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Full paper

CFD Validation for Efficient Gravitational Vortex Pool System

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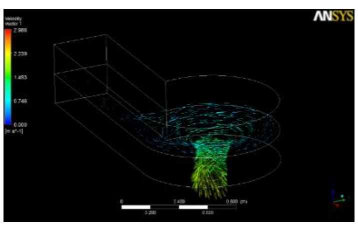
Graphical abstract



Abstract

Mini hydropower plants are expected to have good potential for providing electricity to remote communities. An important part of this economic and clean energy system is the conversion of the low-head potential energy into kinetic energy to drive power turbines. One way of converting the low-head potential energy is using a gravitation vortex pool. This study describes work to optimize the vortex pool to improve energy conversion and hence generate electricity from low water heads of between 0.7 m to 3 m. The commercial Computational Fluid Dynamics (CFD) code ANSYS Fluent was used in this study to investigate the optimum configuration of the vortex pool system by modeling the free surface flow mathematically. In addition, an experimental test rig was set-up to carry out validation of the CFD results. The results of validation prove that ANSYS Fluent is able to model the system correctly.

Keywords: Renewable energy; gravitation water vortex; micro hydropower; high speed camera

■1.0 INTRODUCTION

Exploring renewable energy resources are now necessary for sustainable energy, firstly, to correspond the 70% increase in electricity demand all over the world, secondly, to comply with the needs of the rapid growth of electricity, and thirdly to reduce CO_2 impact on the environment [1]. According to [2-4] hydropower and small mini hydro power plants are considered as high potential renewable energy resources for remote communities, while at the same time contribute to the efforts to decrease greenhouse gas effect on the environment [5]. It is expected that 1000 gallons of diesel fuel per year can be saved by utilizing a 10 KW mini-hydropower system [6]. Gravitational water vortex system is one of the mini/mico hydropower systems, and can be considered as a useful application of Free Surface vortex (FSV) principle. FSV is an important phenomenon in the field of hydraulic engineering. It can be considered as a harmful or useful source according to its location [7]. Many researchers studied this phenomenon in terms of factors affecting its strength or describing its structure and location, whether to eliminate or to strengthen it. FSV is studied according to its usefulness or harmfulness or disregarding to its influence. In this paper, the advantageous use of FSV is considered. In the field of petroleum separation, Popescu [8] presented a method for oil separation based on vortex separation technique. He developed a numerical solution using flex PDE software for geometrical dimensions of waste recovery system, and determined the movement of the free surface shape of the formed funnel, spectrum movement and the velocity distribution.

The chemical engineering and processing field also utilize FSV in mixing fluids. In this application, the effect of a baffle on the flow pattern is very important. Xu *et al.* [9] studied numerically the effect of a baffle on the flow field of stirred tanks showing the formation of a large number of axial and radial vortexes in the baffle stirred tanks. Glover *et al.* [10] presented a numerical model of vortex formation in an unbaffled stirred tank reactor where preliminary results of investigation into the effect of liquid phase properties of the vortex were presented. Furthermore, research work by Assirelli *et al.* [11] studied macromixing characteristics, and vortex behavior in unbaffled tank agitated with Rushton turbine. His findings were in good agreement with the available literature. Moreover, Mahmud *et al.* [12] offered measurements using a laser doppler velocimetry, and numerical simulations using ANSYSCFX CFD code of turbulent flows with free-surface vortex in an unbaffled reactor agitated by a cylindrical magnetic stirrer. The predicted general shape of the liquid free-surface agreed with measurements, while the vortex depth could not be predicted. The vortex shape in a partially baffled agitated vessel was investigated experimentally and numerically by Torré *et al.* [13]. They used 0.9 water isosurface volume fraction instead of 0.5, which gave a very good agreement with the experiments. A useful side-effect of FSV in small mini hydro power plants is the introduction of considerable amount of oxygen in the aeration process, this is described by Wanchat and Suntivarakorn [14]. He analyzed and designed a basin to form a gravitational vortex pool using Ansys Fluent CFD code simulations of the flow conditions and basin configuration.

This research work describes a numerical study that has been conducted on gravitational vortex energy system capable of generate electricity from low water heads of between 0.7 m to 3 m [14], to obtain the optimum configuration of the gravitational water vortex system using ANSYS Fluent code. The CFD model was validated by measurements carried out on a 1/5 model scale of the vortex pool. In addition, a vortex turbine is used in the numerical simulations to assess the system efficiency.

2.0 MATHEMATICAL MODEL

Based on the homogenous multiphase Eulerian fluid approach, the free surface flow in Ansys Fluent code is mathematically described. In this approach, both fluids (air and water) are sharing the same velocity fields and other relevant fields such as temperature, turbulence, etc., and they are separated by a distinct resolvable interface. The governing equations for the unsteady, vicious, turbulent flow are the Navier-Stokes equations, which are written in the following form:

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_i}(\rho u_i) = 0.0 \quad (1)$$

$$(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(-\rho \overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] \quad (2)$$

3.0 VORTEX POOL MODEL AND TEST CASES

The gravitational water vortex pool prototype model is shown in Figure 1. The original vortex pool has an outlet diameter of 200 mm. Five cases were tested in this study, at water depths of 100, 150, 200, 250, and 300 mm at various inlet velocities, as shown in Table 1.

Table 1 Test cases of the gravitational vortex pool system

Water depth in mm	Inlet Velocity (m/s)
100	0.27
150	0.31
200	0.20
250	0.53
300	0.42

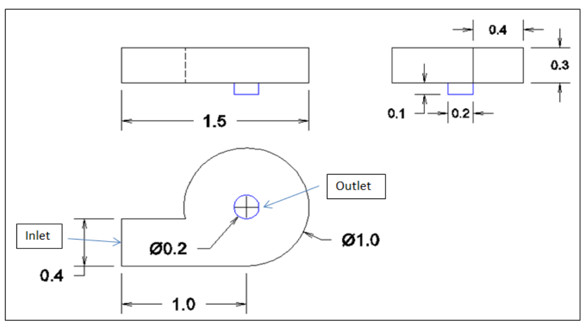


Figure 1 Vortex pool system dimensions in meters showing inlet/outlet boundaries used in Ansys Fluent code

4.0 NUMERICAL ANALYSIS

ANSYS Fluent version 14 was used to stimulate the flow inside the prototype. The original vortex pool has a water depth of 100 cm, and the outlet diameter of 100 cm. Table 2 shows the numbers of unstructured tetrahedral mesh elements for the different cases in this study.

Table 2 Mesh numbers for the five cases

Case	Mesh number
Vortex Pool Model Fluent Solver h 100 mm	486598
Vortex Pool Model Fluent Solver h 150 mm	481920
Vortex Pool Model Fluent Solver h 200 mm	460038
Vortex Pool Model Fluent Solver h 250 mm	477866
Vortex Pool Model Fluent Solver h 300 mm	476318

5.0 EXPERIMENTAL SETUP

To validate the CFD calculations, a 1/5 model scale of Gravitational Water Vortex Pool system was constructed. The system composed of centrifugal pump, water tanks, and vortex pool. A control valve was attached at discharge of the pump to control the water flowrate. The system was constructed as shown in Figure 2.

Figure 2 Vortex pool system model constructed in Universiti Teknologi Malaysia (UTM)

Measurements were carried out using High Speed Camera Phantom V710 to capture the movement of a small floating ball partially filled with water, which simulates a water particle. The test setup is shown in Figure 3 where camera was held by tripod and proper lighting was provided. Velocity was measured at the inlet and outlet at different water depths.

Figure 3 Vortex pool model test setup

6.0 RESULTS AND DISCUSSIONS

Figure 4 represents the velocity of the small balls captured by the high speed camera for different water depths together with Ansys Fluent CFD code simulations results that have been carried out at conditions similar to experimental tests, i.e. at the same water depths and inlet velocity conditions.

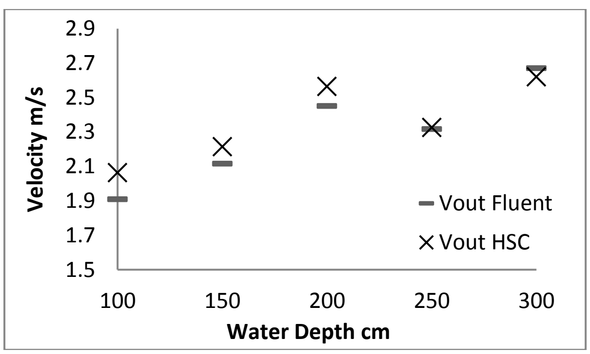


Figure 4 Comparison between CFD and experimental results for the vortex pool system

Three findings can be extracted from these results. Firstly, CFD results showed good agreement with the experimental results as shown in Table 3. Therefore, it can be used in further investigation for the vortex pool configuration optimization process. Secondly, the kinetic energy of the water flow reaches its maximum value at the outlet, which qualifies the system for capturing the energy at the outlet. This approach is different from the previous studies such as Wanchat and Suntivarakorn [14] who studied only the tangential velocity components in the system. Finally, a slight change can be noticed in the outlet velocity by increasing the water depth, so this parameter is not very promising in improving the system efficiency. However, the system was capable of increasing the inlet velocity by almost 5 times at the outlet, which qualifies the system for energy generation. Figure 5 shows the velocity profile at the vortex pool which proved that vortex pool is able to enhance the flow at the outlet and increase the power that can be harnessed from the system. Therefore, there is a need for a turbine to be added to test the system efficiency, which will be discussed in the following section.

Table 3 Comparison between numerical and experimental results for the vortex pool system

Water depth in mm	Inlet Velocity (m/s)	Fluent outlet Velocity (m/s)	Experimental Outlet Velocity (m/s)	% difference
100	0.27	1.91	2.06	7%
150	0.31	2.12	2.22	4%
200	0.20	2.45	2.56	4%
250	0.53	2.32	2.33	0%
300	0.42	2.67	2.62	-2%

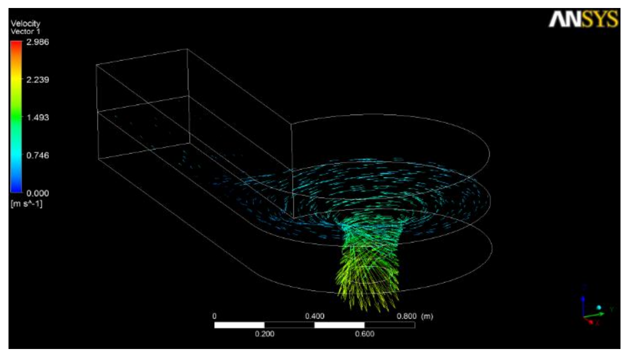


Figure 5 Velocity Profile through the pool

6.1 Turbine Efficiency

In order to test the system efficiency, a special vortex hydro turbine (Figure 6) has been designed for this purpose. The turbine efficiency was studied using the moving reference frame technique in Ansys Fluent code. The inlet velocity of 0.242 m/s, and 300 mm water height were fixed, while the turbine speed was varied from 10 to 50 rpm. The effect of the turbine on the free surface flow inside the vortex pool system is given in Figure 7. The turbine speed against the efficiency is plotted in Figure 8.

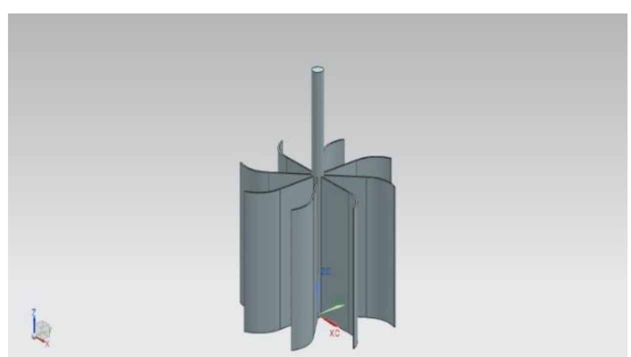


Figure 6 System vortex turbine

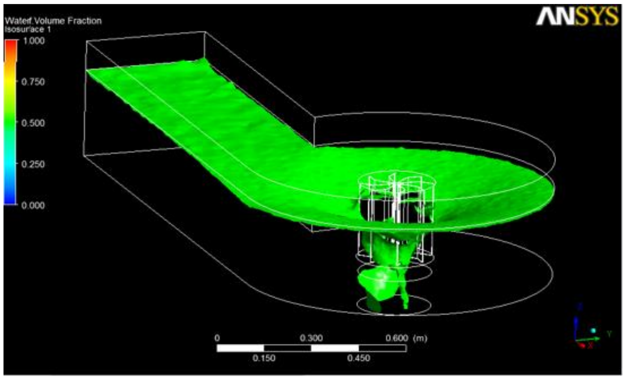


Figure 7 The effect of the vortex turbine on the flow inside the vortex pool system

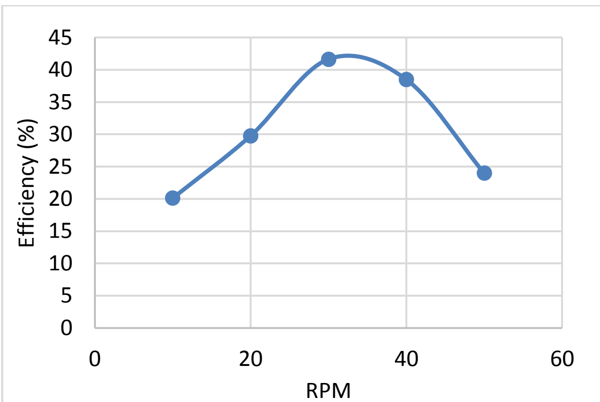


Figure 8 Turbine efficiency at different rotational speeds

The results shows that the maximum efficiency of about 40 % can be achieved in the range between 28 and 38 rpm, which is very close to what is proposed by Wanchat *et al.* [15], and even better. The total efficiency of their system was 30 %. Therefore, future study will investigate the optimum turbine design for the gravitational vortex pool system.

■7.0 CONCLUSION

In this research work, an overview has been given for a vortex pool system, which is capable of generating energy from low heads of 0.7 m to 3 m, which is applicable for ocean wave energy plants. This paper reported results of numerical study using CFD to investigate the optimum configuration of the vortex pool system. In addition, CFD is validated, and numerical results showed good agreement with the experimental results of the high speed camera. Finally, the system efficiency is found to be 40% in the range of 28 and 38 rpm.

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