PERFORMANCE OF GRAVITATIONAL WATER VORTEX ENERGY SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

School of Mechanical Engineering
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JANUARY 2020

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

First and foremost, I would like to thank Almighty Allah, the Beneficent, the most Merciful, who bestowed me with the strength and courage to complete the study.

I would like to express my sincere gratitude to my advisors Prof. Omar Bin Yaakob and Dr. Yasser Mohamed Ahmed for their continuous support of my PhD study and related research, as well as for their patience, motivation, and immense knowledge. Their guidance helped me through all the time of research and writing of this thesis. I could not have imagined having better advisors and mentors for my PhD study.

I would like to thank my family: my parents and my wife and children for supporting me spiritually throughout the writing of this thesis and my life in general.

I am also thankful to my colleagues and friends for their support and who made the tenure of this study quite lively.

I would also like to thank the developers of the utmthesis LaTeX project for making the thesis writing process a lot easier for me. Thanks to them, I could focus on the content of the thesis and not waste time with formatting issues.

I would like to thank Universiti Teknologi Malaysia (UTM) for giving me the opportunity to accomplish my PhD study through the laboratory facilities and library.

Finally, I wish to express my deepest gratitude and sincerest appreciation to all those who offered me advice and suggestions.

ABSTRACT

An essential part of a mini-hydropower system is the conversion of low-head potential energy into kinetic energy to drive power turbines. One way of converting low-head potential energy is using a gravitational water vortex power plant (GWVPP). However, the efficiency at this very low-head is still low. Therefore, this research focused on two fronts: (1) to optimize the vortex pool so as to increase the efficiency of transfer of potential energy to kinetic energy by using the natural vortex and artificially augmented vortex and, (2) to design a turbine to obtain maximum power from such low kinetic and potential energy. This work dealt with the optimization of the vortex pool to improve energy conversion and hence, generate electricity from a very low operating head of 0.2 m to 0.3 m. For this purpose, a numerical and experimental studies were carried out to investigate the vortex flow characteristics in a gravitational water vortex system in the absence and presence of a water turbine. The commercial Computational Fluid Dynamics (CFD) software ANSYS Fluent was used to investigate the optimum configuration of the vortex pool system. Moreover, an experimental test rig was set up to validate CFD results. The results of the validation demonstrated that ANSYS Fluent can model the system correctly. The Reynolds Stress model showed better results than $K - \varepsilon$ and $K - \omega$ models in predicting the vortex flow structure. A parametric study was carried out using the software to determine the main parameters affecting the efficiency of energy conversion. Two different turbines were tested experimentally, revealing that the curved blade turbine was more efficient than the crooked blade turbine by 18%. Finally, six rectangular vanes were used to guide the flow for enhancing system efficiency. Hence, a 50% increment in system efficiency was recorded. The maximum efficiency of the cylindrical pool system with six vanes was about 54%. This system has broad applications in low-head cases such as streams, small rivers, irrigation canals, wastewater, and rainwater harvesting systems. This system can provide rural and remote communities with an economical green source of energy.

ABSTRAK

Satu bahagian penting daripada sistem tenaga hidro mini adalah pertukaran tenaga keupayaan turus-rendah ke tenaga kinetik untuk menjalankan turbin kuasa. Salah satu cara menukar tenaga keupayaan turus-rendah ialah menggunakan air graviti loji janakuasa pusaran (GWVPP). Namun, kecekapan di turus-rendah adalah masih rendah. Oleh itu, kajian ini tertumpu kepada dua bidang, pertama untuk mengoptimumkan kolam pusaran GWVPP untuk meningkatkan kecekapan pemindahan tenaga keupayaan kepada tenaga kinetik dengan menggunakan pusaran semulajadi dan seterusnya diperbesarkan. Kedua, merekabentuk turbin dengan mendapatkan kuasa maksimum dari tenaga kinetik dan keupayaan yang rendah. Kajian ini menumpukan kepada pengoptimuman kolam pusaran untuk meningkatkan penukaran tenaga dengan menjana elektrik dari turus operasi rendah iaitu antara 0.2 m hingga 0.3 m. Untuk tujuan ini, kajian kaedah berangka dan eksperimen telah dijalankan untuk mengkaji ciri-ciri pusaran dalam sistem pusaran air graviti dalam keadaan ada dan tiada turbin air. Perisian komersial Dinamik Bendalir Perkomputeran (CFD) ANSYS Fluent telah digunakan untuk mengkaji kongurasi sistem pusaran optimum. Di samping itu, sebuah pelantar ujikaji telah dibina untuk mengesahkan keputusan CFD. Keputusan menunjukkan bahawa ANSYS Fluent berupaya memodelkan sistem dengan betul. Model tekanan Reynolds menunjukkan keputusan yang lebih baik daripada model $K - \varepsilon$ dan $K - \omega$ dalam meramal struktur aliran pusaran. Satu kajian parametrik telah dijalankan dengan menggunakan perisian untuk menentukan parameter utama yang mempengaruhi kecekapan penukaran tenaga. Dua turbin yang berbeza telah diuji secara eksperimen dan mendapati bahawa turbin bilah melengkung adalah lebih cekap sebanyak 18% berbanding turbin bilah *crooked.* Enam bilah segi empat tepat telah digunakan untuk mengarah aliran dalam meningkatkan kecekapan sistem. Oleh itu, peningkatan 50% dalam kecekapan sistem direkodkan. Kecekapan maksimum sistem kolam berbentuk silinder dengan enam bilah adalah kira-kira 54%. Sistem ini mempunyai aplikasi yang luas dalam keadaan turus-rendah, misalnya aliran, sungai kecil, tali air, air sisa, dan sistem air hujan. Sistem ini boleh menyediakan komuniti luar bandar dan terpencil dengan sumber tenaga hijau yang ekonomik.

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LIST OF ABBREVIATIONS

CF	-	Coriolis Force
CFD	-	Computational Fluid Dynamics
FOV	-	Field of View
FSV	-	Free Surface Vortex
FVM	-	Finite Volume Method
GWVPP	-	Gravitational Water Vortex Power Plant
IGES	-	Initial Graphics Exchange Specification
KW	-	Kilo Watt
LES	-	Large Eddy Simulation
MW	-	Mega Watt
NACA	-	National Advisory Committee for Aeronautics
NS	-	Navier Stokes
PIV	-	Particle Image Velocimetry
PRESTO	-	Pressure staggering Option
PTV	-	Particle Tracking Velocimetry
RANS	-	Reynolds Averaged Navier - Stokes Equation
RPM	-	Revolution Per Minute
RM	-	Malaysian Ringgit
RNG	-	Renormalization Group Theory
RSM	-	Reynolds Stress Model
SAS-CC	-	Scale-Adaptive Simulation-curvature-correction
SHP	-	Small Hydro Power
SIMPLE	-	Semi-Implicit Methods for Pressure- Linked Equation
SST	-	Shear Stress Transport
TM	-	Trade Mark
UIUC	-	University of Illinois at Urbana Champaign
UTM	-	Universti Teknologi Malaysia

US	-	United States of America
VAMCT	-	Vertical Axis Marine Current Turbine
VAT	-	Vertical Axes Turbine
VOF	-	Volume of Fluid Method
WPI	-	Worcester Polytechnic Institute

LIST OF SYMBOLS

A - Cross sectional area of channel (m^2)

Al - Aluminum

A_t - Active area of turbine (m^2)

Ca - Capillary number

CO_2 - Carbon Dioxide

C_p - Power coefficient

d - Outlet diameter (m)

D - Vortex pool diameter (m)

D_ω - The cross-diffusion term

Fe - Stainless steel

Fr - Froude number

g - Gravitational acceleration (m/s^2)

G_k - Generation of turbulence kinetic energy

G_ω - The generation of ω

h - water depth (m)

H - Head (m)

K - Turbulence kinetic energy

L - The dimensionless distance from the rotor shaft centre

P_{max} - Maximum extracted power ($Watt$)

P_{out} - Output power ($Watt$)

Q - Inflow rate (m^3/s)

r - Vortex core radius (m)

Re - Reynolds Number

V_{in} - Inlet velocity (m/s)

V_{out} - Outlet velocity (m/s)

V_θ - Tangential velocity component (m/s)

V_r - Radial velocity component (rad/s)

V_z - Axial velocity component (m/s)

W - Channel width (m)

We - Weber number

Y_k - Dissipation of k due to turbulence

Y_ω - Dissipation of ω due to turbulence

Greek Symbols - :

α - Cone angle

β - The angle of attachment

η - Turbine efficiency

Γ - Circulation of flow (m^2/s)

λ - Tip speed ratio

ω - Turbine angular velocity

ρ - Water density (Kg/m^3)

ε - Block ratio

$\mathit{\Gamma}_k$ - The effective diffusivity for k

$\mathit{\Gamma}_\omega$ - The effective diffusivity for ω

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The search for renewable energy sources like wind power, hydropower and solar energy as alternatives for power generation arose as a response to the social, economic and environmental complications of using fossil fuels (Kaldellis *et al., 2013*). Moreover, nowadays, many developing countries are encountering an energy crisis due to the increase in industrialization for development programs. If this excess demand is supplied from fossil fuels, it will harm the environment. Consequently, exploring renewable energy resources is now necessary for sustainable energy in order to balance the 70 % increase in electricity demand all over the world, to comply with the needs of rapid growth of electricity, as well as to reduce CO_2 impact on the environment (Lahimer *et al.*, 2012).

Renewable energy development in Malaysia is still in its primary stage. Hashim and Ho (2011) estimated that utilization of 5% of renewable energy for five years will save the country RM 5 billion (US $ 1.32 billion). Subsequently, according to the Tenth Malaysia Plan (2011-2015), the expansion of research into green technology is encouraged via commercialization through proper mechanisms such as in (Chua and Oh, 2010).

In this trend, Khan *et al.* (2009) considered energy in flowing river streams, tidal currents, or other artificial water channels as an appropriate source of renewable power. Malaysia is generating 18,500 MW from hydropower, and 30.3 MW of mini-hydropower is under construction, with 490 MW is expected by 2020. Although real potential is expected for micro-hydropower, it is not fully utilized (Ahmad *et al.,* 2011). Furthermore, Malaysia Energy Centre's National Energy Balance expects mini-hydropower to reach 500 MW (Oh *et al.*, 2010).

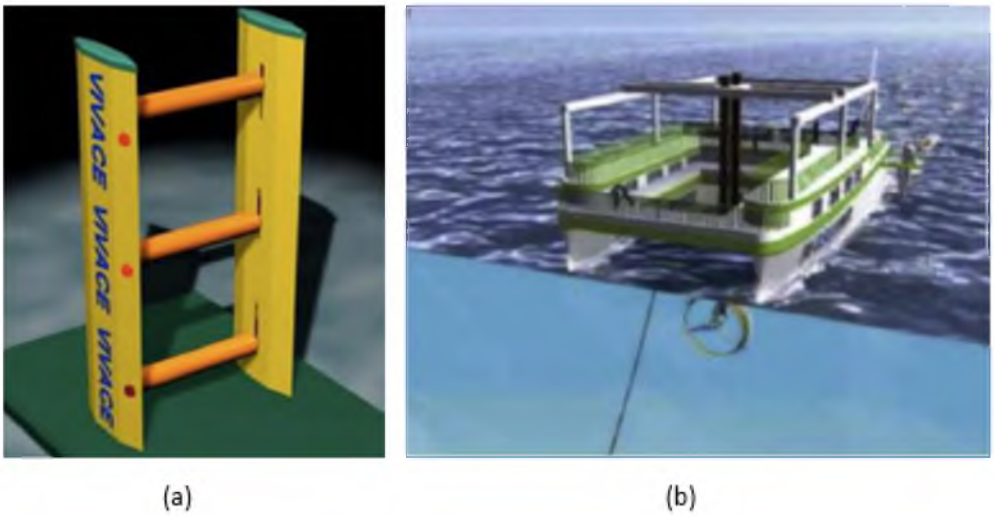
Micro-hydro power plants can provide electricity to remote communities. Many installations have been implemented worldwide, mostly in developing countries. They can be a clean, economical source of energy without the need for fuel (Sopian *et al.,* 2011). Utilizing a 10 KW mini-hydropower system can remove one thousand gallons of diesel fuel per year (Ong *et al.,* 2011). Moreover, small hydropower is supported by international efforts to decrease greenhouse gasses' effects on the environment (Sipahutar *et al.,* 2013). Furthermore, improving hydropower and small hydropower (SHP) plants is considered as a high potential source of renewable energy resources (Sharma *et al.,* 2013).

Khan *et al.* (2009a) divided hydrokinetic energy conversion into two categories: turbine and non-turbine systems, as shown in Figure 1.1 and Figure 1.2, respectively. Figure 1.1 (a) shows a venturi, which is a chocking system that results in water acceleration. This water will then turn a turbine. In Figure 1.1 (b), a vertical axis turbine is driven by an artificial vortex. Figure 1.2 (a), Vortex Induced Vibration for Aquatic Clean Energy (VIVACE), the flowing current passing through cylinder forms a vortex in the downstream. Vortex shedding alternates from one side to another, causing the cylinder to oscillate. The energy produced by the cylinder's movement is then converted to electricity. Figure 1.2 (b) displays a Seasnail device where a vertical oscillation of hydrofoil is capable of generating pressurized fluids, which can be utilized in turbine rotation.

Presently, various turbine concepts and designs are being implemented extensively, whereas non-turbine systems are generally at the proof-of-concept stage (with some exceptions). Therefore, turbine systems are given more attention as they are the most promising for deployment (Khan *et al.*, 2009a). One turbine system technique is Gravitational Water Vortex Power Plant (GWVPP). This system is capable of generating electricity from low heads 0.7m to 3 m and can be applied in mini/micro hydropower plants (Wanchat and Suntivarakorn, 2012). This system also has broad applications in low-head cases such as streams, small rivers, irrigation canals, wastewater and rainwater harvesting systems (Mohanan, 2016).


(a) (b)

Figure 1.1 Examples of turbine systems (a) HydroVenturi TM; (b) (GWVPP) TM. (Khan *et al.*, 2009a)



(a) (b)

Figure 1.2 Examples of non-turbine systems (a) VIVACE ™; (b) Seasnail ™. (Khan *et al.*, 2009a)

GWVPP utilizes the available energy in the gravitational vortex, which is usually generated in a circular pool with a tangential inlet and an outlet at the bottom center, as shown in Figure 1.3. The energy produced by the vortex is captured by a vertical axis turbine employed in the center of the pool, at the vortex core where the rotational speed is maximum. The turbine rotates with the swirling flow, thus generating mechanical power which is converted into electrical energy by means of an alternator.

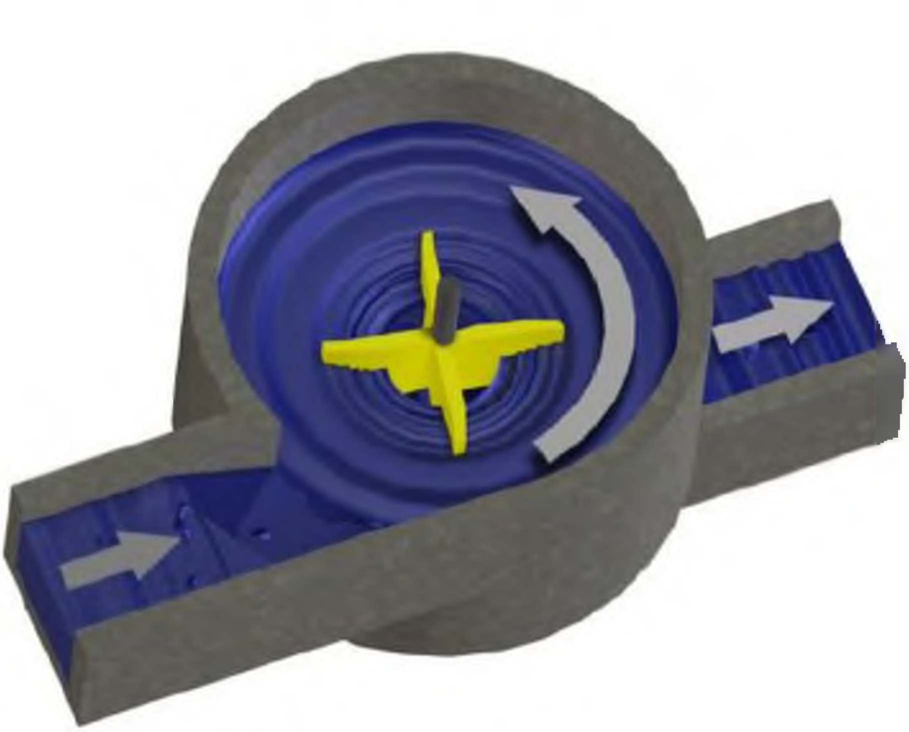


Figure 1.3 Schematic of GWVPP (Power *et al.*, 2016)

1.2 Problem Statement

In GWVPP, the hydrostatic head is low. However, it has been shown that using the natural gravitation vortex formed in nature will enable us to extract more energy, even at low heads. However, the efficiency is still very low. Therefore, there is a need to improve the efficiency by carrying out research on two fronts. First, we must optimize the vortex pool for GWVPP in order to increase the efficiency of transfer from potential energy to kinetic energy, using the natural vortex and artificially augmented vortex. Secondly, the turbine must also be optimized to obtain maximum power from such low kinetic and potential energy.

The goal of this research is to investigate the optimum configuration of the GWVPP and design the appropriate turbine so that the maximum power can be generated.

1.3 Research Objectives

The specific objectives of this research are to:

i. Determine critical parameters in strengthening Free Surface Vortex.

ii. Optimize the vortex pool to increase the kinetic energy.
iii. Select suitable turbine parameters for efficient GWVPP.
iv. Assess the performance of the new vortex system.

1.4 Research Scope

In this thesis, vortex pool configuration has been studied from the fluid mechanic's point of view to capture as much kinetic energy as possible from the water vortex flow. The challenge is to increase the system efficiency while maintaining a very low operating head of 0.2-0.3 m and a flow rate of 0.028-0.064 m^3/s. The range of channel width to the pool diameter ratio studied was between 0.1-0.4. As for the orifice diameter to the basin diameter, it was in the range of 0.16-0.2. Finally, a swirling device is employed in the pool, to enhance the energy conversion in the vortex pool. This idea is a new approach in the mini/ micro hydropower generation fields.

The optimum parameters of the GWVPP were analyzed and determined using CFD. Then, the system prototype had been fabricated for experimental testing.

1.5 Research Significance

This study begins with reviewing hydrodynamics of turbomachinery, examining various designs of water turbines, and using Computational Fluid Dynamics for optimizing the turbine parameters. It will determine the parameters which can be used by CFD to improve the water vortex kinetic energy like vortex configuration, water head, and diameter of orifice, inlet and outlet conditions. The Malaysian climate is taken into consideration in this research to provide small communities with green economic energy.

1.6 Dissertation Organization

This dissertation is organized as follows.

Chapter 2 reviews related works to Gravitational Water Vortex Power Plant (GWVPP). It is divided into three sections: the first section reviews the Free Surface Vortex (FSV) flow showing the different aspects of this phenomenon, the second section summarizes the relevant findings to GWVPP, and the last one surveys various designs of turbines and their performance.

Chapter 3 describes the methodology. It includes five stages. The first stage is the determination of the parameters affecting the performance of GWVPP. The second stage is to optimize the affecting parameters to improve energy conversion. In the third stage, the effect of installing swirling devices in the vortex pool on the system efficiency is numerically investigated. Finally, an experimental study for the employment of two different turbines and system validation are presented.

Chapter 4 presents results and discussions of the five stages. The first one shows the results of the vortex pool parametric study in the absence of turbine, and its validation. The second one is vortex pool configuration and parameters optimization in the presence of turbine. The third is the results of the novel approach of installing a swirling device in the GWVPP vortex pool. The fourth one is a comparison between curved and crooked turbines. Finally, the validation and analysis of the results.

Finally, Chapter 5 presents the conclusions drawn from the numerical simulation and experimental testing of GWVPP vortex pool. Moreover, recommendations for future studies in GWVPP have also been presented.

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