# EFFECTS OF HYDRAULIC HEAD AND BASIN GEOMETRY PHYSICAL PARAMETERS ON THE VORTEX TURBINE HYDRAULIC EFFICIENCY

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## DECLARATION

I hereby declare that the material in this thesis is my own except for the equations, summaries and references which have been dully acknowledged.

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## CERTIFICATION

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# ABSTRACT

Gravitational Water Vortex Power Plant is a green technology where energy is extracted from water vortex instead of hydraulic head. This type of power plant is advantageous because of its capability to exploit the low-head sites. However, lack of experimental and theoretical literatures limit the development of this technology. This thesis describes the effects of the penstock's geometry and outlet diameter on the efficiency of the power plant. A prototyped power plant that simulates the low-head river and power plant was fabricated. The parameter of this thesis includes six penstock models (A, B, C, D, E and F) to represent the different geometries of penstock, five outlet diameters (0.052 m, 0.056 m, 0.064 m, 0.072 m, 0.076 m) and five inlet flow rates (5.6 $m^3/h$, 6.4 $m^3/h$, 7.2 $m^3/h$, 8.0 $m^3/h$ and 8.8 $m^3/h$). These parameters were tested accordingly and the turbine rotational speed, vortex height and resistance force were recorded. The power input, power output and efficiency were then calculated using appropriate formula and analysis were carried out to study their effects on the performance of the prototype. It was found that the efficiency of the prototyped power plant reduced due to the larger penstock's feeding width of penstock model B and C compared to other four models. Peak efficiencies recorded on penstock model B and C were between 17 % to 24 % and 13 % to 21 % respectively at 8.8 $m^3/h$. At similar flow rate, the other four penstocks' efficiency yields 20 % to 30 %. The prototype was found to perform best (efficiency of 28.29 %) when penstock model D was installed along with outlet diameter of 0.072 m at inlet flow rate of 8.8 $m^3/h$. The performance of the prototype was also found to increase with increasing inlet flow rate up to 8.8 $m^3/h$. Other than that, penstock models A, D, E, and F was found to have insignificant effects on the performance of the prototype. Performance of the prototype was found to be better when the ratio of outlet diameter to basin diameter was kept between 0.14 to 0.18.

# ABSTRAK


## KESAN KEPALA HIDRAULIK DAN PARAMETER FIZIKAL GEOMETRI BASIN KEPADA KECEKAPAN HIDRAULIK TURBIN VORTEKS

*Gravitational Water Vortex Power Plant adalah teknologi hijau dimana tenaga diekstrak dari vortex air, bukannya kepala hidraulik. Janakuasa ini bermanfaat sebab ia berkeupaya untuk menggunakan tapak yang mempunyai kepala hydraulik yang rendah. Walau bagaimanapun, kekurangan kesusasteraan eksperimen dan teori menghadkan kemajuan teknologi hijau ini. Tesis ini menerangkan kesan geometri penstock dan outlet lembangan kepada kecekapan janakuasa yang berkenaan. Perkakas yang menyimulasikan sungai yang mempunyai kepala hydraulik yang rendah telah direka bentuk. Parameter tesis ini termasuk enam penstock model (A, B, C, D, E dan F) yang mewakili geometri penstock yang berbeza, lima garis pusat outlet (52mm, 56mm, 64mm, 72mm, 76mm) dan lima kadar aliran yang berbeza (5.6 $m^3$/h, 6.4 $m^3$/h, 7.2 $m^3$/h, 8.0 $m^3$/h dan 8.8 $m^3$/h). Parameter tersebut telah diuji dan kelajuan putaran turbin, ketinggian vorteks dan daya rintangan telah dirakam. Kemasukan kuasa, kekeluaran kuasa dan kecekapan dikira menggunakan formula yang sesuai dan analisis telah dilaksanakan untuk memantau kesan parameter yang disebutkan terhadap kecekapan prototaip janakuasa yang dibina. Dari ekperimen yang telah dijalankan, kecekapan prototaip didapati berkurangan apabila penstock model B dan C yang mempunyai feeding width yang lebih besar berbanding dengan penstock-penstock yang lain. Kecekapan prototaip yang dirakam oleh Penstock B dan C adalah sebanyak 17 % ke 24 % dan 13 % ke 21 % masing-masing sahaja apabila kadar aliran 8.8 $m^3$/h digunakan. Pada kadar aliran yang serupa, empat penstock yang lain berjaya menghasilkan kecekapan sebanyak 20 % ke 30 %. Kecekapan setinggi 28.29 % berjaya dicekapi oleh prototaip ini apabila penstock model D dipasang dengan outlet yang berlembang 0.072 m dan kadar aliran masuk sebanyak 8.8 $m^3$/h. Selain itu, kadar aliran masuk yang meningkat sehingga 8.8 $m^3$/h didapati meningkatkan kecekapan prototaip ini. Penstock model A, D, E dan F juga didapati tidak menjejaskan kecekapan prototaip ini. Kecekapan prototaip ini adalah paling tinggi apabila nisbah antara lembangan outlet dan lembangan besen adalah antara 0.14 ke 0.18.*

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| | | |
|---|---|---|
| **GWVPP** | - | Gravitational Water Vortex Power Plant |
| **CFD** | - | Computational Fluid Dynamic |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $H_{penstock}$ | - | Height of water from the bottom of the basin |
| $H_{inlet}$ | - | Height of water above $H_{penstock}$ |
| $H_{vortex}$ | - | Vortex's height |
| $W_{inlet}$ | - | Width of penstock's inlet |
| $W_{feed}$ | - | Width of the penstock connected to the basin |
| $W_{neck}$ | - | Feeding width of basin |
| $\Gamma$ | - | Circulation |
| $\omega$ | - | Rotational speed |
| $g$ | - | Gravitational force |
| $v$ | - | Velocity |
| $v_\theta$ | - | Tangential velocity of water vortex |
| $Q$ | - | Flow rate |
| $D_b$ | - | Basin diameter |
| $H_b$ | - | Basin height |
| $H_p$ | - | Penstock height |
| $W_p$ | - | Penstock width |
| $D_o$ | - | Outlet orifice diameter |
| $\rho$ | - | Density |
| $A$ | - | Area |
| $V$ | - | Volume |
| $L_{model}$ | - | Length of penstock's model |
| $\tau$ | - | Torque |
| $F$ | - | Force |
| $m_{spring\ balance}$ | - | Mass recorded by spring balance |
| $m_{load}$ | - | Mass of copper weights |
| $\eta$ | - | Efficiency |
| $L_{penstock}$ | - | Length of penstock |

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# CHAPTER 1

# INTRODUCTION

This chapter aims to provide an overview on the research that was carried out. The background of the project, problem statement, aims and objectives of the research were presented. Besides that, scope of research and research activities were presented as well. At the end of the chapter, the chapter organization and research methodology of this thesis was elaborated in order to anticipate the readers.



## 1.1 Introduction

Energy is a property that must be used in order to perform work on an object. Law of conservation of energy states that energy can be converted but cannot be created nor destroyed. Energy comes in many forms that can be a long list if listed out one by one. One of the most common conversions of energy is to convert energy sources into electrical energy or electricity. From billions dollar worth companies and factories to common houses, electricity plays an important role. From huge machines that mass produce numerous products to smartphones that allowed connections without boundaries, electricity was there. After years of transformation and technological advancement, the transmission of electrical energy changed from Telodynamic for cable cars to small lithium ion batteries for calculators. Besides that, electrical energy supplies also transformed from distribution from power plant through local grid to self-supply through solar power system. This kind of technological advancement did not show signs of stopping because more energy researches are in the way due to the increasing demands.

According to Global Energy Statistical (2017), the total energy consumption increased from approximately 8,991 Mtoe (Million Tons of Oil Equivalent) in year 1990 to over 13,903 Mtoe in year 2016. Such increment is alarming because the sources involved are mostly finite energy sources such as oil, coal, gas, biomass, electricity and heat. The increase in consumption is inevitable as well due to increasing demand for electrical energy to replace manual labors with robotics. Increased electrical energy demand also caused the price of finite energy resources to increase rapidly, especially in recent years (Krozer Y., 2013 and Alrikabi N., 2014). Therefore, many countries in the world put their attention on the possibilities of electrical production with renewable energies since it is an infinite source and does not emit carbon dioxide during conversion. In addition, the conversion process does not produce harmful gas for the earth and most importantly, the overall costs for energy extraction are lot lower than finite energy resources. Global Energy Statistical (2017) presented the change in electricity production through renewable energy sources by countries. It is found that Norway is topped in the list with 97.9 % in year 2016. New Zealand, Colombia and Brazil also produced more than 80 % of electricity from renewable energy sources such as wind, solar and hydropower. China is the largest energy consumer since 2009, also showed increasing trend in electricity production from renewable energy resources.



Hydropower is one of the renewable energy resources that operates or generate power from falling or fast running water through mechanical device. The earliest evidence for the energy conversion, dated back to B.C. where the energy was harnessed from water using water wheels (Brown, 2011 and IPCC, 2011). The first commercial hydroelectric power plant was built at Niagara Falls in the year 1879. Since then, the implementation of hydropower to produce electricity has been growing steadily due to the fact that earth's surface is covered by approximately 71 % of water. According to the Key World Energy Statistics (2017), the world hydro electricity production increased from 1,296 TWh in year 1973 to 3,978 TWh in year 2015. Norway ranked at top in the list of domestic hydroelectricity producers with 95.9 %, almost eliminating the usage of finite energy sources (International Energy Agency, 2017).

In hydropower system, water flow through a pipe or channel due to the effect of gravitational pull. Due to the conservation of energy, the velocity of water is maximized at the lower end of the pipe or channel. High speed water is directed to the water turbine either directly or through nozzle. That creates impulsive or reaction forces large enough to rotate the water turbine. Such motions convert mechanical kinetic energy of water turbine into electrical energy through generator attached to the water turbine. The system is continuous and emits zero carbon to the environment. In the case of a large hydropower, huge dam is required in order to contain water at huge volume. The construction of dams was accompanied with flooding of wide area of land, thus having significant negative impacts on social and environments of local habitat. The large hydropower which operates under high water head is able to provide power as high as 22,500 megawatts (USGS Water Science School, n.d.). The negative environmental impact promotes the development of hydropower at smaller scale which has low head requirement and insignificant impacts on the eco-system. Nowadays, many countries are using large scale hydropower station as the main source of electricity because of the availability in high-head water sources. Although the installation cost of the large hydropower plant project is very high compared to other plants, the electricity generation cost is very low. Even though growing interest can be seen on the micro and mini hydropower plant project, it is still under-developed due to the incapability to catch up with the high electricity demands (Dilip, 2009).

It is found that only 5 % of the global small-scale hydropower potential has been utilized properly while its total potential capacity could be as high as 150 GW to 200 GW (Hamududu and Killingtveit, 2012 and Laghari er. al., 2013). The small scale hydropower pant is suitable to supply electricity for rural areas and places with the absence of electricity grid as long as water source is available. It is also found that the cost of construction for a small-scale hydropower plant is relatively lower compared to hydropower plant with high hydraulic head requirements (Dilip, 2009). According to European standards, small hydropower having power generation capacity less than 10MW is very good for environment since the impacts are relatively lower than large-scale hydropower plant (European Small Hydropower

Association, 2006). Different types of hydropower plants are available in the world. Pelton wheel turbine, Francis turbine and Kaplan turbine are used to generate electricity from the water sources. Recently, increased interests on a small-scale hydro power plant invented by an Austrian Engineer can be seen due to its low impacts on the eco-system and low hydraulic head requirements. The hydro power plant is known as Gravitational Water Vortex Power Plant (GWVPP).

GWVPP is one of the small-scale hydro power plants which utilize the energy available from vortex flow generated from low hydraulic head (Ball, 2012; Mulligan and Hull, 2010; Punit and Franz., 2009 and Sezgin, 2014). It is found that the minimum hydraulic head required to generate electricity from GWVPP is 0.7 m. It was invented by an Austrian Engineer, Franz Zotloterer, while looking for an efficient way to aerate the small stream of river. It is considered as a milestone of hydrodynamic development because the new technology does not require additional energy to aerate the water; additionally the water vortex also caused the dissolved oxygen and oxygen saturation in the water to increase significantly (Vortex Brewer, 2014).



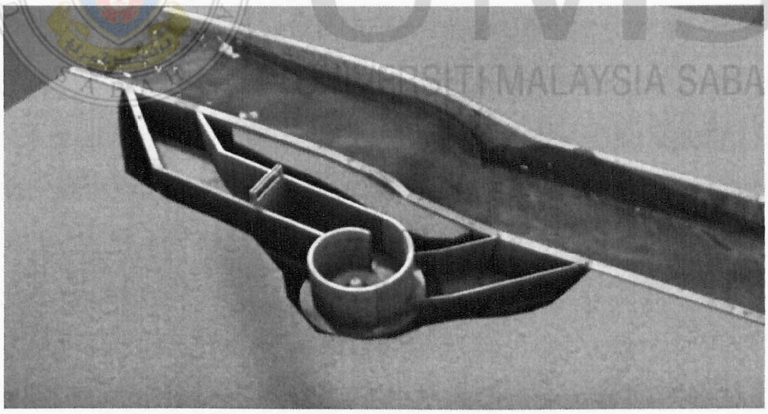

**Figure 1.1 : Structure of GWVPP**

Source : Turbulent Hydro (http://www.turbulent.be/)

As seen from Figure 1.1, the structure of GWVPP consists of a penstock that directs the water from upper end of the river, a basin that helps in the formation of water vortex, a turbine that harness energy from the vortex, an outlet that act as the exit hole for the water and another penstock that is connected to the lower end of the river. The river water passes through a gate, which control flow rate at the penstock. The water from penstock is directed tangentially into the basin. The water exit from the water basin through the outlet at the center of the basin's base and flow into another penstock connected to lower end of the river. The water vortex rotates the turbine positioned at the center of the basin. The turbine's kinetic energy is used to generate electrical energy through a generator.

The GWVPP eliminates the needs of large dam because it works on the dynamic force generated from vortex instead of pressure differential. This mean hydrostatic head is not the most important operating parameter for GWVPP although it helps to increase the power output significantly. Besides that, GWVPP is also found to be advantageous due to the properties of water vortex. Due to the formation of water vortex, water in a stream is forced to move. The water movement aerates and increases the dissolved oxygen and oxygen saturation in the water which promotes self-purification of water. In addition, the water surface area is also increased along with higher flow rate. Therefore, water vortex homogenously disseminates the contaminants of water. For countries with four seasons, water vortex could increase evaporation rate so that the water temperature reduces and builds up a peripheral zone of ice in the winter to isolate the center of the vortex. GWVPP's ring-shaped outlet also ensures the survival of living organisms such as fishes and shrimps. Since no bearing system is required to place under the water in GWVPP system therefore, this technology can be used for aeration in the wastewater treatment plant at low maintenance cost (Gravitational Water Vortex Power Plant, n.d.).



## 1.2 Problem Statement

Large hydro power plant promotes zero carbon emissions. However, its negative impacts on the water quality and wildlife habitats are too significant to ignore. Large hydro power plant also requires huge areas of land; hence it is infeasible to be installed at rural areas. It also prevents the fish migration in the river; thus affecting the eco-system. One of the valid suitable options that can eliminate fish migration problem is GWVPP (Wichian and Suntivarakorn, 2016; Yaakob et. al., 2014; Kueh et. al., 2014).

The concept of this power plant is developed based on the free surface vortex that is one of the important topics in hydraulic engineering. Growing interests on GWVPP can be noticed due to its small size and simplicity in structure. The research works mainly focus on the factors that affecting the vortex strength or describing the vortex structure and location (Yaakob et. al., 2014; Dhakal et. al., 2014; Mulligan and Hull, 2010). Quantification of physical parameters is limited in the literature. In addition, Kueh et. al., in the year 2014 studies the water vortex mathematical model to improve it. The main focus was on hydraulic intake in the free surface flow since undesirable vortex is generated in this region that has significant impact on efficiency and may cause failure of devices. It is also found that the free water surface flow in the naturally organized vortex is generated from swirl motion of water. Kueh et.al concluded that this swirl motion lead the centripetal motion and this motion can be used to overcome centrifugal motion but it is impossible in the case of natural vortex (Kueh et.al. 2014). In the study it is also found that the outlet and cylindrical vortex tank diameter ratio 0.14 to 0.18 is suitable for achieving maximum vortex strength at low and high water pressure respectively. This is quantified for a fixed discharge condition but effects of variable discharge are not yet concluded. It is found that the vortex strength also depends on the quantity of water as well as tangential velocity of water at inlet of the vortex tank. Therefore it is important to study the effects of inlet area and flow condition on vortex strength (Kueh et. al 2014; Nishi and Inagaki, 2017; Dhakal et, al. 2015; Dhakal et. al., 2014).

In addition, the lack of literatures on the direct effects of flow conditions, exit orifice diameter and blade geometry on the efficiency of GWVPP is slowing down the development of GWVPP. It is found that the outlet's diameter validation is lacking for different basin's dimension. The dimensions and effects of different geometry of penstocks that connects tangentially to the basin are very limited, or most often not mentioned in the literature since the emphasis is provided on other physical parameters during design rather than penstock. Additionally, the direct effects of inlet flow rates towards the efficiency of GWVPP also lacks validation (Nishi and Inagaki, 2017; Georgescu et. al., 2011; Nishi et. al., 2014; Shabara et. al., 2015).

The development of GWVPP in every aspect is still relatively slow compared to others alternative options. Additionally, the information about the commercial application of GWVPP is also very limited. The largest GWVPP was developed in Switzerland by GWWK and it claimed to produce annual energy output varied between 80 MWh and 130 MWh (Power C., 2016).

## 1.3 Research Aim

The aim of this research was to improve the efficiency of the GWVPP through experimental investigation of different geometries and parameters of GWVPP.

## 1.4 Research Objectives

The objectives of the research were as follows:

i. To investigate the effects of different outlet's diameters on the efficiency.
ii. To investigate the effects of different penstock's geometries on the efficiency.
iii. To validate the effects of inlet flow rates on the efficiency.



## 1.5 Scope of Research

The research work conducted was limited to the following scope:

i. The study has space limitations (0.8 m x 1.5 m) imposed upon the scaled-down prototype of GWVPP.
ii. The study is limited to water only without particles or impurities.
iii. The maximum inlet flow rate for the study is limited to 10 $m^3$/h.
iv. The experimental was limited to cylindrical-shaped basin only.
v. All the experiments were conducted with one type of turbine blade
vi. The efficiency of the turbine was measured with pony brake mechanism
vii. The outlet orifice diameter of the vortex was limited from 0.052 m to 0.076 m.
viii. The basin diameter is fixed at 2 m in radius and 0.5 m in height.
ix. The diameter of the runner was fixed and it was 0.14 m x 0.20 m.

x. The number of blades in the runner was 3.
xi. The height of the runner was fixed at 0.015 m.

## 1.6 Research Activities

The following activities were planned and carried out for this study:

i. To design a scaled-down, laboratory sized prototype of GWVPP model with space limitations of 0.8 m x 1.5 m.
ii. To design geometries of penstock (opening area) to be investigated for effects against the efficiency in the model. .
iii. To validate the effects of outlet's diameter at different basin's dimension on GWVPP model's efficiency.
iv. To determine the effects of inlet flow rates on the efficiency of GWVPP.

## 1.7 Contribution of the Study

This study provides understanding on the relationship between the geometry of penstock, outlet's diameter and inlet flow rates on the efficiency of the prototype GWVPP. The findings of this study could be used as validation work of past researches as well as further consolidates the design of GWVPP.



## 1.8 Chapter Organization

This thesis starts with Chapter 1, which is the introduction section where the project's background, objectives and benefits are presented. Chapter 1 provides information to the reader with basic understanding and explanation to anticipate the rest of the chapters in this thesis.

Chapter 2 is the literature reviews chapter where past research works, thesis or even cases have been presented after intensive reviews of the documents. An overview of different terminologies and findings related to this study is available in Chapter 2.

Chapter 3 covers the methodology of the present research topic where the detailed prototype designs, test rig configurations as well as step-by-step procedures are included with proper justification.

Chapter 4 is the results and discussion section that mainly presents the data obtained after intensive experiments have been carried out. After the data have been compiled, results can be found from tables in the chapter. The data are also further analyzed and presented in figures to explain the effects of the studied parameters on the performance of the prototype.

Chapter 5 presents the conclusion of the present research works as well as provides future information for extension of research or highlighted research area.

## 1.9 Research Methodology

A set of systematic research method was implemented in order to complete the project within timeline. References towards the flow chart were made from time to time.

First of all, the problems related to the project were identified and mentioned in Section 1.2. After that, literature reviews were carried out to determine the best experimental methodology for investigation on the mentioned objectives in Section 1.4. The experimental methodology was then designed and specified further with limitations. Once the experimental methodology was finalized, the scaled down prototype for GWVPP was designed with CAD software and fabricated for experimentation purposes.

Completed experiments were followed by data analysis where the data was compiled and analyzed. The results and discussion can be found in Chapter 4. Finally, the process will end with the documentation of project.