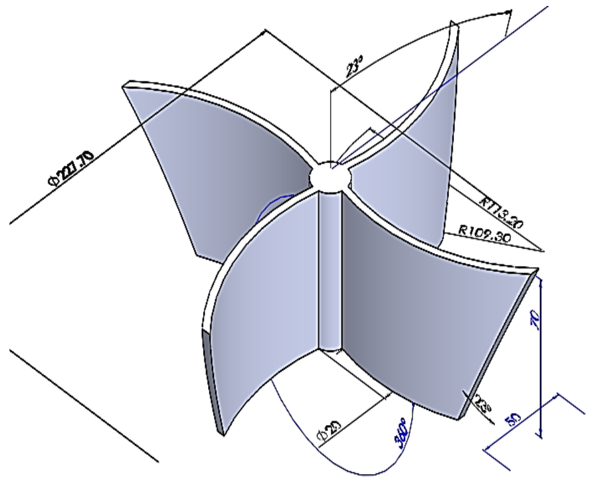
a) Canal



b) Conical basin



c) Main runner

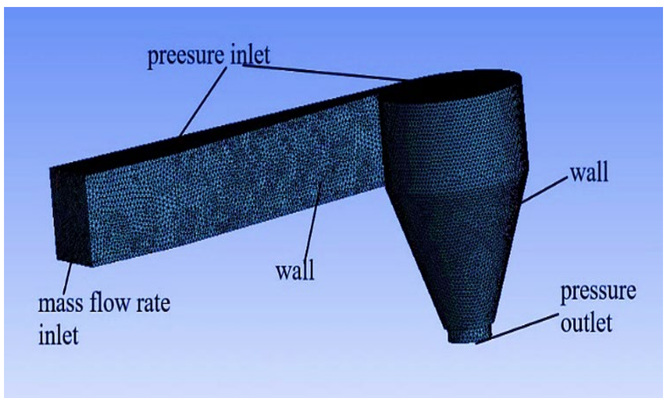


d) Booster runner

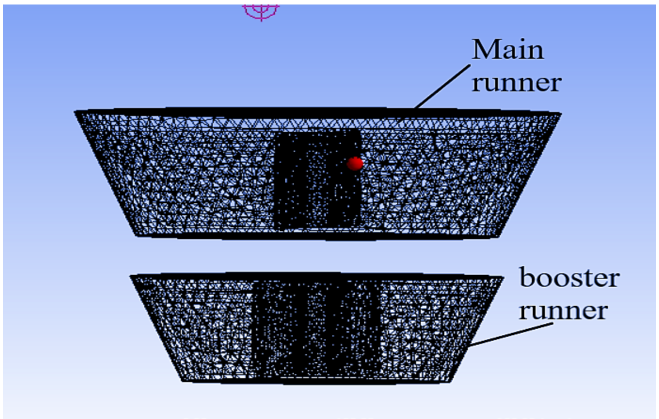
Figure 2. 3D modeling of GWVPP system

3.2. Meshing and boundary condition

Meshing is one of the processes of engineering simulation that is used for breaking complex geometries into simple parts which can facilitate discretizing local approximations into wider domains. The mesh has an impact on the speed, accuracy, and convergence of simulation because this meshing takes a large percentage of total simulation time to give the most possible results [19]. There are two types of domains: rotatory and stationary. The domain of the booster runner and the main runner is used as a rotatory domain and the domain of canal, basin, and a draft tube is used as the stationary domain of the GWVPP structure, which is shown in Figure 3.



a) Stationary domain



(b) Wireframe view of a rotatory domain

Figure 3. Mesh generation (a) Stationary and (b) Rotatory domain of GWVT system

In this work, the very popular Finite Element (FE) computational simulating software ANSYS R2 2020 was used for numerical analysis. During the process of meshing the structure of the GWVT with a different individual component, the elements in orthogonal shape were provided as 9 mm to 18 mm, and the rest of the parameters were set to be the default of the plant. Table 1 summarizes the mesh analysis results of the plant setup.

Table 1. Results obtained from mesh analysis

Name	Obtained results
Number of elements	475188
Orthogonal quality minimum size	0.013535
Orthogonal quality maximum size	0.99366
Aspect ratio	1.15
Number of nodes	95941

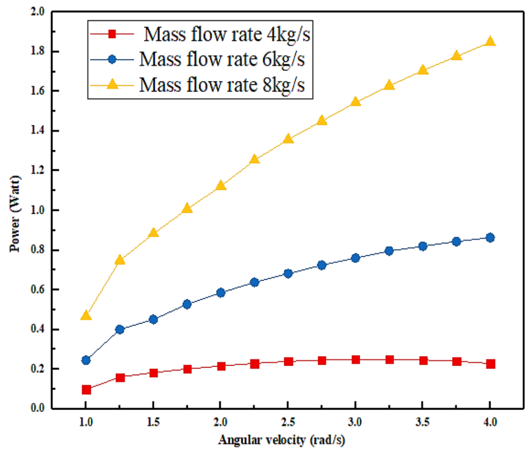
After meshing the whole structure of the GWVPP, the boundary conditions of mass flow rates of 4 kg/s, 6 kg/s, and 8 kg/s were set fixed at the inlet and outlet of the plant following the conservation of mass with variable angular velocities in the range of 1-4 rad/s. The method of formulation, solving, and summary of boundary conditions are depicted in Table 2. A difficut task is to set the condition to get maximum angular velocities (in the range of 1-4 rad/s) so as to choose the favorable gap (out of 10 mm, 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm) after performing various simulations to achieve the maximum output power of the GWVPP.

Table 2. Summary of boundary conditions and features

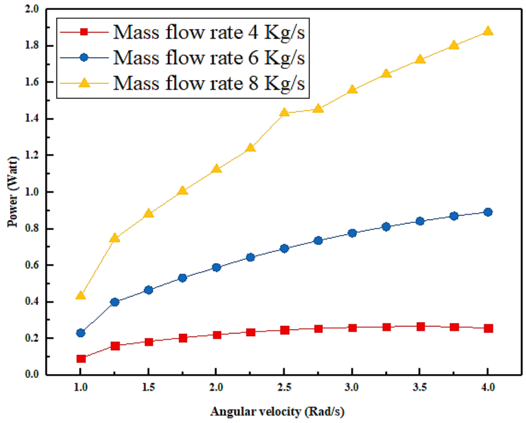
1.	**Boundary type**	**Operating conditions**
i.	Mass flow rate inlet	4 kg/s, 6 kg/s, 8 kg/s
ii.	Pressure inlet	Atmospheric pressure
iii.	Wall	Steel wall
iv	Pressure outlet	Atmospheric pressure
2.	**Feature**	**Technique**
i.	Method of coupling velocity and pressure terms	Simple
ii.	Gradient discretization	Least square cell based
iii.	Pressure discretization	Second order
iv.	Momentum discretization	Second-order upwind
v.	Turbulent kinetic energy discretization	Second-order upwind
vi.	Specific dissipation rate	Second-order upwind
vii.	Maximum number of iterations	350
viii.	Mesh movement algorithm	Smoothing and re-meshing
ix.	Mesh movement algorithm over the fluid-solid interface	System coupling and deformation

4. RESULTS AND DISCUSSION

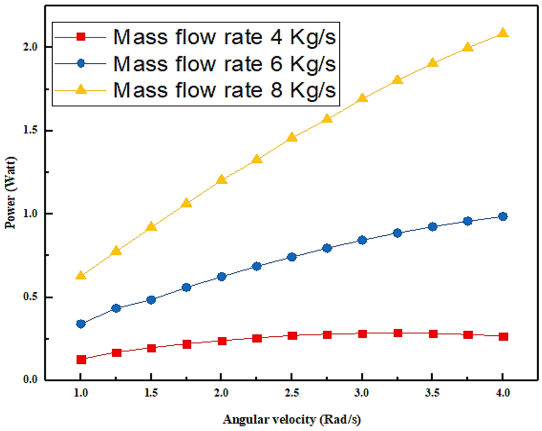
The simulation results are presented in this section. Three mass flow rates (i.e., 4 kg/s, 6 kg/s, and 8 kg/s) were set fixed at the inlet and outlet of the plant and angular velocities changed in the range of 1-4 rad/s in three conditions of the vortex flow of water. In the meantime, the gaps/spacing was increasing correspondingly from the top position of the conical basin and the top position of the booster runner's distances to predict the main runner position set to be fixed in between them. The seven input parameters of angular velocities set fixed in the ANSYS at an equal interval of 0.5 rad/s (in between 1-4 rad/s range) and the power produced through the main runner and booster runners obtained from the numerical simulations at the gaps of 10 mm, 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm with three different mass flow rates are shown in Figure 4.



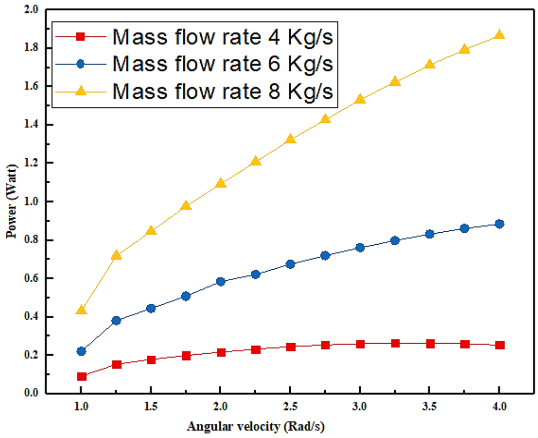
a) 10 mm gap of GWVT



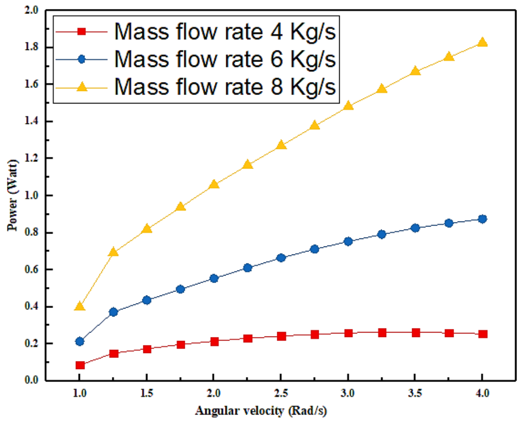
b) 20 mm gap of GWVT



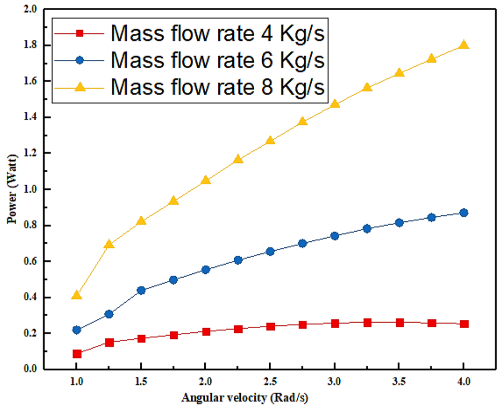
c) 30 mm gap of GWVT



d) 40 mm gap of GWVT



e) 50 mm gap of GWVT



f) 60 mm gap of GWVT

Figure 4. Power output vs. Angular velocity of the main runner and booster runner at various gaps of the GWVT system

The optimum power generation at the gap of 30 mm in between the main runner and booster runner for 4 kg/s, 6 kg/s, and 8 kg/s mass flow rates was found as 0.2862522 Watt, 0.9852612 Watt, and 2.084236 Watt, respectively, as shown in Figure 5. According to the appendix, if the GWVPP plant is installed considering 10 hours of electric use every day, then the plant with a mass flow rate of 4 kg/s will produce an electric energy of 549157.671 kWh in a year, which will be about 43,93,261.37 Rupees (36924.84 $). Likewise, the annual economic analysis for mass flow rates of 6 kg/s and 4 kg/s GWVPP plant can produce 1890164.5 kWh and 3998719.6 kWh electric energies, which will be around 15121316 Rupees (127092.86 $) and 31989756.8 (268870.1 $), respectively. The optimum and cost-effective production of electric energy by the GWVPP plant can be ensured when 30 mm gap be considered in between the main and booster runner at a mass flow rate of 8 kg/s.

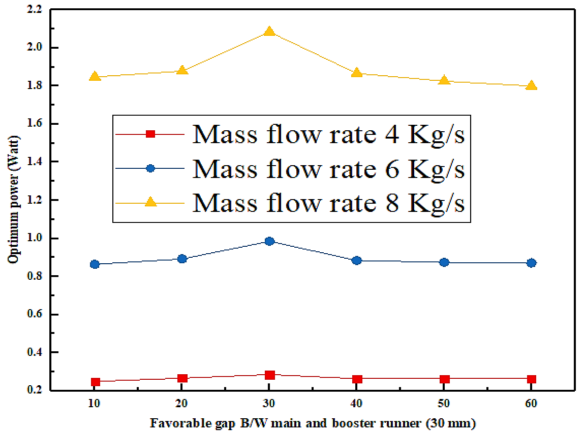


Figure 5. Optimum power of GWVT system and the corresponding favorable gap

5. CONCLUSIONS

This study concluded that the optimum power of the GWVPP plant could be enhanced upon fixing the main runner bottom position at 16.72 % of the distances in between the top position of the conical basin and the top position of the booster runner. CFD analysis of this study illustrated that the 30 mm gap was the most favorable gap between the main runner and booster runner. Also, the optimum power was found to be maximum at the same gap of the main runner and booster runner of the GWVT and the values obtained were

0.2862522 Watt, 0.9852612 Watt, and 2.084236 Watt, respectively. The distance between the top position of the conical basin and the top position of the booster runner taken was 179.39 mm; therefore, the favorable position of the main runner would be 16.72 % of 179 mm, i.e., 29.9940 mm ~ 30 mm gap. This finding was validated according to the computational simulation result. Thus, the present research work aimed to bridge the research gap concerning the optimal power and favorable gap of the main and booster runners of the GWVT system. The optimum power and economic analysis of the entire plant were evaluated at mass flow rates of 4 kg/s, 6 kg/s, and 8 kg/s, respectively. The GWVPP plant being installed considering 10 hours of daily electric use, compared to one year, with a mass flow rate of 4 kg/s will produce 549157.671 kWh electric energy, which will be about 43,93,261.37 Rupees (36924.84 $). Likewise, the yearly economic analysis for the mass flow rates of 6 kg/s and 8 kg/s can produce 1890164.5 kWh and 3998719.6 kWh electric energy, which will be around 15121316 Rupees (127092.86 $) and 31989756.8 (268870.1 $), respectively. At a mass flow rate of 8 kg/s, the plant produces optimum electric energy economically when a 30 mm gap is maintained between the main and booster runners. In addition, the installation of GWVPP by the general public or government authorities and stakeholders will lead to greater convenience, implementation confidence, proper utilization of green energy, thus enhancing a plant's power, cost-effectiveness, and efficiency output. Future related work may focus on the validation of computational numerical simulation results in experimental terms.

6. ACKNOWLEDGEMENT

This research was supported by the "Students Final Year Research Fund" of Tribhuvan University, Institute of Engineering, Purwanchal Campus, Dharan-08, Nepal.

APPENDIX

The economic analysis was carried out based on the mass flow rates of 4 kg/s, 6 kg/s, and 8 kg/s shown below:

For 4 kg/s, we can have 0.2862522 Watt power. Then, the total power in one year = 0.2862522*60*24*365 = 150454.156 Watt.

As is already known, 1 kWh = 1 unit considering that 10 hours of electricity is being used by the consumers every day. Then, the yearly electricity consumed by the consumer = 10 * 365 = 3650 hours/Year.

Also, kWh = 1540454.156 * 3650/1000 = 549157.671 kWh

or Units

549157.671 kWh = 549157.671 units

According to Nepal Electrical Authority, each unit costs 8 Rupees Nepali currency (0.067 $). Therefore,

549157.671 units = Rs. 549157.671* 8 = Rs. 4393261.37 (36924.84 $)

From the above calculation, it can be seen that when the mass flow rate is 4 kg/s, the GWVPP plant can produce 549157.671 kWh electricity power which will be around Rs. 4393261.37 (36924.84 $), yearly.

Likewise, a calculation was done for mass flow rates 6 kg/s and 8 kg/s and it was found that When the mass flow rate was 6 kg/s, GWVPP would generate 1890164.5 kWh, which would be around 15121316 Nepalese Rupees (127092.86 $) yearly; and when the mass flow rate was 8 kg/s, the plant would generate maximum electric energy of 3998719.6 kWh, which is around 31989756.8 Nepalese Rupees (268870.1 $) yearly.

It can be concluded that 8 kg/s mass flow rate will be more economical and optimum electric energy can be harnessed when the gap in between the main and booster runners is maintained at 30 mm.

REFERENCES

1. Dhakal, R., Bajracharya, T.R., Shakya, S.R., Kumal, B., Kathmandu, N., Khanal, K. and Ghale, D.P., "Computational and experimental investigation of runner for gravitational water vortex power plant", ***Proceedings of IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA 2017)***, San Diego, California, USA, (5-8 November 2017), 365-373. (https://doi.org/10.1109/ICRERA.2017.8191087).

2. Kaygusuz, K., "Energy for sustainable development: A case of developing countries", ***Renewable and Sustainable Energy Reviews***, Vol. 16, No. 2, (2012), 1116-1126. (https://doi.org/10.1016/j.rser.2011.11.013).

3. Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P. and Nakarmi, A.M., "Comparison of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant", R***enewable and Sustainable Energy Reviews***, Vol. 48, (2015), 662-669. (https://doi.org/10.1016/j.rser.2015.04.030).

4. Dhakal, R., Dhakal, S., Timilsina, A.B. and Fuyal, D., "Design optimization of basin and testing of runner for gravitational water vortex power plant", ***Proceedings of The 2015 International Capstone Design Contest on Renewable Energy Technology***, Mokpo National University, Mokpo, Korea, (07 January 2015). (https://www.researchgate.net/publication/297967445_Design_Optimization_of_Basin_and_Testing_of_Runner_for_Gravitational_Water_Vortex_Power_Plant).

5. Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P. and Amatya, N., "Mathematical modeling, design optimization and experimental verification of conical basin: Gravitational water vortex power plant", ***Proceedings of Dalam World Largest Hydro Conference***, (2015), 1-23. (https://www.academia.edu/43393673/Mathematical_modeling_design_optimization_and_experimental_verification_of_conical_basin_Gravitational_water_vortex_power_plant?from=cover_page).

6. Mulligan, S. and Casserly, J., "The hydraulic design and optimisation of a free water vortex for the purpose of power extraction", ***BE Project Report***, Institute of Technology, Sligo, (2010). (https://www.itsligo.ie/research/research-projects).

7. Bajracharya, T.R. and Chaulagai, R.K., "Developing innovative low head water turbine for free-flowing streams suitable for micro-hydropower in flat (Terai) regions in Nepal", ***Center for Applied Research and Development (CARD), Institute of Engineering***, Tribhuvan University, Kathmandu, Nepal, (2012). (http://202.70.82.238/cgi-bin/koha/opac-detail.pl?biblionumber=74931&shelfbrowse_itemnumber=102215).

8. Wanchat, S. and Suntivarakorn, R., "Preliminary design of a vortex pool for electrical generation", ***Advanced Science Letters***, Vol. 13, No. 1, (2012), 173-177. (https://doi.org/10.1166/asl.2012.3855).

9. Wanchat, S., Suntivarakorn, R., Wanchat, S., Tonmit, K. and Kayanyiem, P., "A parametric study of a gravitation vortex power plant", ***Advanced Materials Research***, Vol. 805, (2013), 811-817. (https://doi.org/10.4028/www.scientific.net/AMR.805-806.811).

10. Dhakal, R., Bajracharya, T.R., Shakya, S.R., Kumal, B., Khanal, K., Williamson, S.J. and Ghale, D.P., "Notice of violation of IEEE publication principles: Computational and experimental investigation of runner for gravitational water vortex power plant", ***Proceedings of IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)***, (2017), 365-373. (https://doi.org/10.1109/ICRERA.2017.8191087).

11. Kayastha, M., Raut, P., Subedi, N.K. and Ghising, S.T., "CFD evaluation of performance of gravitational water vortex turbine at different runner position", ***Proceedings of KEC Conference***, Kantipur

Engineering College, Dhapakhel Lalitpur, (2019), 17-25. (https://doi.org/10.31224/osf.io/d9qn3).

12. Ullah, R., Cheema, T.A., Saleem, A.S., Ahmad, S.M., Chattha, J.A. and Park, C.W., "Performance analysis of multi-stage gravitational water vortex turbine", ***Energy Conversion and Management***, Vol. 198, (2019), 111788. (https://doi.org/10.1016/j.enconman.2019.111788).
13. Ullah, R., Cheema, T.A., Saleem, A.S., Ahmad, S.M., Chattha, J.A. and Park, C.W., "Preliminary experimental study on multi-stage gravitational water vortex turbine in a conical basin", ***Renewable Energy***, Vol. 145, (2020), 2516-2529. (https://doi.org/10.1016/j.renene.2019.07.128).
14. Wang, Y.K., Jiang, C.B. and Liang, D.F., "Investigation of air-core vortex at hydraulic intakes", ***Journal of Hydrodynamics***, Vol. 22, No. 1, (2010), 673-678. (https://doi.org/10.1016/S1001-6058(10)60017-0).
15. Jahangiri, M., Saghafian, M. and Sadeghi, M.R., "Numerical simulation of hemodynamic parameters of turbulent and pulsatile blood flow in flexible artery with single and double stenoses", ***Journal of Mechanical Science and Technology***, Vol. 29, No. 8, (2015), 3549-3560. (https://doi.org/10.1007/s12206-015-0752-3).
16. Jahangiri, M., Saghafian, M. and Sadeghi, M.R., "Effects of non-Newtonian behavior of blood on wall shear stress in an elastic vessel with simple and consecutive stenosis", ***Biomedical and Pharmacology Journal***, Vol. 8, No. 1, (2015), 123-131. (https://dx.doi.org/10.13005/bpj/590).
17. Jahangiri, M., Haghani, A., Ghaderi, R. and Hosseini Harat, S.M., "Effect of non-Newtonian models on blood flow in artery with different consecutive stenosis", ***ADMT Journal***, Vol. 11, No. 1, (2018), 79-86. (http://admt.iaumajlesi.ac.ir/article_538372.html).
18. Jahangiri, M., Saghafian, M. and Sadeghi, M.R., "Effect of six non-Newtonian viscosity models on hemodynamic parameters of pulsatile blood flow in stenosed artery", ***Journal of Computational & Applied Research in Mechanical Engineering***, Vol. 7, No. 2, (2018), 199-207. (https://dx.doi.org/10.22061/jcarme.2017.1433.1114).
19. Sharifzadeh, B., Kalbasi, R., Jahangiri, M., Toghraie, D. and Karimipour, A., "Computer modeling of pulsatile blood flow in elastic artery using a software program for application in biomedical engineering", ***Computer Methods and Programs in Biomedicine***, Vol. 192, (2020), 105442. (https://doi.org/10.1016/j.cmpb.2020.105442).