# MICRO HYDRAULIC TURBINE FOR POWER GENERATION IN MICRO SCALE CHANNELS

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Dedicated to my beloved family and to soul of my brother Abdalla
for their toleration and sincere help during my life.

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# ABSTRACT

Micro hydrokinetic energy scheme presents an attractive, environmentally friendly and efficient electric generation in rural, remote and hilly areas. However, this scheme is yet to be fully discovered, as researchers are still searching for solution for the main problems of low velocity of current in the open flow channels and low efficiency of hydrokinetic turbines. This research proposes a novel system configuration to capture as much as kinetic energy from stream water current. Deploying acceleration nozzle in channels is a unique solution for increasing the efficiency of channels' current flow systems while the use of micro hydraulic cross flow turbine (CFT)/ Banki turbine is the most proper and practical solution. This system, known as bidirectional diffuser augmented (BDA) channel, functions by utilizing dual directed nozzles in the flow, and surrounded by dual cross flow/ Banki turbines. In this study, numerical and experimental investigations were carried out to study the flow field characteristics of the new system approach with and without turbines. A numerical investigation was carried out in this research work using finite volume Reynolds-Averaged Navier-Stokes Equations (RANSE) code ANSYS CFX and Fluent. Validation was carried out by using experiments, with and without turbines. The flow characteristics through channel and the performance of the twin (lower and upper) cross flow turbines were studied, and it was found that the water flow speed had been significantly enhanced due to the current BDA system in which the speed of the flow was increased by 400%. The maximum efficiency of the overall system with two turbines was nearly 55.7%. The efficiency was relatively low compared to hydraulic turbine efficiency, however, this can be considered very good in view that head available to the present system was very low. The use of this system will contribute towards a more efficient utilization of flows in rivers and channels for electrical generation in rural areas.

# ABSTRAK

Sistem tenaga mikro hidrokinetik merupakan sumber janaan tenaga yang mesra alam dan cekap di luar bandar, pedalaman dan kawasan berbukit. Walau bagaimanapun, sistem ini masih belum dikaji sepenuhnya dan para pengkaji masih mencari penyelesaian kepada masalah halaju yang perlahan dalam saliran air terbuka dan rendahnya kecekapan turbin hidrokinetik. Kajian ini mencadangkan konfigurasi sistem baru untuk menjana seberapa banyak tenaga kinetik daripada arus aliran air. Pemasangan nozel pemecut di saliran merupakan penyelesaian unik untuk meningkatkan kecekapan sistem arus saliran manakala penggunaan turbin aliran lintang hidraulik mikro (CFT)/turbin Banki merupakan penyelesaian terbaik dan praktikal. Sistem ini yang dikenali sebagai saluran penambah serapan dua hala (BDA) berfungsi dengan menggunakan nozel dwi tuju di dalam aliran, dikelilingi aliran dan lintang/ turbin Banki. Kajian berangka dan eksperimen telah dijalankan untuk mengkaji kaedah baru sistem ciri-ciri medan aliran ini dengan dan tanpa turbin. Simulasi berangka telah dilakukan menggunakan kod ANSYS CFX dan Fluent *finite volume Reynolds-Averaged Navier-Stokes Equations* (RANSE). Pengesahan telah dijalankan melalui eksperimen, dengan turbin dan tanpa turbin. Ciri-ciri aliran melalui sistem saluran dan prestasi dwi (bawah dan atas) turbin aliran lintang telah dikaji dan didapati bahawa aliran air telah dipertingkatkan dengan ketara disebabkan oleh sistem BDA di mana kelajuan aliran telah meningkat sebanyak 400%. Kecekapan tertinggi keseluruhan sistem dengan dua turbin adalah hampir 55.7%. Kecekapannya didapati lebih rendah daripada kecekapan turbin hidraulik. Namun, kecekapan ini boleh dianggap sangat baik memandangkan tekanan sedia ada untuk sistem kajian ini adalah sangat rendah. Penggunaan sistem ini akan menyumbang ke arah penggunaan aliran yang lebih cekap di sungai-sungai dan saluran bagi penjanaan elektrik di kawasan luar bandar.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| BDA | _ | Bidirectional Diffuser Augmented Channel |
| CFD | _ | Computaional Fluid Dynamics |
| CF | _ | Cross Flow |
| CFT | _ | Cross Flow Turbine |
| HAT | _ | Horizontal Axis Turbine |
| NACA | _ | National Advisory Committee for Aeronautics |
| PAT | _ | Pump as Turbine |
| RANSE | _ | Reynolds Averged Navier - Stokes Equation |
| RPM | _ | Revolution Per Minutes |
| SIMPLE | _ | Semi-Implicit Methods for Pressure- Linked Equation |
| SST | _ | Shear Stress Transport |
| TI | _ | Turbulance Intensity |
| TSR | _ | Tip Speed Ratio |
| UNDP | _ | United Nations Development Program |
| UTM | _ | Universiti Teknologi Malaysia |
| VAT | _ | Vertical Axis Turbine |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| A | _ | Cross sectional area of turbine (turbine's flow) ($m^2$) |
| $A_c$ | _ | Cross sectional area of channel ($m^2$) |
| $A_f$ | _ | Cross sectional area of helical channel ($m^2$) |
| $C_P$ | _ | Power Coefficient "Hydrokinetic" ($C_p = \frac{T \text{ x } \omega}{0.5\rho A {U_0}^3}$); "Hydropower" ($C_p = \frac{T \text{ x } \omega}{\rho g Q H}$) |
| $d_1$ | _ | Channel diameter ($m$) |
| $d_2$ | _ | Contraction Nozzle diameter ($m$) |
| $D_o$ | _ | Outer diameter of the turbine runner ($m$) |
| $D_i$ | _ | Inner diameter of the turbine runner ($m$) |
| $D_i / D_o$ | _ | Runner diameter ratio |
| $DE$ | _ | Dean Number ($DE = Re \ x \sqrt{\delta}$) |
| D$h$ | _ | Hydraulic depth ($m$) ($D_h = \frac{4A}{p_w}$) |
| $D_\omega$ | _ | The cross-diffusion term |
| Fr | _ | Froude Number ($Fr = \frac{{U_o}^2}{g h_h}$) |
| g | _ | Gravitational acceleration ($m.\ s^{-2}$) |
| $G_\omega$ | _ | Generation of turbulence kinetic energy |
| $G_k$ | _ | The generation of $\omega$. |
| $h$ | _ | Depth of the channel ($m$) |
| $H$ | _ | Head ($m$) |
| $h_h$ | _ | Hydraulic depth ($m$) |
| K | _ | Turbulence kinetic energy |
| $K_h$ | _ | Head ratio of Pump as turbine (PAT). |
| $K_Q$ | _ | Flow rate ratio of PAT. |
| L | _ | CFT runner length ($m$) |
| $L_C$ | _ | Channel length ($m$) |

| | | |
|---|---|---|
| $L_n$ | _ | Nozzle length (*m*) |
| $\dot{m}$ | _ | Water channel mass flow rate ($kg.s^{-1}$) |
| n | _ | Manning's resistance coefficient |
| $p$ | _ | Pitch (*m*) |
| $P_C$ | _ | Maximum extracted power (*W*) ( $P_c = 0.5\rho A U_o^3$) |
| $P_{opt}$ | _ | Optimum power (*W*) |
| $p_w$ | _ | Wetted perimeter (*m*) |
| Q | _ | Runner inlet flow rate ($m^3.s^{-1}$) |
| r | _ | CFT runner radius (*m*) |
| R | _ | Curvature radius (*m*) |
| Re | _ | Reynolds number ($Re = \frac{\rho * U_o * D_h}{\mu}$) |
| $R_r$ | _ | Hydraulic radius (*m*) |
| S | _ | Channel bed slope (*m*) |
| t | _ | Thickness of turbine blade (*m*) |
| T | _ | Channel water draft (*m*) |
| $U_o$ | _ | Water flow velocity (*m/s*) |
| U | _ | Peripheral velocity |
| $u_i$ = (u v w) | _ | Velocity components in the directions of $x_i$=(x y z) |
| v | _ | Absolute velocity/Mean runner inlet velocity (*m/s*) |
| $v_r$ | _ | Relative velocity (*m/s*) |
| W | _ | Width of channel (*m*) |
| $Y_k$ | _ | The dissipation of *k* |
| $Y_\omega$ | _ | The dissipation of *ω* |
| Z | _ | No. of Blades |

**Greek Symbols**

| | | |
|---|---|---|
| α | _ | Blade angle of attack |
| $\beta_1$ | _ | Blade inlet angle |
| $\beta_2$ | _ | Blade outlet angle |
| $\Gamma_k$ | _ | The effective diffusivity for *k*. |
| $\Gamma_\omega$ | _ | The effective diffusivity for *ω* |

| | | |
|---|---|---|
| δ | _ | Helical channel curvature ($\delta = \frac{0.5w\ x\ R}{p^2+R^2}$) |
| ε | _ | Block ratio |
| η | _ | Turbine Efficiency ($\eta = \frac{T * \omega}{0.5\rho A {U_0}^3}$) |
| μ | _ | Water Dynamic viscosity ($N.s.m^{-2}$) |
| $\lambda$ | _ | Angle of CFT entry arc |
| $\lambda_t$ | _ | Helical channel torsion ( $\lambda_t = \frac{0.5w\ x\ p}{p^2+R^2}$) |
| ρ | _ | Water density ($kg/m^3$) |
| τ | _ | CFT blade thickness (*m*) |
| $\tau_{max}$ | _ | Maximum thickness of aerofoil thickness (*m*) |
| $\omega$ | _ | Angular velocity of the turbine (*rad/s*) |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

From 7 billion population of the world, 1.3 billion people still remain without access to electricity, especially those in the rural and poor areas. From this number, 22% are those living in developing countries; mostly living in the sub-Saharan Africa and developing countries in Asia (International Energy Agency's World Energy Outlook 2014). Nevertheless, it is expected that in the beginning of year 2040, at least one billion people gain access to electricity while nearly 500 million still remain without access. Renewable energy is also expected to represent 50% of the total power generation in these areas (International Energy Agency). This is because renewable resources provide efficient solution to achieve a perfect connection between renewable energies and sustainable development in the future. Tidal- current energy is one of the most prominent, clean and predictable renewable power resource from water in the world, especially regarding micro stations which can be deployed in isolated and hilly areas for electrification process (Kai *et al.*, 2013; Hammar. *et al.*, 2012; Liu, *et al.*, 2011*)*.

Micro hydropower scheme is the most suitable and efficient option for generating renewable energies. This is due to its low environmental harmful effect and lower operation and maintenance costs (Paish, 2002). Most rural and hilly areas use micro hydropower plants in order to generate cheap, available and effective electricity supply (Vermaak *et al.*, 2014*)*. Moreover, the micro hydropower schemes present an effective solution which has been recommended by many international organizations such as The United Nations Industrial Development Organization and The World Bank. Hydrokinetic technology is a new type of micro hydro-power that functions by utilizing hydrokinetic turbines in flow of river or channels to produce power (Vermaak *et al.,* 2014*;* Chamorro *et al.,* 2013; Kumar *et al.,* 2011*).* Harnessing kinetic energy from the flow of water in open channels is closely similar to tidal current power generation, so that existing facilities like weirs, barrages and falls can be optimized.

Many countries such as Malaysia that are surrounded by irrigation or rainy channels, have a great potential for exploiting this feature of nature. Adhau *et al. (2012)* carried out extensive study for potential sites, on the hydrological data for feasible development of mini/micro hydro power plant. They concluded that irrigation projects are viably economical and technical for micro power generation. Current or hydrokinetic energy that can be captured from the water flow in the irrigation and rainy channels is a new type of micro hydro-power system. This might be a promising technology in the countries with vast tidal current energy.

The open helical channels has wide range of application in nuclear, chemical, polymer processing, heat and mass transfer fields. These various applications can be developed for expanding the range of their applications, especially in the renewable energy field. The flow in helical channels is able to create centrifugal force from the curved wall to the channel center by which the highest velocity at the outside wall caused (Williams *et al.*, 1902). This accelerates the flowing water through the channels. It is certainly useful in case of energy extraction from the water channels.

On the other hand, accelerated nozzle in channels, a subject in the renewable energy fields that little attention is paid to, is the most efficient choice to accelerate the flow and increase the harnessed power of the flowing water.

In the last four years, researches were focused on studying the stream of water in channel technology in both flow pattern and turbine system viewpoint. They have discussed the developments on the open channel flow and the most appropriate turbine system which can be utilized in these channels. There are various conventional current energy turbines which can be used to capture the hydrokinetic energy from the flowing of water, horizontal axial flow turbines and vertical axis flow turbines.

Besides, one of the most attractive turbines is cross flow turbine (CFT) which is known as Banki and Ossberger turbine. This type of turbine is more practical than the other types of existing micro hydropower turbines. It is easy to construct and cost effective (Olgun 1998). These turbines are also suitable for high and medium flow rates and low head (Ghosh *et al.,*2011) capable of generating average efficiency of 80% for small and micro power outputs (Ossberger GmbH Co. 2011). This value is, however, lower than those of other most popular hydro turbines such as Pelton, Turgo, Francis and Kaplan (Okot 2013). In comparison, the main advantage of this turbine is its ability to keep maximum efficiency with different ranges of flow (Walseth 2009). Hence, the CFT is more appropriate for run-of-river applications due to its lower requirement for large head, and it is depending on the flow rate than other types of hydro turbines (Olgun 1998).

## 1.2 Problem Statement

Nowadays, irrigation or rainy channels have a great potential for developing renewable energy sector in the developing countries. Though potential, this scheme is yet to be fully discovered to the considerable extent, as researchers are still searching for solution for the main problem of low velocity and low depth of current in the open flow micro channels. This low current characteristic is the main consideration of this study. This is become important when it is known that conventional tidal current turbines are highly dependent upon the current speed and water depth. Moreover, another drawback of the conventional tidal current turbines is its low efficiency.

## 1.3 Objectives of the Study

Due to the shortcomings explained in the problem statement, the flow in the channel system needs to be accelerated in order to increase the harnessed power.

Deployment of a novel turbine configuration in the channel is a solution to overcome the low efficiency of conventional hydrokinetic turbines. Therefore, the main goal of this research is to improve the flow characteristics and enhance overall efficiency of the system for better extracting tidal current energy from flow in a channel, stream or river.

The objectives are to:

i. Develop a new configuration system with bidirectional nozzles in two directions of the micro channel.
ii. Develop a new type of hydraulic cross flow turbine system suitable for the micro scale water channels.
iii. Evaluate turbine operation and performance in the new channel arrangement in order to analyze the whole system.

## 1.4 Scope of the Study

In this study, a novel system configuration has been proposed in order to capture as much as kinetic energy from the water flow in micro scale channels. This idea is fairly a new approach in the hydrokinetic energy generation fields. The system, known as bidirectional diffuser augmented channel (BDA), is totally dependent upon utilizing bidirectional nozzle in two different flow directions, surrounded by dual cross flow/Banki turbines.

The optimum parameters of the bidirectional nozzle and CFT runners utilizing in micro channels were analyzed and determined using CFD. Then, prototype of the BDA channel with optimized CFT rotors had been fabricated for using in experiment.

## 1.5 Significance of the Study

Micro hydropower stations are significantly cost effective in socio-economic development, particularly for isolated hilly and rural areas. Moreover, hydrokinetic is a novel type of micro hydropower energy by which the energy can be extracted from rivers, irrigation/rainy channels and shallow waters. Development of hydrokinetic or current schemes involves with a main problem which is the appearance of low velocities. Installing nozzles in channels is the most efficient solution to overcome this issue. The current study proposed a new system of nozzles to be deployed in micro rainy and irrigation channels.

Implementation of cross flow turbine (CFT) or Banki turbine also is the most proper solution to overcome the low efficiency of conventional tidal current turbines. It is observed that this solution is more practical; efficient, simple and cost effective. The use of CFT with current configuration is a new concept of hydrokinetic power generation.

Numerical and experimental investigations were carried out in this research in order to evaluate the novel approach system. Moreover, CFD is becoming an important tool to investigate and design the cross flow turbines and it is supported by validated results.

## 1.6 Organization of the Thesis

Structure of this thesis is organized in six chapters. First chapter presents an overview of the current study. It also provides the objectives, scope and the significance of the present research with respect to the literature review findings.

In chapter two a detailed review of the previous researches which are related to the current work are provided. For the clarity of presentation, the literature review has been grouped under different headings namely, open channel flow, tidal current power (hydrokinetic power) turbines, operation and performance of low head micro hydropower turbines and cross flow turbines/ Banki turbines.

Chapter three presents objectives, scopes and numerical and experimental research methods of different stages. Mathematical model, grid generation, computational method, and its assumptions are explained in this chapter. Experimental methodology which gives the detailed description of facilities, experimental set up and apparatus and the test procedure are also included.

Chapter four proposes the numerical results for the usage of helical channel and different nozzle shapes in micro scale open channels. It also presents the experimental and numerical results and findings of a new configuration system known as bidirectional diffuser-augmented channel which utilizes bidirectional nozzles in two directions of channels with and without turbines.

Chapter five discusses the numerical results of flow characteristics of helical and nozzle channel. Furthermore, special configuration of ducted channel and dual cross flow turbines performance are discussed experimentally and numerically in four sections.

Finally, chapter six presents the conclusions drawn from the numerical simulation and experimental test of the special configuration of nozzle system and cross flow turbines. In addition, recommendations for future studies in this field have also been presented.

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