24th Australasian Fluid Mechanics Conference – AFMC2024
Canberra Australia
1-5 December 2024

Paper No: AFMC2024-124

Preliminary numerical investigation on varying flow field and power output of a Gravitational Water Vortex Power System

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Abstract

Gravitational Water Vortex Power System (GWVPS) is a low head, cost-effective method of extracting hydro power. However, it is considered a less efficient hydropower system; thus, more research is needed to improve its performance. In this paper, a numerical investigation was carried out to examine the performance of a gravitational vortex power system with a cylindrical basin and a 5-bladed curved vortex turbine attached. It was studied in terms of the velocity flow field and power output under varying vortex pool conditions. The Moving Reference Frame (MRF) in Ansys Fluent was used, along with the turbulent k–ω SST in the Volume of Fluid (VOF) model. Four basins with varying basin outlet ratios of 0.17, 0.18, 0.20, and 0.30 were subjected to different rotational turbine speeds of 40, 60, 80, 100 and 120 revolutions/minute (RPM). The study showed that for an outlet ratio of 0.18 at 80 RPM, the water velocity was the maximum at the drain outlet but decreased thereafter for higher drain outlet ratios. The maximum power output for the cylindrical basin was 80 W indicating better performance.

1. Introduction

Extracting electricity from small-scale hydro systems is increasing due to no large dam and less cost and environmental pollution. Gravitational Water Vortex Power System is one of such small hydropower technologies which have been on high demand in recent times due to its low cost and environmentally friendly nature (Nakajima *et al*., 2008; Yah *et al*., 2017). A GWVPS consists of inlet and outlet water channels, a cylindrical basin and a vortex turbine. Water enters the basin at the top and exits at the bottom hole. It is considered an open channel flow with a free surface. The movement causes vortex water flow which turns turbine. blades to produce electricity. Since it has very small head difference, it works by the dynamic forces generated by the vortex rather than the pressure head difference (Feng *et al*.,2009).

For the maximum vortex strength, the basin to outlet ratio should lie within 14-18% (Dhakal *et al*., 2015), where the outlet ratio is denoted by d/D where d and D are diameters of the drain outlet and the basin respectively. According to Nishi *et al*. (2014), the basin outlet ratio of 0.16 was suitable to produce higher torque. Edirisinghe *et al*. (2023) confirmed that greater torque was achieved using the 0.17 outlet ratio on a conical basin coupled to a curved vortex turbine. The study by Kedar *et al*. (2016) shows that vorticity is the key factor influencing the power output. Wanchat *et al*. (2011) observed that although a conical basin performed better, a cylindrical basin performed even better when its diameter was increased. The present investigation is intended to conduct a numerical study using a modified cylindrical basin to study the velocity flow field, torque and power.

2. Geometry

To validate the numerical simulation results of this study, the conical basin inserted with an 8- bladed curved vortex turbine was designed based on the specifications used by Edirisinghe *et al*. (2023), which is shown in Figure 1. After the validation, a cylindrical basin having similar dimensions and coupled to 5- bladed curved vortex turbine is used in the present study.

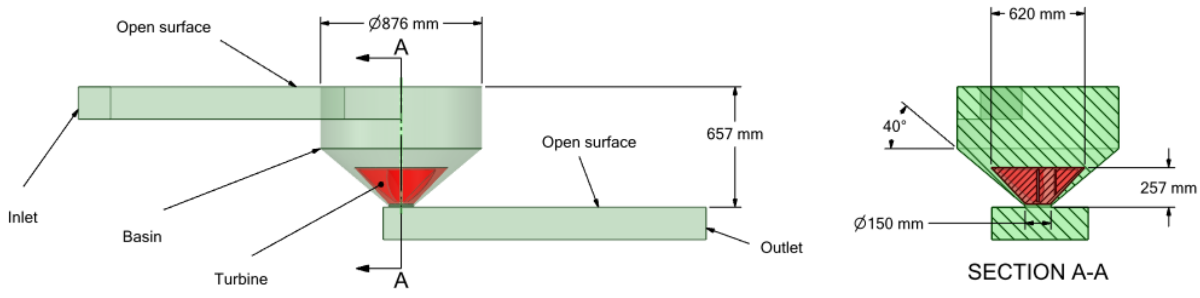


Figure 1. The conical basin used by Edirisinghe *et al*. (2023), which is used for the validation of the present study.

3. Numerical simulation method

In the present study, all numerical simulations were performed using Ansys Fluent version 2023 package.

3.1 Governing equations for the Moving Reference Frame

The MRF model in Ansys Fluent was used in the numerical simulations. It is a steady state approximation approach. It permits unsteady problems with respect to the absolute reference frame to be steady in respect to the MRF. The rotary fluid zone consists of the turbine. The stationary zone consists of the inlet, outlet and basin wall. In MRF, the turbine is steady, but the rotary domain is assumed to be rotating with the same angular velocity of the turbine. The Navier -Stoke Equation in the rotating frame is derived by substituting the relative velocity on the blade in eq. (1) into the governing incompressible steady Navier - Stoke Equation in eq. (2).

$$U = U_r + \Omega \times r \qquad (1)$$

$$\nabla.(UU) = -\frac{1}{\rho}\nabla P + \nabla.(\nu\nabla U) \qquad (2)$$

where U is the inertia velocity, U_r is the relative velocity, Ω is the rotation vector, r is the distance vector, $\Omega \times r$ is the rotational velocity component, ρ is density, P is pressure, and ν is kinematic viscosity of fluid, respectively.

3.2 Meshing of the computational model

Meshing was created in Ansys Fluent Space claim using Mosaic meshing technology. Prism cells, poly hexacore cells and transition cells were assigned to the wall, the interior and the inflation boundary layer, respectively. A total of 2.4 million cells were generated for the cylindrical basin with an orthogonal quality of 0.2. Numerical simulations were considered converged when all monitoring parameters' residuals of 10^{-3} were reached.

3.3 Boundary conditions

The boundary conditions include a velocity of 0.86 m/s, VF (water) = 1, pressure outlets for openings and boundary outlet, and a static pressure at the outlet equal to 0. The flow is gravity driven. The turbulent k–ω SST model in VOF was used with the pressure-velocity coupled method. No slip conditions were assigned to the turbine blades and basin wall.

3.4 Validation of numerical simulation result

To validate the numerical simulations of the present study, numerical simulations with the conical basin inserted with an 8-blade curved turbine used by Edirisinghe *et al*. (2023) were carried out. The numerically obtained torques from both studies were compared, with the results presented in Figure 2, which shows that the differences are within 10%, validating the numerical simulations of the present study with acceptable accuracy.

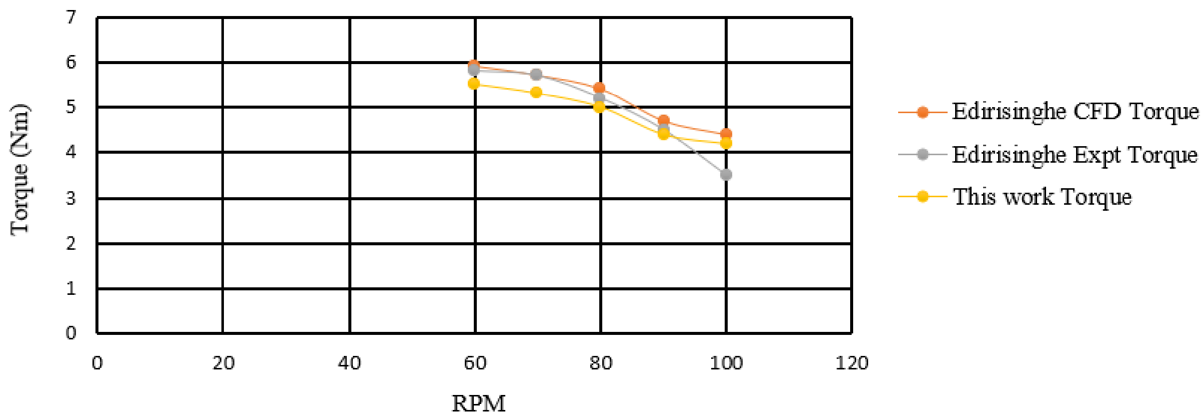


Figure 1. Comparing between the numerical simulation results of the present study and the results by Edirisinghe *et al.* (2023).

4. Design of the numerical study using cylindrical basin

In the present study, a cylindrical basin is used, with a 5-blade curved turbine attached, as sketched in Figure 3. Four cylindrical basins with varying outlet diameters of 150 mm, 160 mm, 200 mm and 300 mm were subjected to five different rotational speeds of 40, 60, 80 100, 120 RPM. Torque and power were calculated from the numerical simulation results.

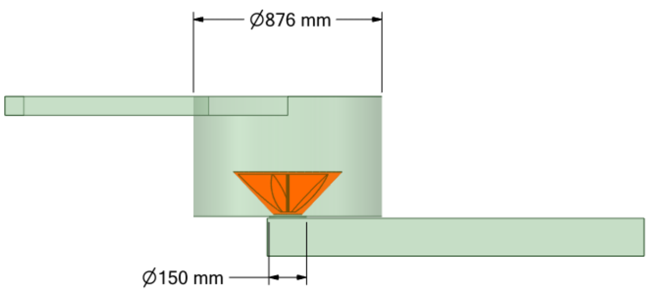


Figure 3. Sketch of the cylindrical basin with a drain outlet diameter of 150 mm.

5. Result and discussion

5.1 Velocity contours and vectors

The numerically obtained velocity contours and vectors were presented in Figure 4 with varying outlet diameters at 80 RPM.

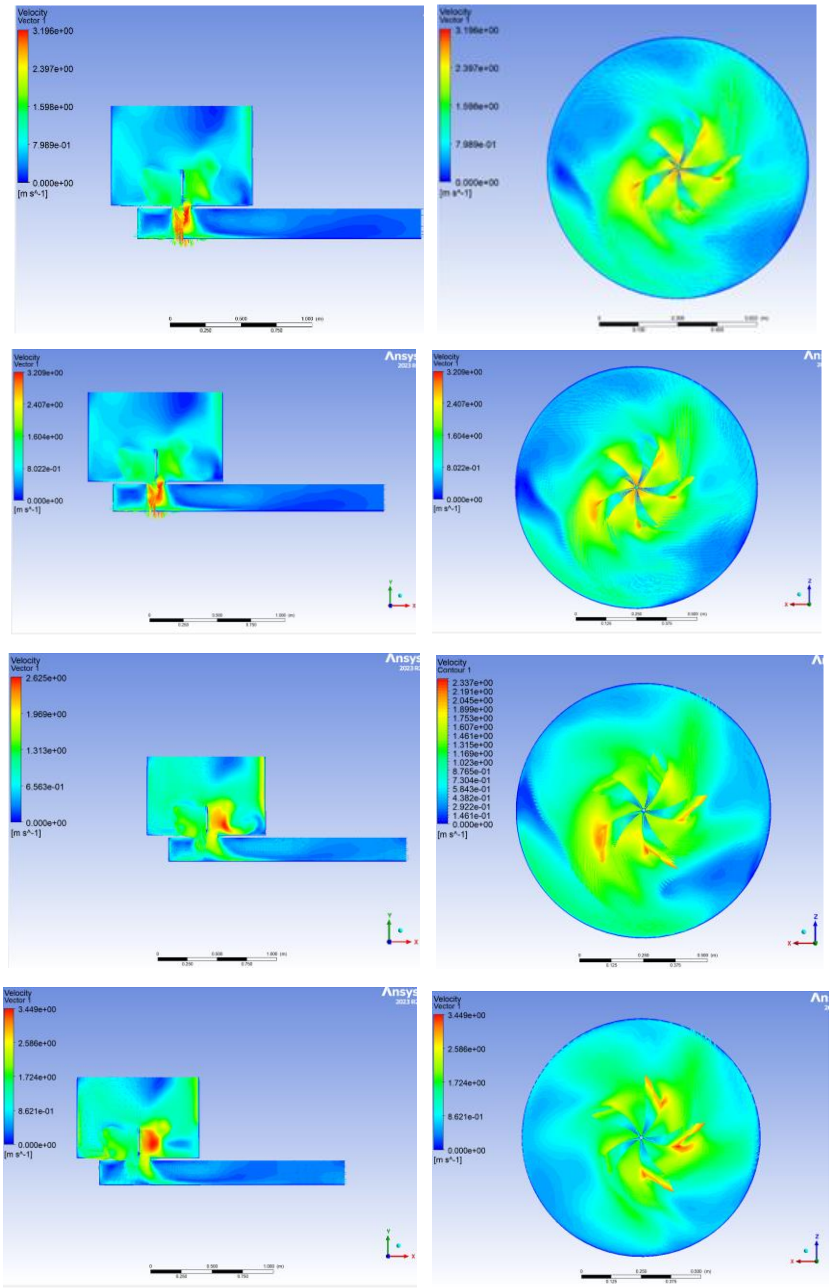


Figure 4. Velocity contours and vectors in the basins with different outlet diameters: 150 mm (top row), 160 mm (second row), 200 mm (third row), and 300 mm (bottom row), all at 80 RPM.

From Figure 4, it can be concluded that as the drain outlet diameter increases, the water discharge velocity magnitude decreases after d = 160 mm (or d/D = 0. 18). This may be contributing to reducing the pressure difference thus resulting in minimal power generation.

The radial circulation of the velocity field becomes distorted towards the bottom as indicated by the velocity vectors. This agrees with that of Dhakal *et al*. (2015), in which the flow was disruptive towards the bottom.

5.2 Radial velocity distribution

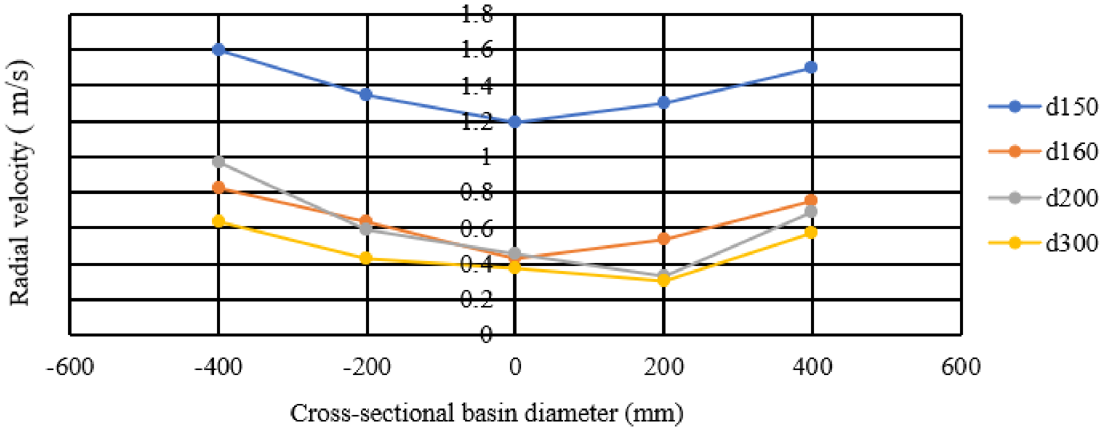
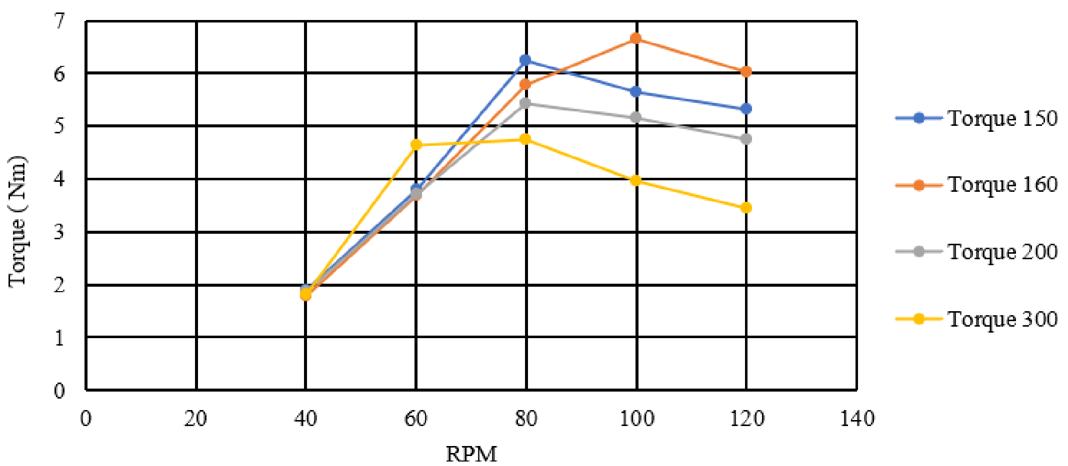


Figure 5. Radial velocity distribution in the basins with different outlet diameters.

A semi parabolic curve radial velocity distribution is seen across the span of the basin for each outlet diameter, as seen in Figure 5, indicating that the radial velocity magnitude is minimal towards the centre of rotation. As the drain outlet diameter increases, radial velocity decreases. For a larger drain outlet diameter, the water reaches the exit and discharges more easily. It should be noted that given the larger blade arm, it may be advantageous to assume that it is utilising the higher radial velocity near the wall to contribute to the generation of power. This agrees with the results obtained by Wanchat *et al.* (2011) in that the cylindrical basin performed even better when its diameter was increased.



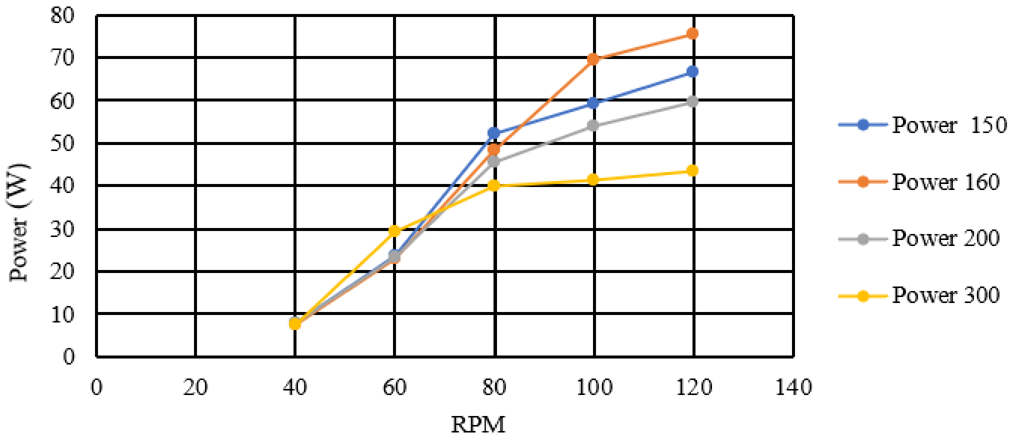


Figure 6. Numerical obtained torque (top plot) and power (bottom plot) plotted against the rotational speed for different outlet diameters.

From Figure 6, it can be concluded that torque and power were the highest for the basin with the outlet diameter of 160 mm (*d/D* = 0.18) at the rotational speeds between 80 RPM and 100 RPM.The studies by Dahal et *al*. (2019) and Yadav *et al*. (2022) confirmed that curved vortex turbines performed better in both conical and cylindrical basins, while the study by Edirisinghe *et al*. (2022) found that the vertical twist turbine performed better in a conical basin. A horizontal curve turbine was considered to perform better in cylindrical basins (Sritram *et al.*, 2021).

6. Conclusions

The cylindrical basins coupled with a 5-blade curved vortex turbine were studied numerically under varying rotational speeds. The results demonstrate there are some improved swirling velocity flow fields at the outlet diameters of 160 mm but decreased afterwards. The maximum power output of 80 W was generated with the rotational speeds between 80 RPM and 100 RPM for the outlet diameter of 160 mm (*d/D* = 0.18).

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