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Presenter Information

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Development of a 1 kW gravitational water vortex hydropower plant prototype

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Abstract: *A pilot testing of a Gravitational Water Vortex Hydropower Plant (GWVHP) has been done to evaluate the applicability in a real-world scenario and validate the results from the lab-scale model. A scaled-up model of a capacity of 1 kW was constructed for the evaluation purpose. The test provided data in good agreement with a lab-scale model and a proper visualization to install Gravitational Water Vortex in real-world scenarios. The project lasted for nearly four months and thus provided important information on the problems that might arise in scaling up the lab model to a micro-hydro system. The pilot testing shows an overall plant efficiency of 49%, validating the lab-based studies conducted beforehand. The information obtained from this pilot study shall be implemented in a micro-hydro project on a larger scale.*

Keywords: *Gravitational water vortex, Low-head hydropower, Micro-hydro, Pilot study, Similitude.*

1. INTRODUCTION

In modern society, electrical energy has become a critical commodity. Wind, solar, and small-scale water supplies can generate electricity in rural areas using renewable energy technologies. Pico/micro-hydro can be deployed at a lower cost than solar PV, grid extension, and diesel generators and thus tends to be a relatively inexpensive solution for rural electrification (Green et al. 2005; World Bank 2007). While some Pico/micro hydropower plants use small-scale replicas of commercially successful large turbine units, others use specifically designed new technologies. These new technologies are mainly "Run-of-the-River" schemes that do not necessitate heavy civil constructions and thus are less expensive and more environmentally friendly but are highly dependent on local hydrological trends (Watson et al. 2010). Gravitational Water Vortex Hydropower Plant (GWVHP) is one such technology developed by Austrian inventor Franz Zotlöterer; the prototype was installed in 2006 at the Ober-Grafendorf River, Austria. Numerous research has been done on design variation in the vortex chamber and the runner since then. The turbine system considered in this research is depicted in Figure 1 to better understand terms and terminologies that appear frequently in this article.

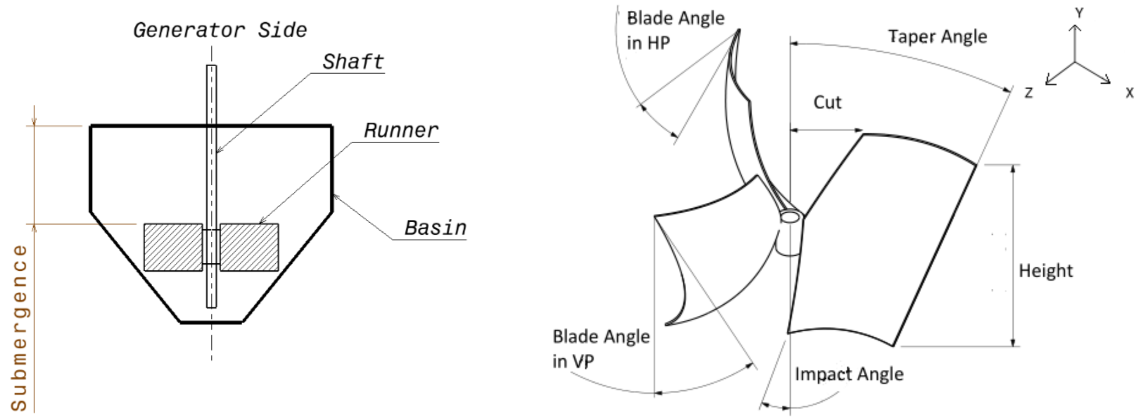


Figure 1 – On the left: basin and turbine schematics of a GWVHP (Reproduced with permission from Bajracharya et al. (2018)). On the right: a runner showing different geometric parameters (Retrieved under CC BY license from Bajracharya et al. (2020))

An experimental study (Bajracharya & Chaulagain 2012) analysing the effect of the cylindrical basin depth showed no substantial increase in power output. However, the research paved the way for modifying the basin shape into a cone (decreasing basin cross-section diameter with the depth). Later, the vortex speed and the power propulsion of the modified cylindrical and conical basins were compared by Dhakal et al. (2013). The runner was designed using the impulse turbine concept. A parametric analysis of the conical basin was conducted to determine the effect on flow velocity measured in the impeller's midplane (Dhakal et al. 2014). The optimal range for different parameters was defined; the most sensitive parameter was basin opening. Dhakal et al. (2015) showed the superiority of conical basin (Figure 2) and identified the optimal submergence with impulse type runner 65 – 75% of the basin height. To further investigate runner design, seven different geometrical parameters and their optimal range were identified by Bajracharya et al. (2020). The most efficient runner (Figure 2) had a system efficiency of 47.85%. After the study of 22 different runners, Bajracharya et al. (2020) recommended that the turbine runner respects the 5 rules below to get an efficient GWVHP design:

(i) Runner height to basin height ratio of 0.31 - 0.32,
(ii) Taper angle conforming to the basin cone angle,
(iii) Blade impact angle of 20 degrees,
(iv) Blades curved when viewed from the top only with blade angles 50º - 60º,
(v) Cut ratio less than 15%.

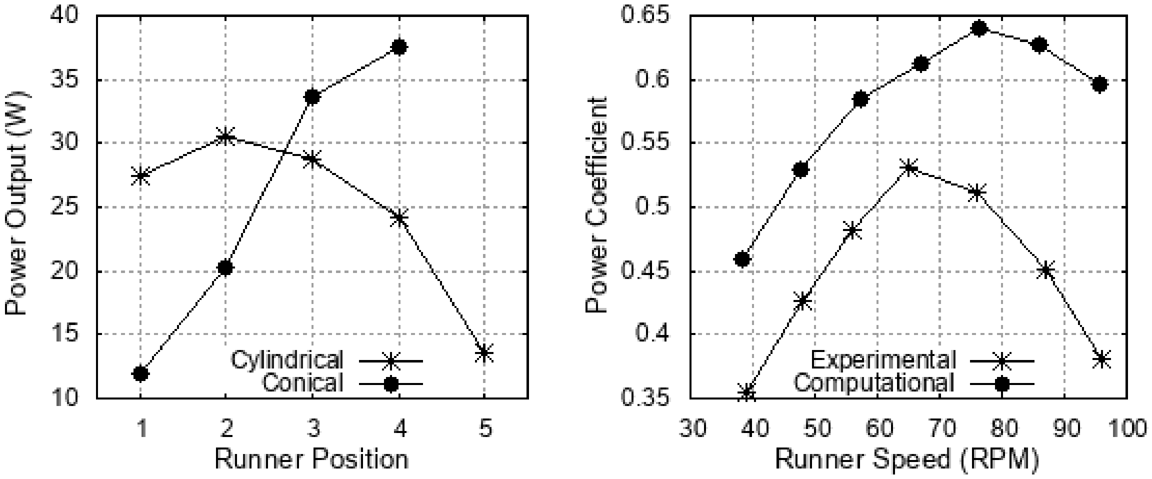


Figure 2 – On the left: Cylindrical basin vs. Conical basin (Reproduced with permission from Bajracharya et al. (2018)). On the right: Performance curve of the most efficient runner with conical basin (Retrieved under CC BY license from Bajracharya et al. (2020))

Gravitational Water Vortex (GWV) is an emerging technology with many variations for vortex chamber proposed to date. However, the vortex flow phenomenon and harnessing power from this technology is not yet fully understood. Research is being conducted on this topic to understand the flow regime in each type of basin with numerical simulation or experimental modelling or both and harness the mechanical power from the swirling flow efficiently with an appropriate turbine system. This study develops a 1 kW pilot project of GWV with a conical basin from experience gained from different lab-scale studies. The system is developed at premises of Centre for Energy Studies, Institute of Engineering. This pilot study has been done to provide a steppingstone for a handful of yearlong research done within the institute. The authors hope this study would provide ample information for routing this technology towards power production in real-world scenarios, predominantly rural and/or grid-isolated areas.

2. SIMILITUDE: MATERIALS AND METHODS

Similarity requires confirmation of geometries (shape), kinematics (motion), and dynamics (forces) between two different models. In practice, the dynamic similarity is satisfied implied that this also satisfies the other two mechanical similarities. The flow in GWVPP is an open channel flow, a fluid flow with a free surface subjected to atmospheric pressure. The dimensionless numbers to be considered in open channel flow in GWVPP are Reynolds number and Froude number. Achieving both similarities simultaneously is not possible in this study, and this gives rise to scale effects between model and prototype (Heller 2012). Due to the nature of gravity dominant flow, only Froude similitude is considered. The calculated Froude number is used to evaluate the width of the inlet canal based on the canal height. The conical basin is scaled up by a factor of 5 compared to the lab model. The basis for exit hole diameter is maintained as 18% of basin diameter, as suggested by Mulligan & Casserly (2010). Since the basin must handle the designed flow rate, the basin height was adjusted for a safety factor of 2 based on the discharge coefficient of the model. With a discharge coefficient of 0.0182, the height of the basin for the scaled-up model was calculated and rounded off to be 1.4 m. The design summary of hydraulic components is presented in Table 1:

Table 1- Hydraulic Components Sizing

Description	**Sizing**
Designed flow capacity of canal (Q_D)	0.15 m^3s^{-1}
Cross section area of canal	0.5 (b) * 0.6 (h_c)= 0.3 m^2 (factor of safety 2 used for height)
Diameter of cylindrical basin (D_b)	2 m
Diameter of exit hole (d_b)	0.36 m
Total height of basin (h_b)	0.5 m (cylindrical) + 0.9 m (conical) = 1.4 m
Cone angle (ϕ)	42º
Width of rectangular weir (w_w)	1 m
Capacity of one pump (Q_p)	0.009 m^3 s^{-1}
Total capacity of pumps (Q_{max})	15*(Q_p) = 0.135 m^3 s^{-1}

The runner's design is based on the lab-scale model studied by Bajracharya et al. (2020), adapted here for a large-scale model. The submergence requirement fixes the position of the runner. At this fixed position, the runner requires a clearance from the basin wall to prevent any runner blade – basin wall interaction during operation. Bajracharya et al. (2020) suggest clearance is required so that the runner placement does not stop the basin's vortex formation. The prototype runner was designed based on the computational efficiency (64%) of the model runner since the experimental efficiency of the model runner incorporates several losses starting from manufacturing precision to operating condition. For scaling up the GWV turbine, the dimensionless relationships considered are specific speed, discharge coefficient, and power coefficient whose numerical values are 58.56, 0.00181, and 2.511E-6, respectively.

The runner diameter is determined based on these dimensionless numbers as the prototype runner's top outer diameter (D_1). All other parameters are evaluated based on these calculated values and suggestions made by Bajracharya et al. (2020). The runner height ratio of 0.3 used for calculations is adjusted to 400 mm to maintain the designed head with some clearance for the flow circulation. The parameter cut (Bajracharya et al. 2020) has been adapted here slightly differently as the radial cut; defined as the ratio of the top outer diameter to top inner diameter. The runner from the lab model has a top outer diameter and the hub diameter of 360 mm and 40 mm, respectively. The radial cut equivalent to a cut of 15% is 0.245, whereas the angle of inclination obtained for the inner edge of the blade is 8.11º. The parameter cut used in the lab model study can now be replaced by inclining the inner edge runner blade (λ) against the runner's axis. From the geometry of the runner-basin system the bottom outer and diameters are given by equation (1) where X_1 and X_2 are the distance of the outer tip of the blade from runner axis at top and bottom edge of runner blade, respectively.

$$\begin{aligned} X_1 &= \sqrt{\left(\frac{D_1}{2}\right)^2 - \left(\frac{H\tan\gamma}{2}\right)^2} \\ X_2 &= X_1 - \frac{H\tan\psi}{\cos\gamma} \\ D_2 &= 2 * \sqrt{{X_2}^2 + \left(\frac{H\tan\gamma}{2}\right)^2} \\ d_2 &= d_1 - \frac{d_1}{D_1} * (D_1 - D_2) \end{aligned} \tag{1}$$

For modelling and manufacturing, all the runner dimensions are rounded off to suitable integer values.

The dimensions are listed in Table 2. Shigley's mechanical design (Budynas & Nisbett 2011) has been followed for proper shaft selection, transmission pulleys and belts, and bearings. Table 3 shows different components and their selection sizes.

Table 2 - Turbine Runner Sizing

Description	**Sizing**
Runner height (h)	400 mm
Inlet/Outlet blade angle in HP (β)	54º
Impact angle (γ)	20º
Taper angle/Inclination of outside edge (ψ)	30º
Inclination of inside edge (λ)	8.11º
Top outer diameter (D_1)	1010 mm
Top inner diameter (d_1)	250 mm
Bottom outer diameter (D_2)	520 mm
Bottom inner diameter (d_2)	170 mm
Runner clearance with basin wall (δ)	60 mm
Number of blade (N_b)	9
Runner position (H_{max})	1050 mm (below from the top of the basin)

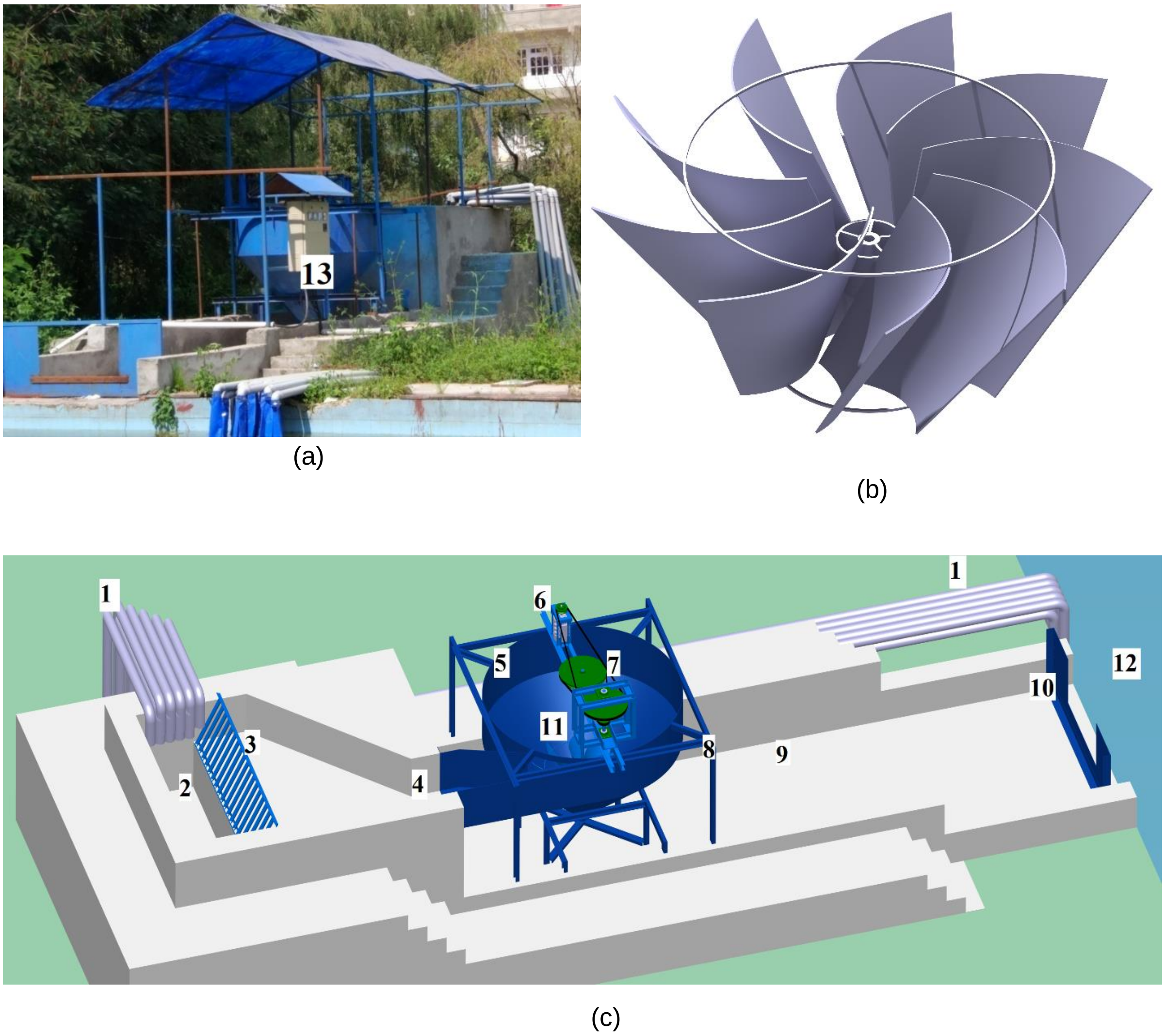
Table 3 - Mechanical Component Sizing

Description	**Selection and Sizing**
Shaft power rating	1 kW
Shaft speed rating	70 RPM
Factor of safety for shaft	3
Shaft diameter	30 mm
Gear ratio for single stage transmission	1400/70 = 20
Gear ratio for two stage transmission	$\sqrt{(20)} = 4.47 \approx 4.5$
Pulley belt configuration	V-belt type B, double groove
Factor for safety for pulley	1.25 (Stage 1) & 1.7 (Stage 2)
Bearing reliability	0.9 (0.97 for each)
Bearing type	Deep groove on the top and tapered roller on the bottom

Fifteen submersible pumps, each with their supply pipeline, convey water from an adjacent pond to the installed plant, then discharge back to the pond following the plant operation. The flow is varied by switching individual pumps. The drop chamber serves as a forebay for the system while both the drop chamber and the trash rack help dissipate the turbulence introduced by intake pipes and settle any unwanted debris if present. Water flows to the basin via the intake canal, forms a counter-clockwise vortex, and exits via the bottom exit hole. The turbine placed coaxially with the basin converts hydraulic energy into mechanical energy. The mechanical energy is transmitted via 2 – stage pulley system to a generator (induction motor used as a generator) which supplies power to a control panel. Several incandescent bulbs and a ballast load dissipate the power. The exit water flows back into the pond. At the end of the tailrace, a weir is used to measure the flow rate. Figure 3 shows the plant layout and runner with different components.

3. RESULTS AND DISCUSSION

The computational efficiency of the model runner studied in the lab is 64%; hence the expected power output for the given head and flow rate of the prototype is 0.659 kW. Also, the estimated operational speed of the prototype runner is 63 RPM. However, due to the spillage, seepage from concrete structures, and intake pipes, the flow into the basin is reduced and thus corrected here for calculation purposes. The data acquired from installation and operation are used to evaluate the overall system efficiency of the micro-hydro plant. The hydraulic power input to the system was:



1) Intake
2) Drop chamber
3) Trash rack/Speed neutralizer
4) Inlet canal
5) Conical basin
6) Induction motor used as generator
7) Transmission pulley arrangement
8) Basin support structure
9) Tail race
10) Rectangular weir
11) Turbine runner with shaft
12) Pond
13) Power supply/Multipurpose control panel

Figure 3 – (a) Experimental Facility: Plant installed at CES, IOE, (b) runner 3D model (c) plant layout

- Maximum Flow measured (Q_{max}) = 0.1175 m^3s^{-1}
- Head (H) = 0.9 m
- Input power (P_o) = $\rho g Q H$ = 1031 W = 1.031 kW
- Turbine runaway speed = 88 RPM
- Generator Speed = 1750 RPM

The installed power plant is run under various flow rates by controlling water supply pumps and variable load by changing the electrical load. Several standard 100 W incandescent bulb has been used, and load has been varied in the step of 100 W from the control panel. Figure 4 shows the part-load electrical efficiency of the system under various flow rates. The best efficiency points are chosen and presented as part flow efficiency of the system.

Figure 5 shows the system in operation. The power generated from the vortex runner is glowing 100 W bulbs.

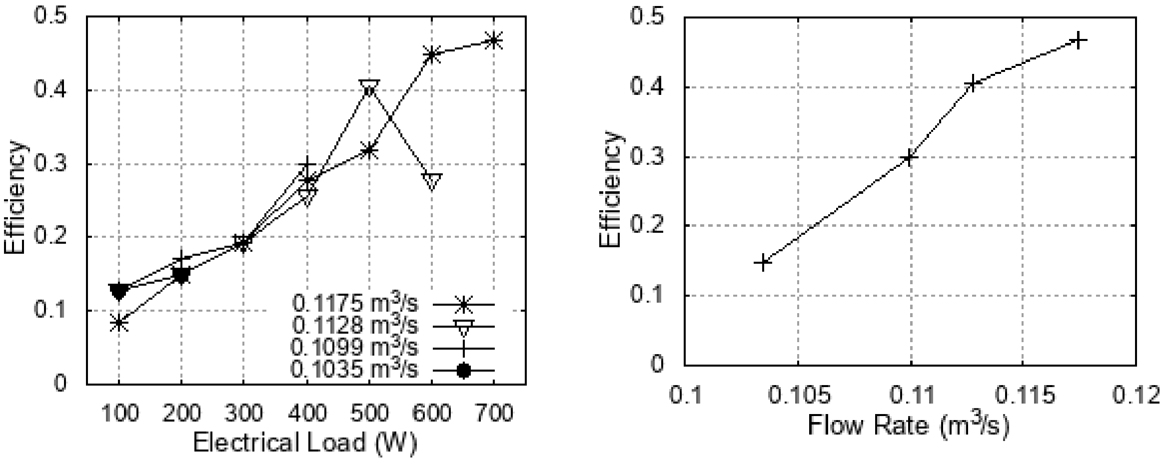


Figure 4 – On the left: Efficiency trend of the micro-hydro plant for various flow rates. On the right: Part flow efficiency of the micro-hydro plant

Figure 5 – Working of the Plant

Figure 4 shows that the maximum efficiency gradually decreases when subsequent pumps are turned off. This suggests that the plant should be operated nearer to its design condition, preferable to hydro turbines. However, a flat efficiency curve for some flow rates suggests that the plant can operate with relatively good efficiency like Pelton and Turgo turbines. Also, it gives us more insight into the operational nature of GWVPP itself. Overloading the plant under lower flow conditions can negatively affect power production, as shown by the dipping nature of the 0.1128 m^3/s curve in Figure 4. Also, a sweet spot exists for maximum efficiency, suggesting that flow regulation could help achieve better efficiency when the end load demand is lesser. After analysing the results, the following conclusions can be made about the pilot study and GWVHP in general:

(i) The system can be considered a suitable micro-hydro alternative where the availability of low head and high flow rate does not suit conventional turbine systems.
(ii) This type of system has a flat efficiency curve for a specific flow interval. The vortex formation is impossible, and the plant does not operate below a threshold flow rate or above the rated load.
(iii) The efficiency curve can be better understood by increasing the resolution of the loads.

4. DESIGN, ERECTION ASPECTS, AND GUIDELINES FOR GWVHP

This section is presented as a general guideline that can be helpful in successfully deploying a GWVHP. This section covers different aspects of GWVHP related to design, construction, material selection, transportability, cost-effectiveness, inspection, maintenance, etc. The guidelines presented here depend on the available literature, general practices, and experiences gained during the lab studies and prototype deployment.

- The inlet canal should be designed with a factor of safety that pertains to possible high flow in the intake canal. The canal width should be at least twice its height. A slight slope of a few degrees is preferred in the intake canal.
- The flow diversion from the river should be made at an angle closer to 90º. Also, the location should be chosen so that the headrace and tailrace span over longer lengths. This selection helps mitigate river currents and upstream river effects in the hydropower and settles the turbulent exit water before re-entering the river.
- Due to the sloshing effects, the plant is not beneficial to run above the designed flow rate due to spillage along the sides of the basin and canal closer to the basin.
- Small debris can easily pass through the hydropower plant, while larger debris needs a trash rack. Since sophisticated technology is not available at a remote place, the trash rack should be placed to be cleaned manually and less frequently.
- The cylindrical height of the basin is determined by canal height, whereas the available head determines cone height. The discharge coefficient determines the basin diameter. The exit diameter is taken as 18% of the basin diameter.
- Since using concrete to shape a cone can be costly and cumbersome, a metal basin, a concrete intake canal, and a concrete tailrace is preferred. The floors of the basin and intake canal should be made smooth to mitigate friction losses.
- Small panels should be developed into a cone and welded on-site to avoid the expensive transportation of a large basin. A metal basin makes it easier to couple all the mechanical components like pulley and shafts to the basin.
- Two bearings are needed to hold the shaft and runner in place. The lower bearing design needs special attention. A water-lubricated bearing is preferred, but a ball bearing properly sealed should suffice at the bottom of the shaft.
- Pulleys are preferred to gearboxes owing to low maintenance and cost-effectiveness. A two-stage or three-stage pulleys could be designed as per requirements. The selection of shaft, pulley, bearings, and belts are to be made based on available design guidelines.
- An induction motor can be used as a single-phase or three-phase generator. A standard ELC circuit with a proper current/voltage rating is suggested.
- Several components should be protected against wear and erosion. The metal components are to be coated against rust. Also, the s-metal coating is suggested for erosion if possible. The moving components are to be lubricated. The floor beneath the basin exit hole should be provided with means like a drop chamber to reduce the excavating effect of exit water.
- The control room should be secured against possible thefts and other hazards. A few spare parts should be kept in stock.
- Supervision from an engineer is suggested during installation. The issue of turbine eccentricity, basin–canal alignment, proper installation of all other moving components should be checked thoroughly. Also, a scheduled maintenance/inspection should be taught to locals.

5. CONCLUSION

The development of the 1 kW system provided a valuable experience regarding the successful development of a Gravitational water vortex power plant. The major problems encountered were transportation and installation. As the conical basin was fabricated in a single piece, it required large truck for transportation and a crane for erection at the installation site. To reduce this, it is recommended to develop basins in small sections and weld on site (or bolt) to form the entire basin. This would reduce both the transportation and erection cost. Evaluation of global systems of GWVHP (Timilsina et al. 2018) revealed that the average system efficiency is about 53%, and total efficiency of the system developed was 49% which can be considered competitive among similar technologies. From the tests performed and performance evaluation, it can be concluded that conical basin can successfully be deployed in site and with little considerations in design can be developed as an immediate energy relief device in disaster hit area.

6. ACKNOWLEDGMENTS

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