Investigate How Inlet Geometry Affects Vortex Power

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Abstract

The energy demand is increasing day by day and putting pressure on traditional energy sources, which allows researchers to work on alternative energy sources. Traditional energy sources and conversion technology are also under threat due to their environmental impact. One kind of environmentally friendly technology that generates power from vortexes created by gravity pulls is the gravitational water vortex power plant. Because of its favorable effects on the environment and low hydraulic head need, this kind of power plant is desirable. However, a lack of literature and exposure held back the development of this technique. This study focuses on how the geometry of the penstock affects the power plant's efficiency. We developed an experimental configuration that resembles the low-head river and power plant. Experiments revealed that an increase in the feeding breadth of the penstock decreased the power plant's efficiency. It was also discovered that the power plant's efficiency was mostly unaffected by the model's length for the penstock. The power plant's efficiency was determined to be at its peak when the ratio of the basin's diameter to the outflow diameter was within the range of 0.16 and 0.18. Ultimately, the power plant's performance was determined to be enhanced by raising the inlet flow rate by the researchers. These results suggested that additional research on this technology is required to fully use low-head sites.

Keywords
Renewable Energy, Water Vortex, Alternative Energy, Hydraulic Machinery.

Introduction
To work on an object, one needs to use a property called energy. Energy can be transformed, but it cannot be created or destroyed, according to the rule of conservation of energy. There is a vast array of different forms that energy can take. Converting energy sources into electrical energy, or electricity, is one of the most popular energy transformations. The overall amount of energy consumed increased from about 8,991 Mtoe (million tons of oil equivalent) in 1990 to over 13,903 Mtoe in 2016, according to Global Energy Statistics (2017). The fact that the sources of this increase are primarily limited energy sources—oil, coal, gas, biomass, electricity, and heat—makes them concerning. The rising demand for electrical energy makes the growth in consumption inevitable as well. Finding a sustainable energy source is currently imperative (Krozer Y. 2013; Alrikabi N. 2014). As a result, many nations concentrate their attention on the potential for producing electricity using renewable energies, as they have limitless sources, don't release carbon dioxide that would be harmful to the environment, and—most importantly—have far lower total prices than finite energy supplies. According to Global Energy Statistics (2017), Norway topped the list with 97.9% of power produced in 2016 from renewable energy sources. Other nations were also represented on the list. Additionally, more than 80% of the electricity produced in Brazil, Colombia, and New Zealand comes from renewable energy sources, namely hydropower, solar power, and wind. China, which has been among the biggest

energy consumers since 2009, has also demonstrated a growing trend in the generation of electricity from renewable energy sources.

Hydropower is an environmentally friendly energy source that captures the energy of descending or swiftly moving water through efficient methods. The inaugural development of a hydroelectric power plant for commercial use occurred in close proximity to Niagara Falls in the year 1879. Following that, there has been a steady increase in the use of hydropower for the generation of electricity. Based on the Key World Energy Statistics (2017), the worldwide production of hydroelectric electricity rose from 1,296 TWh in 1973 to 3,978 TWh in 2015. Norway holds the top position among nations in terms of domestic hydroelectricity generation, boasting an impressive rate of 95.9%. This greatly diminishes dependence on limited energy sources.

Water moves through a pipe or channel in a hydroelectric system because of gravity's pull. At the bottom of the pipe or channel, the water's velocity will be extremely high. The water turbine will revolve due to the impulsive force produced by the high-speed water. After that, the water turbine will modify the rotational energy and use a generator to ultimately transform it into electrical energy. There is no carbon released into the atmosphere during the entire process. Large-scale dam-based hydropower projects, however, were thought to have a detrimental effect on both the environment and civilization. Although the big hydropower facility can produce up to 22,500 megawatts of electricity when it works at a high water height, by encouraging hydropower on a smaller scale that runs at low water heads and has less ecological impact, the environmental effects can be completely eradicated. Because the development of micro-scale hydropower plants could not keep up with the growing demands for electricity, large-scale hydropower stations continued to be the primary source of electricity in most countries. (Dilip, 2009). Only about 5 percent of the world's potential for small-scale hydropower has been realized, despite the possibility of 150–200 GW of total potential capacity. (2013) Laghari et al. Additionally, the provision of electricity in remote locations and those without access to the national grid is becoming more and more crucial. Furthermore, compared to a hydropower plant, the building cost of a small-scale hydroelectric plant is comparatively lower. Since the environmental effects of hydropower facilities are often less severe than those of large-scale hydropower plants, those with an electricity generation capacity of less than 10 MW are particularly advantageous.

One of the small-scale hydropower facilities that makes use of the energy present in a vortex flow at a low hydraulic head is the Gravitational Water Vortex Power Plant (GWVPP). (Sezgin, 2014; Ball, 2012) This kind of power plant can operate with a hydraulic head as low as 0.7 meters. Because it reduced the need for extra energy to aerate the water and raised oxygen saturation levels, the invention of the water vortex power plant represented a turning point in hydrodynamic evolution. The largest GWVPP to date was created in Switzerland and was capable of producing 80,000–130,000 kWh of energy annually. (Power C.2016; Bajracharya et al. 2020)

A penstock at the upper end of the river distributes water to the basin as part of the GWVPP. An area of water is utilized to create a vortex of water. In order to capture energy from the water vortex, a turbine is positioned in the middle of the basin. A penstock which is connected to the river's lower end is located at the outflow, along with an exit hole for the water. A flow rate control gate will let the water river enter the penstock. Water will then be poured into the basin tangentially, creating a vortex as a result. The outlet and an additional penstock that is attached to the river's lower end are where the water vortex will leave the system. The turbine, which is located in the middle of the basin, will revolve in the interim due to the water vortex that forms. A generator will transform the rotational motion of the turbine into electrical energy (Regmi et al. 2020).

The primary benefit of GWVPP is that, by relying on the vortex's dynamic force rather than pressure differential, it does away with the requirement for a large water dam. This indicates that although the hydrostatic head contributes to the plant's increased power output, it is not the most significant parameter. Comparing this kind of plant's development to that of solar technology, it is still progressing more slowly in every area. Even though this technology has been in use for more than a decade, there aren't many commercial uses for this kind of power plant. Since the development is moving relatively slowly in comparison to other renewable energy technologies, the purpose of this article is to ascertain how inlet geometry and power output relate to one another. A thorough literature review was conducted in order to finish this project, and the results are summarized in Table 1.

Table 1. Summary of Literature Review

	Research Methods	Research Parameters	Findings
Turbine Configurations			
Marian et. al. (2012)	Theoretical	Position of multiple turbines	• Vortex ∝ rotational speed • Vortex height affect the efficiency of GWVPP
Marian and Sajin (2013)	Theoretical and Experimental	Position of multiple turbines	• Turbine extracts more energy near the outlet • Experimental results agree well with theories
Venukumar A., (2013)	Theoretical	Turbine blades design	• Advantages of GWVPP were discussed
Dhakal et. al. (2014)	Experimental	Position of turbine Number of blades of turbine	• Maximum power was extracted near the outlet • Power reduced as number of blades increased • Maximum efficiency = 25.36%
Dhakal et. al. (2015)	Experimental	Position of turbine Basin's Structure	• Optimal position of turbine is 65% to 75% of GWVPP's height • Conical basin has higher overall power output
Sitram et. al. (2015)	Experimental	Turbine materials	• Aluminum is more efficient than steel
Christine et. al. (2016)	Experimental	Number of blades of turbine Size of blades of turbine	• Efficiency∝number of blades • Efficiency∝size of turbine • Maximum efficiency = 15.1%
Wichian P. and Suntivarakorn R. (2016)	CFD and Experimental	Effect of turbine baffling Inlet flow rate	• 50% baffled turbine created highest torque and efficiency • Increased flow rate increased the efficiency of GWVPP
Inlet and Outlet Configurations			
Wanchat et. al. (2013)	Experimental	Outlet diameter varied	• Maximum efficiency = 30% • Outlet diameter between range of 0.20m and 0.35m
Shabara et. al. (2015)	CFD and Experimental	Outlet diameter varied	• Outlet velocity$\frac{1}{\propto}$ outlet diameter • Maximum outlet velocity at highest H_{inlet}
Sreerag S. R. et. al. (2016)	CFD	Outlet diameter varied	• Optimal outlet's diameter was 30% of basin's diameter
Christine et. al. (2016)	Experimental	Inlet flow rate $H_{channel}$	• Highest efficiency at maximum inlet flow rate • Optimal $H_{channel}$ at one-third of basin's height
Basin Configurations			
Wanchat and Suntivarakorn (2012)	Simulation	Basin's structure	• Cylindrical basin with inlet guide has the best flow field
Sagar et. al. (2014)	Simulation	Basin's dominant parameter	• W_{in} should be as small • Cone angle should be as big • $H_{channel}$ should be high • Shouldn't exceed optimum value
Chattha J. A. et. al. (2017)	Simulation	Basin geometry	• Tangential velocity increased with the formation of air core in vortex

			• Increased outlet's diameter also increased the tangential velocity

Research Methodology

The tailstock, cylindrical basin, and penstock make up the Gravitational Water Vortex Power Plant (GWVPP). This work aims to develop the geometry of the penstock for GWVPP. The diameter of the basin outlet is also changed to investigate how it affects the plant's efficiency. As seen in Figure 1, this power generation system uses a cylindrical basin with dimensions of 400 mm for the diameter and 500 mm for the height. Because the inlet flow rate demand was moderate, the diameter to height ratio was considered adequate. To install the outlets with varying sizes, a 130-mm hole was bored at the center bottom of the basin. According to S. Mulligan and P. Hull (2010), an ideal vortex strength can be attained when the diameter ratio of the exit to the basin is within the range of 0.14 and 0.18. An outflow with a diameter of 56 to 72 mm would be ideal for a basin with a 400 mm diameter. Consequently, five outlets (shown in Figure 2) with dimensions of 52 mm, 56 mm, 64 mm, 72 mm, and 76 mm have been selected for this investigation.

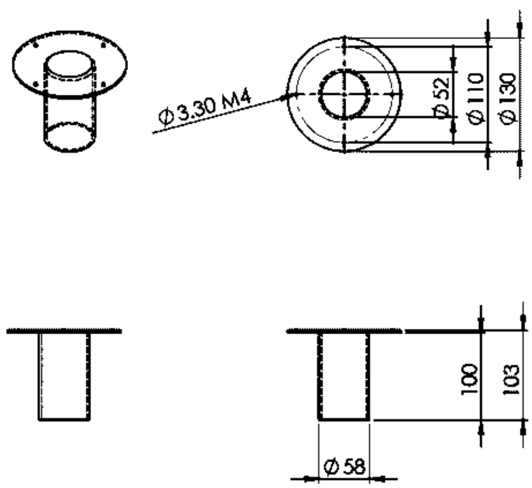

Figure 1. Basin Geometry

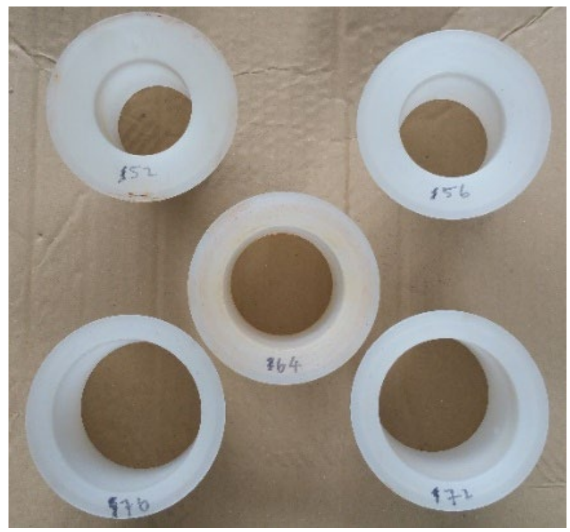

Figure 2. Different types of basin outlet

According to Dhakal et al. (2014), the feeding width of the penstock should be as minimal as feasible to maximize the vortex's tangential velocity. As a result, the tangential velocity will change significantly as the area of the channel decreases. The goal is to narrow the penstock's feeding width. The penstock's dimensions remain unchanged at 150 mm in width, 500 mm in height, and 700 mm in length. Subsequently, a few models were created to suit the penstock and modify its geometry, as seen in Figure 3. For documentation purposes, the area that changed along the penstock was labeled alphabetically. The models' dimensions that need to be put into the GWVPP penstock in order to apply geometry adjustments are displayed in Table 2.

Figure 3. Different type of penstocks

Table 2. Geometry of different penstocks

Models	W_{feed} (mm)	L_{model} (mm)
A	40	510
B	65	510
C	90	510
D	40	385
E	40	257
F	40	128

In order to extract energy from the vortex and produce electrical energy, a vortex power plant must include a turbine. A vertical-axis turbine with a flat blade is employed in this investigation. A stainless steel turbine with three blades is constructed. By using stainless steel, the turbine's weight is decreased and its blades' contact area is increased. To maximize the area of contact between the flat-blade turbine and the water vortex, it was positioned roughly 16 mm above the basin's bottom. The GWVPP that was created with the 3D program is displayed in Figure 4.

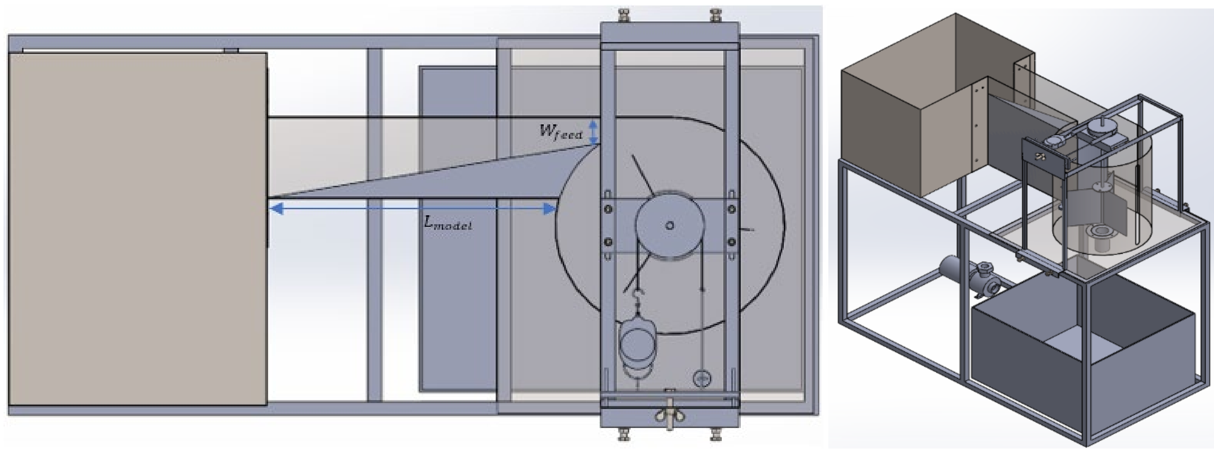

Figure 4. Three dimensional drawing of GWVPP

A Prony braking system is employed to measure the turbine's power output. The turbine's torque is measured using the Prony braking system. A prony braking system consists of slotted weights, a spring balance, and a friction belt. A revolving drum featuring a slot was constructed and fastened to the turbine's shaft. A dead load and a spring balance are fastened to opposite ends of the belt, which will be coiled around the revolving drum.

The experiments are conducted in a very simple manner. Three physical characteristics are taken into account and tested in accordance with each other: flow rates, penstock shape, and basin outlet diameter. Five distinct flow rates (5.6 m^3/hr, 6.4 m^3/hr, 7.2 m^3/hr, 8.0 m^3/hr, and 8.8 m^3/hr) are maintained for every set of tests. Following the completion of the tests, data is collected, and efficiencies are computed for various basin outlet diameters, penstock forms, and water flow rates.

Results and Discussion

As seen in Figure 5, the efficiency is computed at various flow rates and penstock diameters (52 mm to 76 mm) at the exit. The link between basin outlet diameters and model power plant efficiency for various penstocks is depicted in Figure 6. The data presented in Figure 6 indicates that Penstock A has the best efficiency at 8.8 m^3/hrr, while Penstock C has the lowest efficiency with an outlet diameter of 52 mm and a flow rate of 5.6 m^3/hrr. For the 56 mm outlet diameter, the highest and lowest efficiency were 24.64% and 10.50%, respectively. It was discovered at a flow rate of 8.8 m^3/hrr. Penstock E had the greatest efficiency, measuring in at 27.5%, while Penstock C had the lowest efficiency, measuring in at 5.6 m^3/hr with only 4.57%. The maximum efficiency with Penstock E at 8.0 m^3/hrr was 27.67% at an output diameter of 64 mm. Penstock C, on the other hand, had the lowest efficiency of the model-prototyped power plant, at 2.3%, with a flow rate of 5.6 m^3/hr.

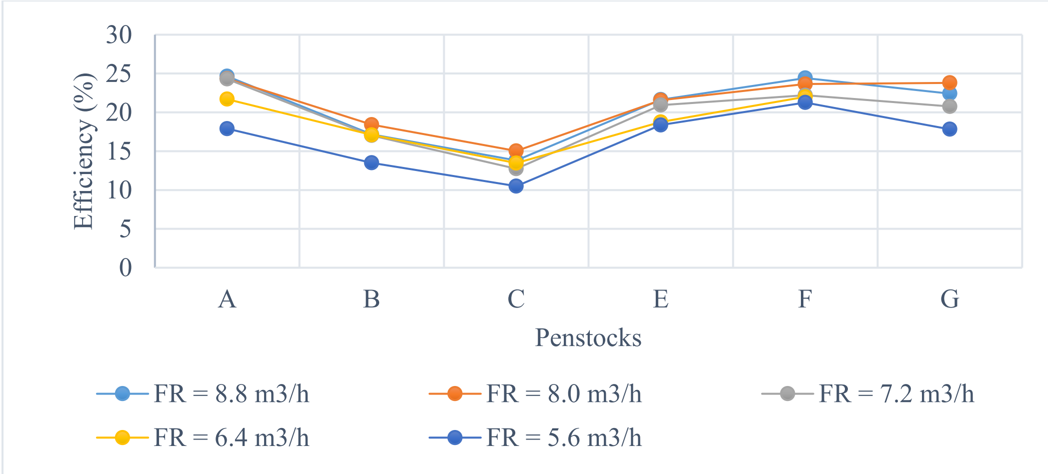

Figure 5. Efficiency of GWVPP for different penstock and flow rate

Penstock B was determined to have the lowest efficiency of 7.11% at a flow rate of 5.6 m^3/hr at an outlet diameter of 72 mm. Conversely, the most efficiency ever measured was 28.29% using Penstock D with a flow rate of 8.8 m^3/hr. Apart from that, the measured power plant's efficiency was 28.17% under the same configuration but at a flow rate of 8.0 m^3/hr, which is marginally less than the maximum efficiency attained under the same outlet's diameter and Penstock D. For 76 mm of output diameter under various inlet flow rates and penstock configurations. Based on Figure 6, it can be shown that Penstock E has the highest efficiency of 26.59% at 8.0 m^3/hr. On the other hand, Penstock C and an inlet flow rate of 5.6 m^3/hr produced the lowest efficiency. Only 15.13% of the efficiency was recorded.

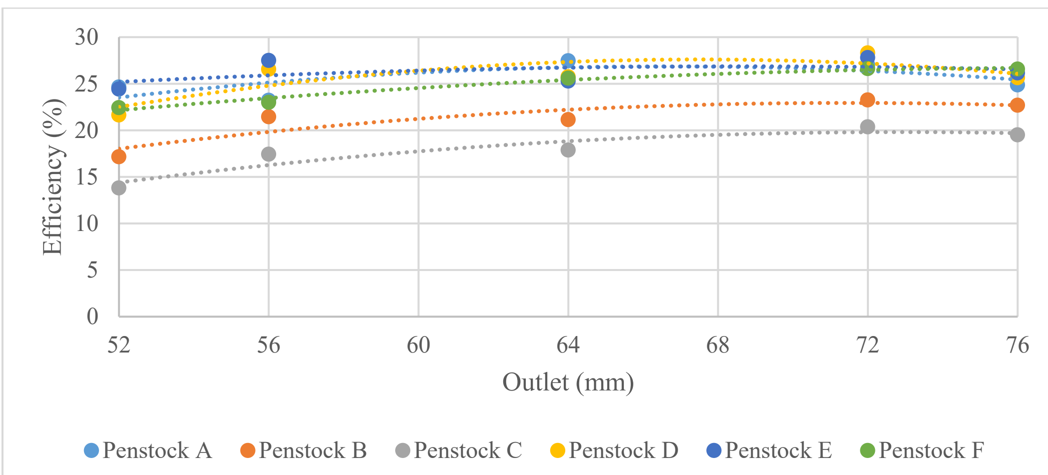

Figure 6. Efficiency of GWVPP for different t basin outlet diameters

When the outlet diameter was 72 mm, the flow rate was 8.8 m^3/hr, and Penstock D was used, the maximum possible efficiency among the five outputs was 28.29%. In the meantime, 2.3% was discovered to be the lowest efficiency when using Penstock C with an outlet diameter of 64 mm at 5.6 m^3/hr. It is important to note that all outlets with the lowest efficiency were measured with an input flow rate of 5.6 m^3/hr under a comparable setup, primarily Penstock C. Penstock E was discovered to produce high efficiency for three exits together with input flow rates of 8.0 m^3/h and 8.8 m^3/hr. The highest efficiency varied amongst three penstocks, A, D, and E. The flow rates of 5.6 m^3/hr, 6.4 m^3/hr, 7.2 m^3/hr, 8.0 m^3/hr and 8.8 m^3/hr were fixed to find out the highest and lowest efficiency under different outlet diameter and penstocks. The results presented in the Figure 7

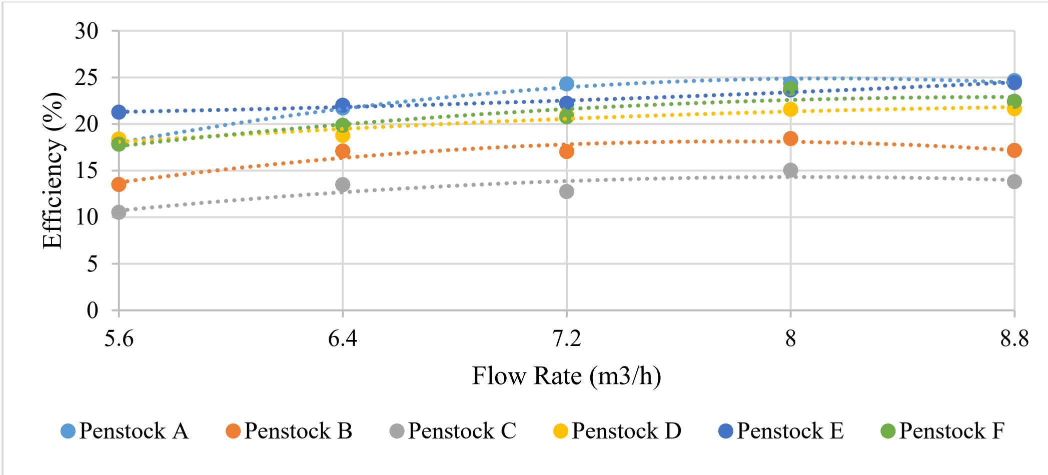

Figure 7. Efficiency of the GWVPP for different flow rates

With Penstock D and the outlet's diameter of 72 mm fitted with an input flow rate of 8.8 m^3/hr, the tested power plant achieved the maximum efficiency among the five flow rates. Up to 28.29% efficiency was recorded. On the other hand, when Penstock C was put in conjunction with an outlet that had a 64 mm diameter and an inlet flow rate of 5.6 m^3/hr, efficiency as low as 2.3% was noted. It was found that installing Penstocks A, D, and E beside outputs with a diameter of 64 and 72 mm often yields the maximum efficiency for each flow rate. Conversely, it was discovered that Penstock C and outputs with 64 mm and 52 mm dimensions were responsible for the built power plant's low efficiency at all measured flow rates. It was discovered that, among the six penstock models, an incoming flow rate of 5.6 m^3/hr was always present in conjunction with the low efficiency of the constructed power plant, regardless of the penstocks. The power plant recorded decreased efficiency at most setups due to the inlet flow rate of 5.6 m^3/hr when compared to other flow rates at comparable setups. This was particularly true when a 64mm-diameter exit was used with a 5.6 m^3/hr intake flow rate.

Conclusion

Five different entrance flow rates were assessed on the laboratory-sized GWVPP with different penstock geometry and outlets connected. It was found that the GWVPP's efficiency will increase when the inlet flow rate is raised from 5.6 m^3/hr to 8.8 m^3/hr. Other than that, several hypotheses led to the conclusion that the GWVPP efficiency was barely affected by penstock models A, D, E, and F. More experiments were needed to validate the hypotheses. Conversely, it has been discovered that Penstock Models B and C, with their larger feeding widths, lower the GWVPP efficiency. The optimal diameter range for the prototype was found to be 64–72 mm at intake flow rates of 8.8–8.0 m^3/hr. The maximum efficiency of 28.29% was attained with an output diameter of 72 mm and a penstock model D running at a flow rate of 8.8 m3/h. In conclusion, Mulligan and Hull (2010) advise that the output diameter be maintained at a ratio of 0.14 to 0.18 in the GWVPP design, but the feeding width for the penstock should be reduced. Furthermore, the inflow flow rate must be as high as practical given availability.

Acknowledgements

The authors would like to acknowledge the support of the World University of Bangladesh to provide financial assistance and the opportunity to work in the laboratory. The author wishes to thank every staff member and colleague at the WUB for their cooperation and support during this research period. The author also wishes to thank all his friends and colleagues for their help and encouragement during this research at WUB.

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Biographies

Md. Mizanur Rahman is currently employed as a professor at the World University of Bangladesh. In addition, he has worked on the Renewable Energy Technology in Asia (RETs in Asia) project at KUET and AIT from January 1999 to December 2004 as a research assistant, research engineer, and consultant. Following that, he went to work for an NGO called BRAC Bangladesh as a program support professional. He joined Rural Power Company Ltd. (RPCL) in February 2006 and remained there as assistant manager until July 2007. In July 2007, he began his doctoral studies at Universiti Malaysia Sabah in Natural Draft Chimney. Dr. Rahman began serving as a lecturer at the TAS Institute of Oil and Gas in July 2009 and continued to do so till August 2012. He then moved on to become a senior lecturer at Universiti Malaysia Sabah before enrolling in the World University of Bangladesh. In addition, he holds a life fellowship in the Institutes of Engineers Bangladesh and is a professional member of the IEOM.

Mustafizur Rahman, currently a senior lecturer in World University of Bangladesh's Department of Mechatronics Engineering, was formerly a lecturer in City University Bangladesh's Mechanical Engineering Department. He brings a great deal of knowledge to the table, having completed a Bachelor of Science in Mechanical Engineering at IUBAT in 2018 and a Master of Science in Automotive Engineering at Coventry University, United Kingdom in 2021. Mustafizur is a researcher whose interests include Automotive Development, Green Energy, and Nanotechnology. He has worked in academia for over three years and in industry for over two. His work in both academia and industry shows his dedication to developing engineering knowledge.

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Ahmed Farhan is working as a lecturer in the department of Mechatronics Engineering at World University of Bangladesh (WUB). He completed his Bachelor of Science (B.Sc.) in Electrical and Electronic Engineering at the renowned Islamic University of Technology (IUT) with the OIC scholarship. During his time at IUT, Mr. Farhan demonstrated exceptional dedication to his studies and a passion for learning that set him apart from his peers. After earning his B.Sc. degree, Mr. Farhan continued his educational journey by pursuing a Master of Engineering (M.Engg.) degree from Harbin Engineering University (HEU) with the prestigious CSC scholarship. His journey from IUT to HEU is a testament to his ambition and determination to reach new heights in the world of engineering and technology. As Mr. Farhan continues to advance in his career, his educational achievements and personal qualities position him as a promising individual who is poised to make significant contributions to his field and society as a whole. Mr. Farhan has published three international journal papers and one conference paper. His research interests are biomedical engineering, image processing, and renewable energy.

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Dr. Mohammad Mashud is a research fellow at the Aerospace Center at UTEP, USA, and a professor in the mechanical engineering department at Khulna University of Engineering & Technology, Bangladesh. In 1975, he was born in Dhaka, Bangladesh. He graduated with a doctorate in aerospace engineering. In 2006, I received my degree from Nagoya University in Japan. In 2003, he graduated with a Master of Engineering from the same department and Japanese university. At Bangladesh's Khulna University of Engineering and Technology (KUET), he earned a Bachelor of Science in Engineering (Mechanical). He began working as a lecturer in the KUET Mechanical Engineering Department in 1999.