

# GRAVITATIONAL WATER VORTEX: FINITE ELEMENT ANALYSIS BASED DESIGN AND IMPLEMENTATION

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The following work gives the details of the modelling, simulation, and testing of a small portable gravitational water vortex (GWV) based power plant. The gravitation water vortex is an ideal source of renewable energy for rural areas that have a small body of flowing water. For this purpose, we have selected a small size for the vortex chamber that enables it to form a vortex with limited amounts of water. The paper gives the details of the simulation of the GWV in COMSOL FEA software and the parameters that were chosen for optimization. These parameters were the height of the vortex chamber, the number of blades, the length of the blades, and the tilt angle of the blades. These parameters were systematically varied step by step, to observe their effect on the speed of the rotor. The results of the parametric sweep that was performed on all the parameters are also presented. Based on the simulation results an optimal set of parameters was chosen for the physical implementation of the GWV. The paper also goes into the details of the construction of the physical GWV, the experimental setup that was devised for the testing and verification of the simulation results.

**Keywords:** gravitation water vortex, renewable energy, green energy, finite element analysis, FEA modelling

## 1. INTRODUCTION

The energy sector has started changing in promising ways, with the widespread adoption of renewable and related technologies boding well for a sustainable future (IRENA, 2020). Renewable energy grew three times faster than fossil fuels and nuclear over the last five years. In 2019, a record 200 gigawatts (GW) of renewable power capacity was added, more than three times the level of fossil fuel and nuclear capacity (REN21, 2020). Renewable technologies (excluding large hydro) raised their share of global generation to 13.4% in 2019, from 12.4% in 2018 and just 5.9% in 2009 (Frankfurt School-UNEP Centre/BNEF, 2020). Renewable energy has so far been the energy source most resilient to COVID-19 lockdown measures (IEA, 2020). The pandemic has underlined the hydropower sector's resilience and its critical role in delivering clean, reliable, and affordable energy, especially at times of crisis (Heffron et al., 2021). It is estimated that by 2060, half of the world's energy consumption will be from renewable sources (Timilsina et al., 2018). To limit the global temperature rise to below 2°C above pre-industrial levels, it is suggested that global hydropower capacity would need to increase by 25% by 2030, and by 60% by 2050, which predicts significant growth in the hydropower sector (IRENA, 2019). Total global hydropower installed capacity reached 1,308 gigawatts (GW) in 2019 (Heffron et al., 2021).

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With the advancement of technology, it is now possible to set up economically mini, micro, and pico-hydropower plants on existing canals and fall structures, dam outlets, and small streams (Cherni et al., 2007; Tripathi et al., 2016). Gravitational Water Vortex Power Plants (GWVHP) using gravitational water vortex turbines (GWVT) have become superior to other conventional technologies mainly because of their potential to operate under small flow rates and head (Rahman et al., 2017). This type of plant can be installed along the sides of a water stream to generate a small amount of power. The main advantage is that the total cost can be greatly reduced as dams or reservoirs are not required for their operation. Transmission losses are minimized as these plants are installed near the center of utilization. Such plants disseminate homogeneously contaminants in the water (Dhakal et al., 2015). Moreover, without any greenhouse gas emissions, GWVT is acclaimed for its environmental friendliness, in addition to power generation. The waterworks on all the turbine blades at the same time and hence higher power can be generated compared to other hydro turbines (Guzmán and Glasscock, 2021). A large number of innovative GWVPP technologies improving efficiency, reducing cost, and ease in the installation have been implemented in the last decade. Lower initial expenditure and retaining a lower spatial and environmental footprint is another attraction (Ramos et al., 2012). In addition, in comparison with other plants, gravitational vortex plants enjoy the advantage of the highest capacity factor along with the lowest cost per watt as these plants can be installed even in drainage water (Guzmán et al., 2019).

GWVHP generates electricity by utilizing the natural phenomenon of water to form a vortex. The vortex then produces a swirl that can rotate a turbine. GWVHP generally uses an upstream channel, a basin with a hole or orifice at the bottom, a runner or rotor with blades, and a shaft. The water flowing through the stream tangentially enters the chamber and forms a vortex. This vortex gradually enhances and causes the rotation of the water to speed up. Naturally, the atmospheric air forms like an air core in the middle of the vortex. A rotor converts the flow energy into mechanical power with the help of its blades on it. The rotor shaft can be coupled with the alternator to produce electrical energy (Lahamornchaiyakul, 2021; Timilsina et al., 2018).

CFD and FEA simulation are widely used as tools for the design of turbines and their analysis. This is used for both wind and water turbines. The CFD and FEA combination is a powerful tool for finding the numerical solutions and analysis to develop a water turbine generator. FEA can also analyze the failure of turbine blades, and improve the effectiveness of the turbine. There are several works in the literature that elucidate the use of FEA for designing turbines, and one of the seminal works using FEA for water turbines is the work done by Lahamornchaiyakul (2021). This work explores all aspects of the turbine including rotation speed, displacement, pressure, and breaking point under various conditions. Nazarudin et al. (2022) reviewed and tested various significant parameters using the CFD analysis to get a clear picture of the prime components of the turbine on its performance, based on the pressure, velocity, and water vorticity. Another work done by Bajracharya et al. (2018) uses FEA simulation and CFD to analyze the interaction of the fluid with the turbines during operation. This work explores the pressures that the turbine blade is subjected to and its structural deformation under pressure. In a recent work, Nejadkhaki et al. (2021) performed the fluid-structure interaction analysis to study the variations in wind turbine blade cross section by the effect of aerodynamic load. To compare the cross section before and after changing the blade segment twist, FEA simulations were also performed.

In this paper, we are designing a modified gravitational water vortex using FEA simulation. The re-design is performed to improve the efficiency of GWV and to adapt it to implementation in small water bodies with limited flow. The FEA-based analysis is done primarily on the impeller, namely the number of blades, the shape of the blades, and the angle of inclination. A modified and improved GWV is constructed based on the results of FEA analysis.

## 2. METHODS

### 2.1. Principle of vortex

A vortex can be defined as a rotation of a multitude of particles around a common centre (Lugt, 1983; Mulligan et al., 2016; Ullah et al., 2019). In GWVHP, a free-surface vortex causes rotation of water around a common centre generally coinciding with the orifice or outlet at the bottom of the chamber. The modelling of the water vortex is based on the assumption of steady, axisymmetric and incompressible flow. Figure 1 shows a basic design for a GWV, and shows the basic principle of working that is described in this section.



Fig. 1. Water Vortex formation in GWV

Computational fluid dynamics (CFD) can be used to convert complex fluid system governing into a set of easier to solve algebraic equations (Sayama, 2009). A CFD mainly consists of three parts: pre-processor, which defines boundary conditions, solver, which specifies convergence criteria, and post-processor, which examines the results. Under this assumption, for vortex modelling, the continuity equation and the Navier–Stokes equations in cylindrical coordinates can be described as:

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} + \frac{V_r}{r} = 0 \quad (1)$$

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

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

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

where,  $V_\theta$ ,  $V_r$  and  $V_z$  are tangential, radial, and axial velocity components respectively,  $\nu$  is kinematic viscosity,  $\rho$  is fluid density and  $g$  is the gravitational acceleration (Schetz and Fuhs, 1999). CFD methods are used to approximate a solution, as it is impossible to obtain analytical solutions directly due to the complexity of the equations.

### 2.2. Finite Element Analysis (FEA)

FEA is a modelling method, utilizing computer software that works based on numerical solving of complex partial differential equations that are used to describe the physical behaviour of the modelled system. FEA works based on a system of points called nodes, which are generated by a grid or mesh that is superimposed on the geometry of the system being modelled (Bawiec et al., 2013; Hughes, 2012). This modelled system is then analyzed after the material properties of the materials involved in the model and boundary conditions

are assigned. The finite element analysis once performed, can then give a prediction about how the system will behave, based on the input parameters. The advantage of finite analysis is that the material properties, the dimensions of the system, and the system itself can be varied once the model is constructed. Once the model is verified based on some physical conditions or output, the parameters of the model can be varied at will to create several iterations of the experiment, without having to physically construct each and every iteration.

COMSOL Multiphysics® is a modern commercial finite element analysis software designed to address a wide range of physical phenomena. Comsol Multiphysics as the name suggests is designed to combine and interface multiple modalities and is capable of generating and executing a model that can predict the combined effects of the interactions of all the involved physics of the model (Dickinson et al., 2014). This capability of merging multiple modalities and combining their interactions makes COMSOL an ideal tool for modelling a complex system such as a gravitational water vortex. COMSOL Multiphysics implements equations using “physics interfaces”. These are pre-built packages of physical equations and a choice of associated boundary conditions are fixed based on the understanding of how the actual physical system works. In the case of a GWV the material properties of all the construction material, the fluid dynamics of the flowing water, the interaction with the rotor based, the physical motion of the blades, and the associated shaft can be modelled and simulated.

The flow of the water in the runner and the chamber was modelled based on the RNG  $k-\varepsilon$  turbulent model. This model was chosen based on the literature review, where most of the work related to water vortex turbulence uses the model. The simplicity of the model, and the ease of implementation for simulating turbulent conditions in COMSOL Multiphysics, were also considered while choosing the RND  $k-\varepsilon$  turbulent model.

### 2.3. Constriction of GWV

The gravitational water vortex was constructed based on the results obtained from FEA simulation results. The results are given in the Results section. The GWV is constructed as a cylinder, with a water channel connected to it for the water inflow, and an outlet under the cylinder, as shown in Figure 2.

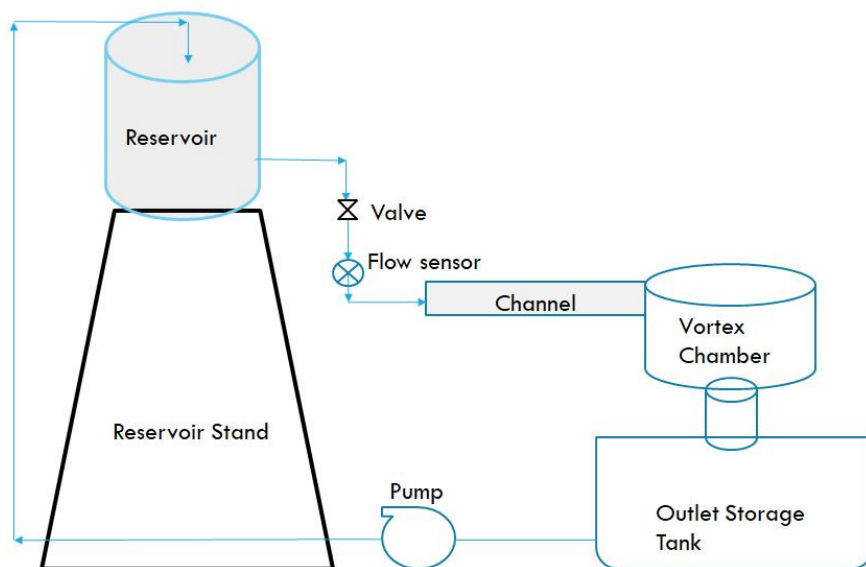


Fig. 2. Schematic of Gravitational Water Vortex experimental setup

The gravitational water vortex consists mainly of a water chamber with a spiral design, as shown in the schematic in Figure 3. The chamber has a tapered inlet that helps to generate a vortex flow inside the

chamber. The water in the chamber is let out through an outlet at the bottom of the chamber. The water flowing into the water chamber is provided by a water reservoir, which is connected through a water channel that supplies that water vortex. The water channel and the complete setup of the GWV are given in Figure 2. The generator itself consists of a power generator connected to the rotating shaft. The rotating shaft is rotated by the water vortex. The chamber as mentioned before is fed by a water channel. The water that goes out of the main chamber is collected in a collection tank and is pumped back to the main water reservoir using a pump for the experimental setup. The body of the GWV and the water channel is made of (polycarbonate) and the dimensions of the GWV are given in the diagram. The Specifications of the GWV in the experimental setup are given in Table 1.

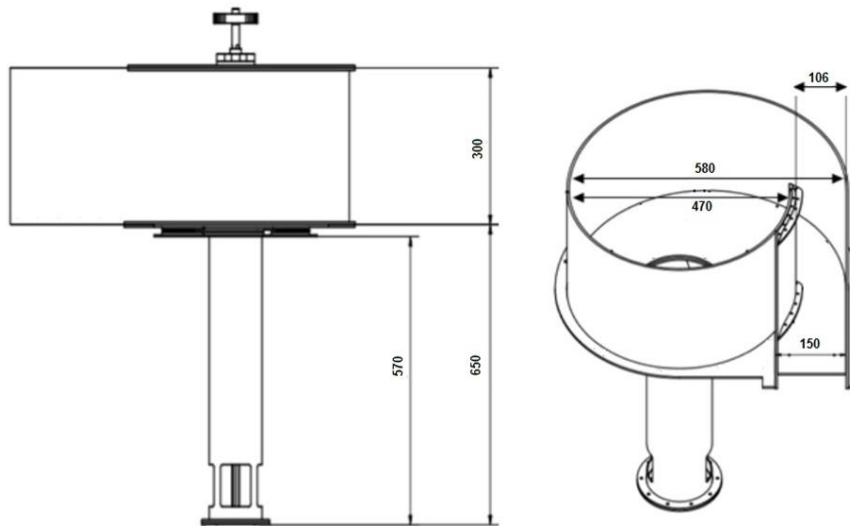


Fig. 3. Schematic of Water Vortex chamber (all dimensions in mm)

Table 1. Specifications of the GWV experimental set up

Item	Specifications
Water pump	1 HP
Main water reservoir	500 litre
Collection tank	300 litre
Chamber material	Polycarbonate
Tachometer	Digital laser tachometer DT2234C
Flow sensor	Ultrasonic flow transducer US0014-001

The width of the channel is 150 mm; it is 300 mm in height, and 1450 mm in length as shown in Figure 3. The flow rate is determined by the inlet of the upper circular vortex generator with 106 mm width and the water flows inside the vortex generator. The outlet tube is 570 mm in length. This means that the vortex chamber is 570 mm from the ground level. The vortex chamber is constructed in the shape of a spiral as shown Figure 3. The diameter of the inner vortex chamber is 470 mm and the outer spiral arm that connects to the water channel has a diameter of 580 mm. The gravitational water vortex experimental setup is shown in Figure 4 and the schematic of rotor design is shown in Figure 5.

The water channel is designed in such a way that the water flowing into the main vortex chamber is in the form of a steady laminar flow. This is to ensure that the water vortex is maintained at a proper steady speed so that the rotation of the shaft and the power generated is steady. To ensure a laminar flow, the water from



Fig. 4. Gravitational Water Vortex experimental set up

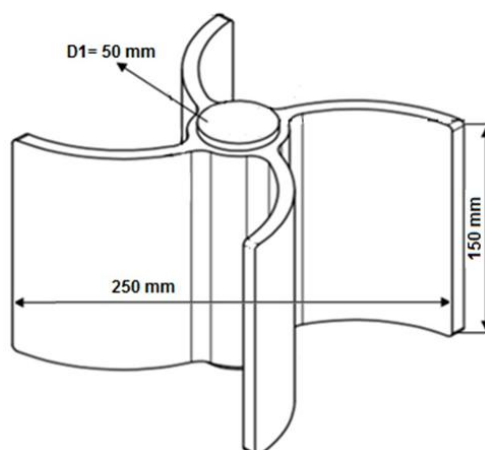


Fig. 5. Schematic of rotor design

the main water reservoir is poured into a set of chambers, with interspersed walls, with an opening on the bottom of the water channel, and the top of the water channel respectively. This ensures that the water flows into the main length of the water channel in a laminar flow.

The total diameter of the blades or the span of the curved blade is 250 mm. The blades are 150 mm tall. The blades are connected and fixed to the rotating shaft. The rotating shaft is what drives the power generating mechanism. The diameter of the shaft is 50 mm. The blades are made of acrylic and the shaft is made out of wood for optimal strength to weight ratio.

The two sets of rotor blades that are used in our current design are shown in Figure 6. The blades are constructed based on the FEA analysis, as per the results shown in the results section. Figure 6a shows the basic rotors that had the dimensions that are mentioned above. Figure 6b shows the second version of the rotor design. This has the same dimensions as the rotor blade, except for the difference in the blade angle, which is set as 10 degrees, with respect to the shaft of the rotor.



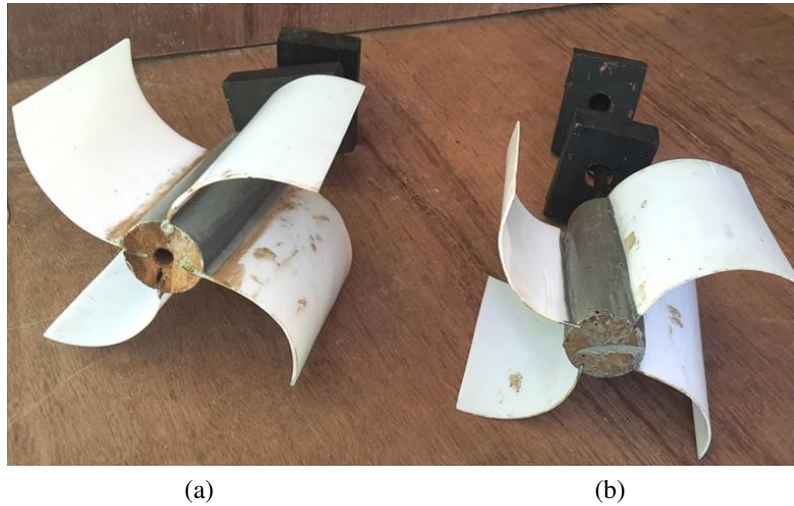


Fig. 6. Rotor blades (a) straight blades (b) inclined blades

### 3. RESULTS AND DISCUSSION

#### 3.1. FEA Simulation results

GWV was designed in COMSOL Multiphysics to determine the best possible parameters that are to be used in the construction. The main vortex chamber, and the rotor design, along with the meshing are shown in Figure 7. The mesh is used by FEA to calculate the desired parameters based on finite element theory automatically and is solved by COMSOL. The areas with more minute details, areas of importance, areas with junctions or intersections, etc. have finer meshing, as can be seen in Figure 7.

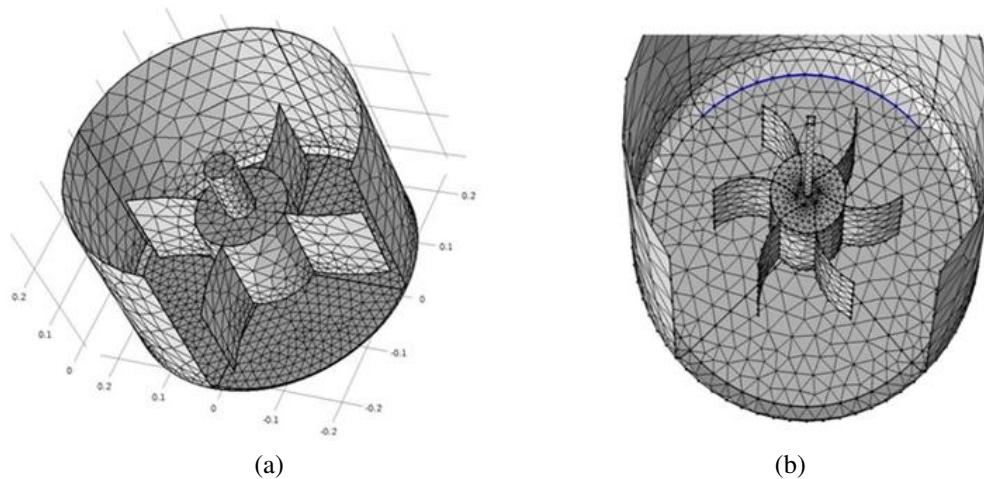


Fig. 7. FEA simulation of rotor (a) with 4 blades (b) with 6 blades

In the current work, the FEA simulation was done primarily to determine the best possible values for four parameters, namely the height of the main vortex chamber, the number of blades, the outer diameter or the length of the blades, and the tilt angle of the blade, i.e. the angle that the blades make with the main shaft of the rotor. There are several parameters that can be modelled, simulated, and varied to explore their effect on the final performance. We choose the above-mentioned parameters based on literature review and the parameters of importance that previous authors have determined to be the important parameters that influence the rotor speed the most.

Figure 8 shows the magnitude of the velocity of the water flow, which in turn is determined by the vortex, and turbine blade design. The flow speed is translated to the amount of electricity produced. Figure 9 shows the base speed profile of the system with a larger vortex tank. Notice how the maximum speed does change, for all the same parameters except tank height.

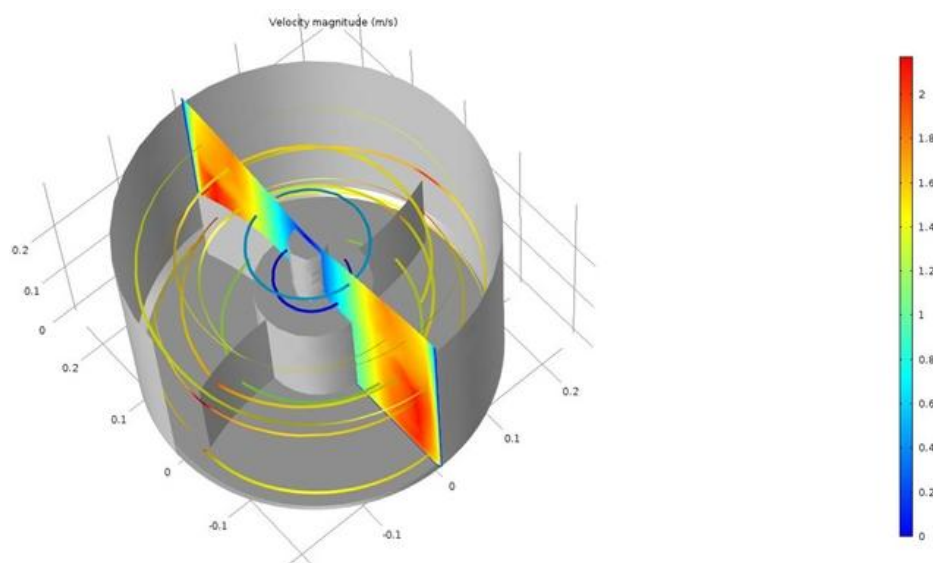


Fig. 8. FEA simulation of rotor velocity

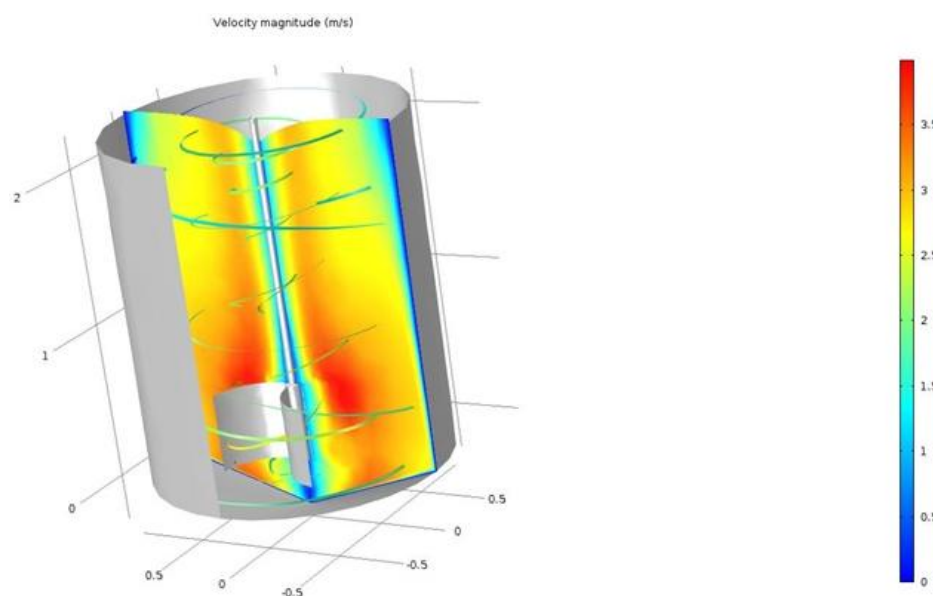


Fig. 9. FEA simulation of rotor speed profile

Figure 10 shows the basic pressure profile that the water vortex and its working applies on the tank walls and the rotor. The pressure profile is calculated to determine the integrity of the system under working conditions. The pressure profile was determined to be within the breakpoint tolerance of the materials used for tank and turbine construction. The size of the blade was varied to determine the optimal size that can produce the maximum rotor speed without the pressure reaching the breakpoint.

The rest of this section shows the results of the parametric simulation results. For obtaining the best possible results, each of the four parameters mentioned above, i.e., the number of blades, height of the chamber, length of the blades, and the angle of the blades, were selected one by one and varied over a range of values. The model used for the simulation was fixed at the values given in Table 2 and only the parameter being



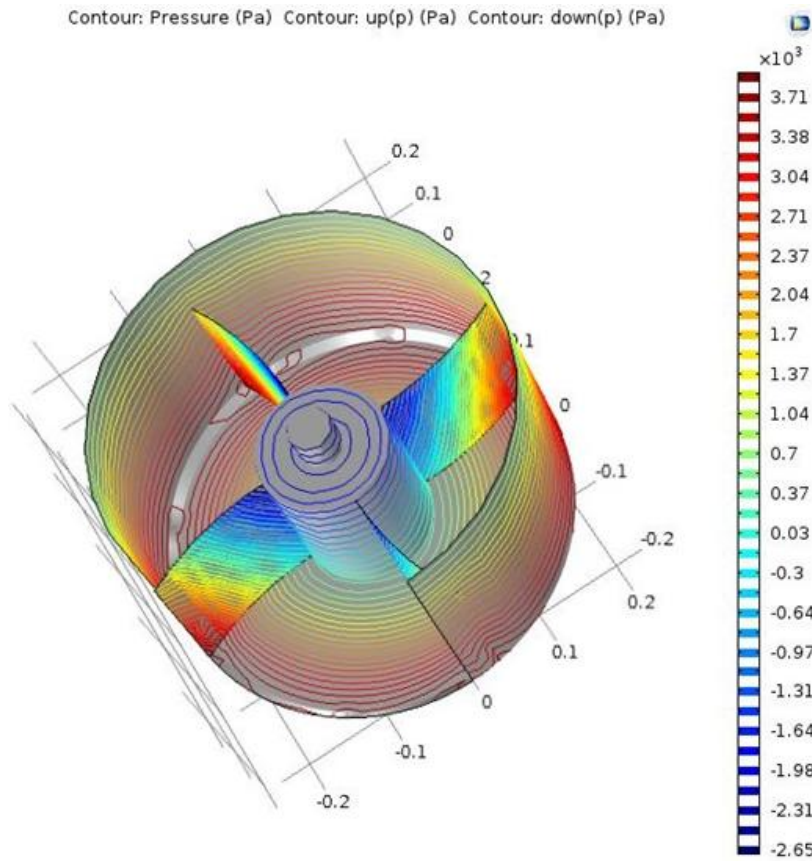


Fig. 10. FEA simulation of pressure profile during operation

Table 2. Parameter values for the simulation

Condition	Parameters	Value
While varying the height of the chamber	Blade length	200 mm
	Number of blades	4
	Tilt angle of blades	5 degree
While varying the number of blades	Blade length	200 mm
	Height of the chamber	400 mm
	Tilt angle of blades	5 degree
While varying the blade length	Number of blades	4
	Height of the chamber	400 mm
	Tilt angle of blades	5 degree
While varying the tilt angle of blades	Blade length	200 mm
	Height of the chamber	400 mm
	Number of blades	4

explored was varied at a time. The speed of the rotor was selected as the factor indicator for the effect of the change in the value of that particular parameter. For each parameter, the speed of the rotor is plotted against the change in the value of that parameter. These results are given in Figure 11.

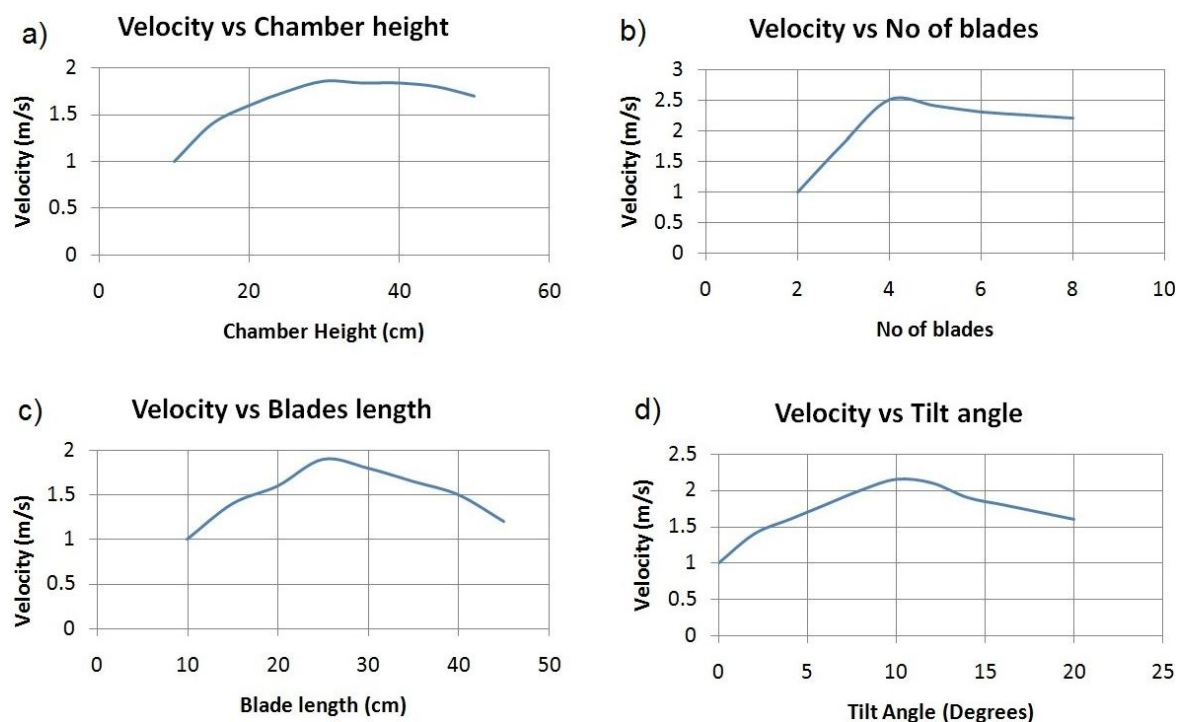


Fig. 11. (a) Velocity vs chamber height; (b) velocity vs number of blades; (c) velocity vs blade length and (d) velocity vs tilt angle

Based on the simulation results, depicted in Figures 7 to 11 the values used for the construction of the physical GWV were determined. The ideal height for the main vortex tank was determined to be around 300mm, the width of the blades was determined to be 250mm, the number of blades was determined to be 4 and the tilt angle was determined to be 10 degrees with the main rotor shaft. The best possible parameters that were used for the construction are shown in Table 3.

Table 3. Best possible parameter from simulation results

Parameter	Value
Height of the chamber	300 mm
Blade length	250mm
Number of blades	4
Tilt angle of blades	10 degree

### 3.2. GWV system testing

Based on the simulation results a physical GWV system was constructed, as described in the methodology section (2.3). This GWV was tested for its performance measures. The two rotor blade designs, as mentioned in the methodology were tested, i.e. the straight blade, and the 10-degree inclined blade. The designs were verified by measuring the speed of the rotor rotating as a result of the water vortex using a tachometer, and the speed was observed to be 2m/s, this is within 10% of the rotor speed value predicted by the simulation. This verifies that the simulation reflects real-world conditions and that the results of the simulation are accurate. The simulated design and the physically constructed versions of the GWV were compared and it was found that the physical values of rotor speed match the simulated design.

#### 4. CONCLUSIONS

The feasibility of a gravitational water vortex based power plant, implemented as a compact, portable unit that can be used with a small flow and water head was explored in this work. The design parameters of the GWV, i.e. the dimensions of the vortex chamber, and all the related parameters were estimated based on the extensive literature review that was performed on the previous realizations of the GWV. A GWV design was implemented in COMSOL, FEA simulation software based on this. This model was used to explore the effect of varying four primary parameters, on the output produced by the GWV. The simulation results pointed to an ideal set of parameters, for the small portable dimensions of the GWV that was chosen for this work. A physical GWV was constructed based on the simulation results and was tested. The GWV was fed with a water tank-based experimental setup, for ease of repeated testing, and to maintain steady experimental conditions. The physical GWV was observed to have a similar rotor speed as predicted by the simulations, and hence the simulation was verified to be accurate.

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