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CFD Simulation of Water Gravitation Vortex Pool Flow for Mini Hydropower Plants

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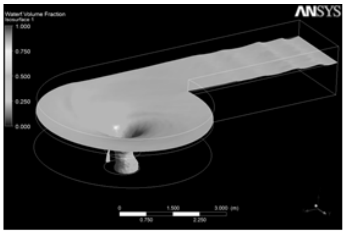
Graphical abstract



Abstract

Mini hydropower plants can be expected to have a good potential to provide 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 the power turbines. One way of converting the low-head potential energy is using a gravitation vortex pool. This paper describes work to optimize the vortex pool to improve energy conversion and hence generate electricity from low 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. The free surface flow of this system was mathematically described. A parametric study was carried out using the software to determine the main parameters affecting the efficiency of the energy conversion. This parametric study utilized Fluent, which focused on the effect of changing water depth and outlet diameter on inlet/outlet speed; which is novel approach. The results from this study could help in the investigation of the optimum configuration of the vortex pool system.

Keywords: CFD; vortex pool; energy extraction; gravitation water system; mini hydropower

■1.0 INTRODUCTION

The search for renewable energy sources like wind energy, hydropower and solar energy as alternatives for electricity production is arising due to the social, economic and environmental dispute of using fossil fuels [1]. Moreover, nowadays many developing countries are facing energy crisis due to the increase of industrialization for several development programs. If this increasing demand is continuously supplied from fossil fuels, it will further tally the catastrophe on the environment. Therefore, exploring renewable energy resources is necessary for producing and reserving sustainable energy, through several steps. Firstly is to correspond to the 70% increase in electricity demand all over the world. Secondly is to comply with the needs of the rapid growth of electricity, and thirdly to reduce CO_2 impact on the environment [2]. According to Sharma *et al.* [3], improving hydropower and small hydro power (SHP) plants is considered as the most potential source of renewable energy resources. In this trend, the research made by Khan *et al.* [4] proposed for the energy in flowing river streams, tidal currents or other artificial water channels as applicable sources of renewable power. Recently, various turbine concepts and designs are being pursued, whereas the non-turbine systems are generally still at the proof-of-concept stage (with some exceptions). Subsequently, turbine systems have been given more attention as they are the most promising for deployment soon [4]. One of the techniques of applying turbine systems is through using gravitation water vortex. This system is capable of generating electricity from low heads of 0.7m to 3 m and can be applied for mini/micro hydro power plants [5, 6]. Although a good potential is expected for micro- hydropower, it has yet been fully utilized [7]. Moreover, micro hydro power plants can provide electricity to remote communities far from the grid. Many installations have been implemented worldwide, essentially in developing countries, as they can be considered as an economic clean source of energy without the need of fuel [8, 9]. 1000 gallons of diesel fuel per year is lessened by utilizing 10 KW mini-hydropower system [10]. Also, small hydropower is supported by international effort to decrease greenhouse gas effect on the environment [11]. Gravitational Water Vortex is considered as a useful application of the Free Surface Vortex (FSV), which is an important phenomenon in the field of hydraulic engineering. It can either be considered as a harmful or useful source according to its location. Many researchers study this phenomenon in terms of factors affecting its strength or describing its structure and location, whether to eliminate or to strengthen it. Literature regarding this matter is thus reviewed according to FSV usefulness or harmfulness.

FSV is studied as a harmful source; for example, in the hydraulic intakes research as in [12], which explored the hydraulic characteristics of the vertical vortex flow. In [13], the author investigated an effective numerical model for simulating vertical vortex. Moreover, Shi *et al.* [14] studied the free-surface vortex to provide some theoretical proposals and to get the mechanism of circulation propagation and vortex formation. In this trend, not only FSV had been studied, but also anti-vortex devices had been used to eliminate its bad effect as in Reference [15], where Trivellato presented a new funnel-shaped device whose performance had been proven experimentally to be successful. In the Mold Casting field, Li and Tsukihashi [16] conducted a water model experiment to observe the vortexing flow in the steel slab continuous casting mold.

In addition, chemical engineering, especially hydrocyclone, can be harmfully influenced by vortex formation, as shown by Reference [17], who did experiments and CFD-modelling for different inlet flow rate in presence, as well as in absence, of gas-core to qualify the pressure drop characteristics of the hydrocyclone. Furthermore, Evans *et al.* [18] performed simulations of the flow within the solid–liquid hydrocyclone, operating with an air core and with an inserted metal rod using Finite-volume method and Reynolds Stresses Model (RSM) to model the turbulence characteristic of the flow. Finally, FSV effects on Liquid Propulsion System had been studied by Basu *et al.* [19], who carried out simulations using Volume of fluid method to investigate air- core vortex formation, and validation was adapted from literature results.

FSV had also been proven potential as a useful source for the field of petroleum separation. Popescu and Robescu [20] presented a method for oil separation based on vortex separation technique. Chemical engineering and processing field also depend on FSV in mixing fluids. In this trend, Glover and Fitzpatrick [21] presented a numerical model of vortex formation in an unbaffled stirred tank reactor. Furthermore, Mahmoud *et al.* [22] offered measurements using a laser doppler velocimetry, and numerical simulations using ANSYS CFX of turbulent flows with free-surface vortex in an unbaffled reactor. The predicted general shape of the liquid free-surface agreed with the measurements, but the vortex depth could not be predicted.

Last but not least, in the field of renewable energy, not only electric energy can be generated from FSV, water can also be aerated and a considerable amount of oxygen can be introduced to living organisms, which is a positive impact to the environment, apart from the bad impact of large hydropower. Consequently, Wanchat and Suntivarakorn [5] analyzed and designed a basin to form a gravitational vortex pool. The author used ANSYS Fluent to simulate the flow conditions and basin configuration. However, further investigation is still needed for the vortex pool optimization to determine the specifications of a gravitational water vortex pool prototype [5].

In this research, a parametric study was conducted on gravitation vortex energy system for investigating the optimum configuration of the gravitation water vortex system, so that the maximum power could be harnessed. This parametric study was performed using ANSYS software.

■2.0 MATHEMATICAL MODEL

The mathematical description of the free surface flow in Ansys CFX is based on the homogenous multiphase Eulerian fluid approach. In this approach, both fluids (air and water) share 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:

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

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

Where,

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(pk + \frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{3}$$

And

$$\rho = \sum_{\alpha=1}^{2} r_\alpha \rho_\alpha , \qquad \mu = \sum_{\alpha=1}^{2} r_\alpha \mu_\alpha , \qquad \sum_{\alpha=1}^{2} r_\alpha = 1$$

The SST turbulent model can be expressed in the following mathematical form

$$\frac{\partial(pk)}{\partial t} + \frac{\partial}{\partial x_i}(pku_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k \tag{4}$$

$$\frac{\partial(p\omega)}{\partial t} + \frac{\partial}{\partial x_i}(p\omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega \tag{5}$$

In the previous two equations, Γ_k and $\Gamma_\omega$represent the effective diffusivity for k and ω. G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, and G_ω represents the generation of ω. Y_k and Y_ω represent the dissipation of k and ω due to turbulence. D_ω represents the cross-diffusion term.

■3.0 NUMERICAL ANALYSIS

ANSYS Fluent V14 was used in the calculation of the prototype vortex turbine pool. A 1/5 scale model of the vortex pool is shown in Figure 1. In order to do parametric study, two parameters were chosen, which were, water depth and outlet diameter. The original vortex pool had a water depth of 100 cm, and the outlet diameter of 100 cm. This calculation was done for full scale prototype, while in Reference [5] simulations have been implemented for model scale.

Figure 1 Vortex pool

The analyses were carried out for two conditions, designated as Case 1 and Case 2, as shown in Table 1.

Table 1 Parameters for the two cases

Condition	#1	#2	#3
Water height (cm)	100	80	60
Outlet dia. (cm)	100	100	100

(a) Case 1

Condition	# 1	# 2	# 3
Water height (cm)	100	100	100
Outlet dia. (cm)	125	100	75

(b) Case 2

For Case 1, the water height was changed in order to investigate its influence on the velocity distribution along the pool, while in Case 2, the water height was kept constant, and the outlet diameter was changed. This effort to calculate the outlet speed is a novel study, since the only calculations implemented by Reference [5] showed the tangential velocity along the radial direction only. This prepares the system for cascading, which means that the amount of energy captured from the vertical velocity at the outlet is much more compared to the radial velocity.

■4.0 RESULTS AND DISCUSSIONS

4.1 Case 1

The results of the analyses at water heights 60, 80 and 100 cm are given in Figure 2. The outlet velocity increases by increasing the inlet velocity. For instance, at water depth 60 cm, which seems to be the best trend due to the shallow water effect, and frictional forces, which increased at low speeds. When the inlet speed increased gradually, it overcame the frictional forces. Meanwhile, at 80 cm water depth, it showed a very narrow change in velocity, because it was a bit far from the bottom. Finally, at 100 cm, the highest increase in velocity, almost 6 times, was achieved. Therefore, from this graph it is clear that by increasing the height, higher velocity can be obtained without limitations in increasing height. This agrees with Bernoulli's equation.

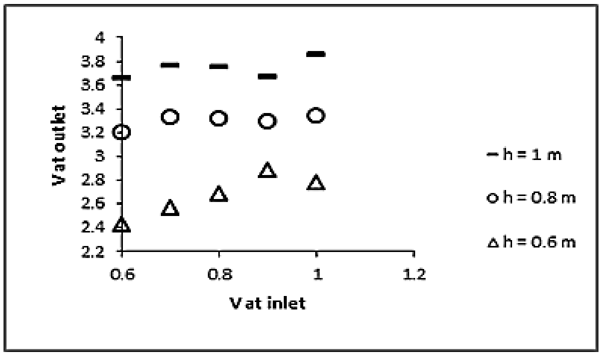


Figure 2 Effect of changing inlet velocity (100 cm outlet diameter and different water heights)

As an example to evaluate the effect of changing water height on the outlet speed, 0.8 m/s inlet velocity was chosen, as shown in Figure 3.

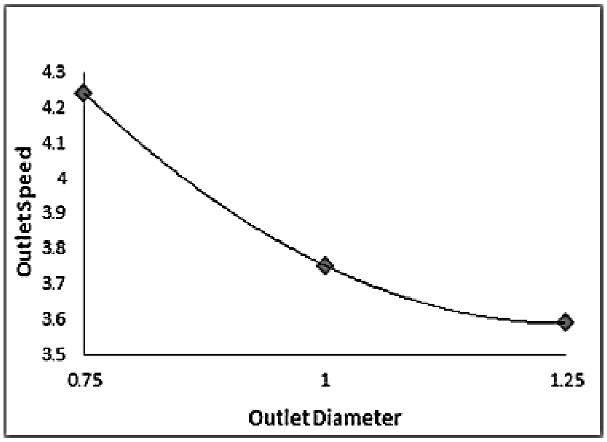


Figure 3 Outlet speed versus water height at 0.8 m/s inlet speed

The linear relationship between the water height the outlet speed demonstrated the potential energy conversion into kinetic energy.

4.2 Case 2

In this case, three different diameters were studied, which were 125 cm, 100 cm, and 75 cm, the highest outlet speed at 125 cm diameter corresponded to 0.9 m/s inlet velocity. At 100 cm outlet diameter, very slight change in speed could be seen. Finally, at the smallest diameter of 75 cm, the best trend could be seen, where the maximum speed corresponds 0.8 m/s.

The data plotted in Figure 4 show that as the outlet diameter decreased, the speed increased, which implies continuity equation.

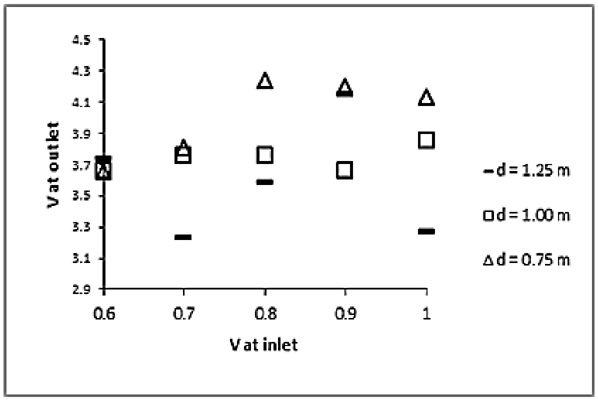


Figure 4 Effect of changing inlet velocity (100 cm water height and different outlet diameters)

The effect of changing the outlet diameter on the outlet speed can be seen in Figure 5.

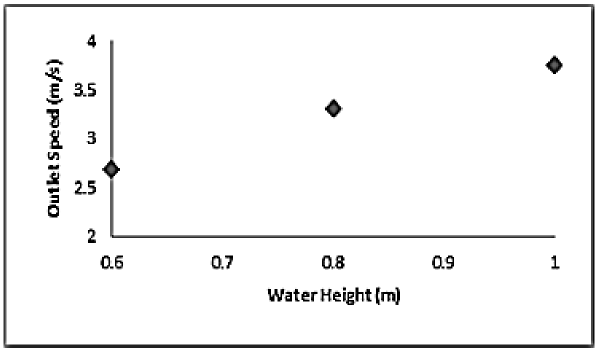


Figure 5 Outlet speed versus outlet diameter at 0.8 m/s inlet speed

Polynomial trend line of Figure 5 indicates the effect of changing the outlet diameter on the outlet speed, which is inversely proportional.

The velocity vectors at the free surface for 0.8 m/s as the mean speed for 100 cm diameter was shown in Figure 6.

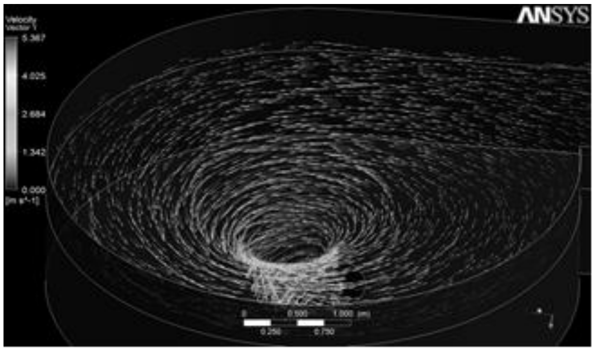


Figure 6 Velocity vectors at the free-surface

This velocity profile at the radial direction showed a gradual increase in velocity due to rotational swirling and potential energy conversion, which agrees with Reference [5]. For the same condition, the isosurface for a water free surface can be seen in Figure 7.

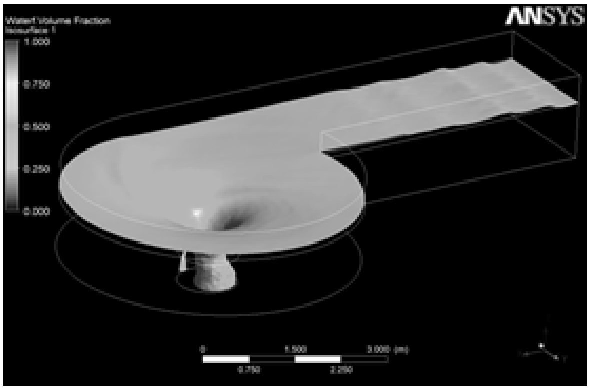


Figure 7 water volume fraction

As mentioned in Section 2, based on the homogenous multiphase eulerian fluid approach, the interface between air and water, as shown in Figure 7, the vortex core which included air inside helped in aerating the water, which is a positive impact on the environment.

■5.0 CONCLUSION

In this research work, an overview has been given on a vortex pool system, which is capable of generating energy from low heads of 0.7 m to 3 m, which is applicable in ocean wave energy power plants. This paper presents the results of parametric studies which used CFD and focused on the effect of changing water depth and outlet diameter on inlet/outlet speed; which is novel approach to investigate the optimum configuration of the vortex pool system. From the results, we concluded that by increasing the water depth, higher velocity can be obtained. On the other hand, as the outlet diameter is reduced, the speed increases. The CFD should be validated in future work, while other parameters can be explored.

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