Performance analysis of a two-stage gravitational water vortex turbine

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Abstract. In the present study the performance of two-stage gravitational water vortex turbine (GWVT) assembled in a conical basin with Savonius blade profile configuration has been investigated at different flow rate and vortex elevation. Two-stage GWVT with conical basin, not only increases the performance parameters with increase in flow parameters, but the lower stages also feed additional impact to the stage located above it because of forced vortex generation in the vicinity of top stage. Moreover, maximum hydraulic head drop near the orifice is the main contributor in the power generation of the bottom stage, by giving rise to strong tangential velocity. A stage starts power production as soon as the parabolic surface of the vortex approaches the corners of the blades even in the absence of a significant water-blade interaction. The developed analytical model qualitatively predicts the performance of the turbine minutely leading the experimental results quantitatively.

1. Introduction

Gravitational water vortex power plant (GWVPP) is a relatively new technology in the field of micro hydro power plants (MHPPs) for electricity generation. In a GWVPP, the power from an artificially induced water vortex under gravity is extracted through a non-conventional co-axial gravitational water vortex turbine (GWVT) that works under a head of 0.7-3m [1-3]. The past studies have mainly used a cylindrical basin for generation of gravitational vortex [4-10] with an optimum orifice diameter to basin diameter ratio of 14% - 18% [5, 7, 8], however, a similar combination for conical basins is yet to be investigated [11]. Experimental studies on GWVT performance with cylindrical basin considered the effects of various parameters such turbine position along the height of the basin, the blade size, blade numbers, testing of different blade profiles, numbers of blades and blade materials [2, 9-12]. The said experimental investigations have been missing for a GWVT with a basin of conical configuration until the recent work of Dhakal et al. [11, 13]. The vortex strength dominates in conical basin over cylindrical basin and hence, gives more output power for the same input parameters [13]. The literature has reported the use of CFD tool to trace the effect of basin diameter, notch length, canal height and cone angle on the vortex formation in conical basin [15].

The past studies have used only a single runner in a GWVT setup. However, it was suggested that a multistage turbine can be installed to extract the power of vortex reformed in a conical basin after its initial distortion by single runner [14]. Moreover, the researchers have used blades of conventional turbines which tend to cut the flow stream and is undesirable in a GWVT [5, 7, 8]. The present study addresses the aforementioned concerns by introducing the profile of Savonius type blades with conical configuration in the present study along with the performance investigation of two-stage GWVT at
various flow rates and vortex elevation. Rotational speed, torque and power have been examined experimentally as well as analytically for a prototype multistage GWVT.

2. Experimental methodology
The schematic of experimental setup used in the present study for the testing of two-stage GWVT has been shown in Figure 1. The complete facility consists of a water storage tank (415 L), a centrifugal pump (3hp), an overhead water reservoir (230 L), a basin and a multistage GWVT assembly. The two valves located at the entrance of upstream channel and at the exit of basin are adjusted to ensure a proper vortex formation and maintenance of desired vortex elevation in the basin. The exiting water from the water storage tank from where the water is recirculated through a centrifugal pump. The GWVT setup has been assembled in a conical basin with 2 runners each having 4 blades. Each runner is independent in terms of power generation because of telescopic shafts arrangement. The inlet flow rates been measured with the help of volumetric (bucket) method [2, 12, 14]. Flexible arrangement for variation in flow rates is justified with the help of upstream and downstream valves. The rotational speed in revolutions per minute (rpm) was measured with photo/contact tachometer (Lotron DT-2236B). Prony brake mechanism provided the support for the measurement of torque.

3. Results and Discussions
The performance of a two-stage GWVT has been examined experimentally along with analytical calculations by computing speed, torque and power of each stage of the turbine. Though, the aforementioned parameters are important for each individual stage; however, in the present study, main emphasis has been given to the inter-stage relationship, i.e. the effect of one stage on the other. A comparison of analytical performance parameters (APP) has been made with the experimental performance parameters (EPP) for the same conditions. This will provide validation to the analytical model as well as prediction of extended performance. The comparison has been established by investigating the effects of constant and variable inlet flow rates and vortex elevation for two-stage turbine. For the performance evaluation of both stages, ratio of rotor to basin diameter is kept constant at 0.69.

In the forthcoming cases the experimental and analytical results reveal an agreement on the same trend line of rpm, torque and shaft power (Figure 2 and Figure 3). Therefore, it can be inferred that the analytical model qualitatively predicts the correct results with some experimental limitations. \( N_{e1} \) and \( N_{a1} \) represent the experimental and analytical calculated rpm for stage 1, where i stands for stage number. Moreover, the same technique has been followed for torque and power. It has been found that
EPP for S2 supersedes the APP, showing an additional contribution to the performance parameters which has not been reported before [2]. In case of a two-stage GWVT with conical basin, the performance parameters not only increase by the flow parameters (flow rate, vortex and hydraulic potential head) but the lower stage i.e stage one (S1) also feed additional impact to the stage located above it; stage two (S2), to increase power generation in terms of vortex strength. This is the advantage that the two-stage GWVT with conical basin, provides better performance than a single stage GWVT with uniform basin in addition to multiple power from multiple stages.

3.1. Effect of inlet flow rate

The effect of inlet flow rate is important to determine the potential of two-stage GWVT to be installed at a particular water stream. For this purpose, performance comparison between analytical calculations and experimental results of GWVT has been presented for variable inlet flow rates in Figure 2. Initially, a relationship between S1 and S2 has been investigated because of the fact that a maximum flow rate of 5.5 L/s with downstream valve completely opened, the vortex elevation ensures to have water contact with both stages (S1 and S2) of turbine. All cases shown in Figure 2 represents a zero value of performance for S2 at a flow rate of 3.5 L/s, showing that the surface vortex is only in contact with S1. Increase in flow rate causes an increase in vortex elevation because of which runner of S2 starts power production. The variation in EPP as well as APP is negligible at all flow rates above 4L/s since S1 is completely submerged in the vortex. Rpm, torque and shaft power for S2 shows a rise in their values because of the fact that forced vortex generated by the stage below it (i.e. S1) strengthens the vortex in the vicinity of S2 (Figure 2). Another possible reason for the said increment is the gradual increase in the vortex height ensuring a rise in performance parameters with more vortex-blades interaction. In case of S1, experimental and analytical results are in good agreement both qualitatively and quantitatively.

In the absence of any stage below S1, all the power produced by it can be attributed only to the water flow rate and head drop. A small variation in effective head drop significantly affects the vortex tangential velocity. Therefore, the head drop is the main source of power generation located near the outlet. An overall assessment of Figure 2 reveals that S1 outperforms S2 in terms of rpm, torque and shaft power for all investigated inlet flow rates.

3.2. Effect of vortex elevation

![Figure 2. Effect of inlet flow rate on (a) Rotational speed (b) Torque](image-url)
The vortex elevation is the vertical straight-line height of the free surface of the vortex from the bottom of the basin. This is an important parameter both from the vortex formation and power generation point of view. The effect of vortex elevation on the performance parameters have been examined in context of the relationship of the stages of GWVT. At first, APP and EPP of S1 and S2 at constant inlet flow rate of 5.5 L/s have been conducted for all the two-stage of GWVT by maintaining the same flow rate of 5.5 L/s as shown in Figure 3. In all cases, outlet valve is adjusted in such a way to get fixed vortex elevation during experimentation and thus S1, may be considered completely submerged in water at all vortex heights. On the other hand, the submergence of S2 start at vortex elevation of 0.607m. An important observation need to be considered that the top stage start power production as soon as the parabolic surface of the vortex approaches the corners of the blades, though the vortex-blade contact is not significant. Therefore, the performance parameters below vortex elevation of 0.607m of S2 represent smaller magnitudes than because of the said effect.

Figure 3. Effect of vortex elevation on (a) Rotational speed (b) Power

For the relationship between S1 and S2, it can be observed from Figure 3 that there is a sharp decline in the rotational speed (rpm), torque and shaft power of S1. The decrease in said performance parameters may be attributed to the effect of vortex distortion because of S2. Moreover, APPs are over predicted than EPPs for all investigated vortex elevations showing that the analytical method does not account for the vortex distortion because of the neighbouring stage. On the other hand, the performance parameters for S2 increases as well as APPs are observed to have been under predicted. Since, area of contact between gravitational vortex and S2 blades increases with the increment in vortex elevation thus, there is a gradual increase in the performance parameters. Moreover, the forced vortex generated by the stage below it (i.e. S1) strengthen the vortex near the region of S2, thus the performance of S2 is enhanced. It is of worth mentioning that the analytical model is unable to accurately predict the forced vortex effect which makes it limited.

4. Conclusion
In the present study, the performance of a two-stage gravitational water vortex turbine (GWVT) in a conical basin with Savonius blade profile has been examined. An advantage of a two-stage GWVT assembled in a conical basin is that the performance parameters of top stage are fed because of forced vortex generation from the lower stage. The study concludes that the power generation of bottom stage, located near the outlet is strongly supported by hydraulic head drop. The top stage may start power
production as soon as the parabolic surface of the vortex approaches the corners of the blades, though vortex-blade interaction is not significant.

5. References
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