WATER TUNNEL TURBULENCE INTENSITY INVESTIGATION FOR MICRO-HYDROKINETIC TURBINE APPLICATION

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by

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ENDORSEMENT

I, Viknaraj A/L Subramaniam hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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(Signature of Examiner)

Name:

Date:

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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(Signature of Student)

Date:

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WATER TUNNEL TURBULENCE INTENSITY INVESTIGATION FOR MICRO-HYDROKINETIC TURBINE APPLICATION

ABSTRACT

Water tunnel is used to investigate the hydrodynamic behavior of immersed body in fluid dynamics study. Water tunnel is essential to provide a controlled condition for fluid flow research. The operational principle of water tunnel is identical to the wind tunnel but with different working fluid and higher flow-pumping capacity. Tests such as flow visualization in wind tunnel is more difficult to be conducted as turbulent flows in wind dissipate quickly whilst water tunnel is more suitable for such purpose due to higher fluid viscosity. However, the turbulence in the test section must be less than 10% or lower in order to produce a valid result. The present work focuses on improving the design criteria for each components and to maximize the performance of the water tunnel that was developed previously in terms of turbulence intensity reduction and improvement in flow uniformity. The design criteria of several primary components are studied and altered to reduce the turbulence intensity. The modified components were designed, fabricated and assembled to complete the modified water tunnel. This study also includes quantitative analysis on the velocity profiles and uniformity of the water flow at the test section. This is done by collecting data of the velocity at every point in the cross-section of water flow. That result was then used to plot the uniformity graph and to calculate the turbulence intensity in the water tunnel test section. The final turbulence intensity in the test section with the modifications made yielded a minimum result of 6.77%. The previous design yielded a turbulence intensity percentage of 9.66% comparatively. Thus, the turbulence intensity in the water tunnel was reduced by 29.92 %.

KAJIAN KEAMATAN PERGOLAKAN TEROWONG AIR UNTUK APLIKASI TURBIN MIKRO-HIDROKINETIK

ABSTRAK

Terowong air digunakan untuk menyiasat kelakuan hidrodinamik badan yang direndam dalam kajian dinamik bendalir. Terowong air adalah penting untuk menyediakan keadaan terkawal untuk penyelidikan aliran bendalir. Prinsip operasi terowong air adalah sama dengan terowong angin tetapi dengan cecair yang berbeza dan keupayaan mengepam aliran yang lebih tinggi. Ujian seperti visualisasi aliran dalam terowong angin lebih sukar dilakukan kerana aliran turbulen dalam angin menghilang dengan cepat sementara terowong air lebih sesuai untuk tujuan tersebut kerana kelikatan bendalir yang lebih tinggi. Walau bagaimanapun, pergolakan di bahagian ujian mestilah rendah untuk menghasilkan hasil yang sah. Kerja-kerja ini memberi tumpuan kepada peningkatan kriteria reka bentuk untuk setiap komponen dan untuk memaksimumkan prestasi terowong air yang telah dibangunkan sebelum ini dari segi pengurangan intensiti pergolakan dan peningkatan keseragaman aliran. Kriteria reka bentuk beberapa komponen utama dikaji dan diubah untuk mengurangkan keamatan pergolakan. Komponen yang diubahsuai, direka dan dipasang untuk melengkapkan terowong air yang diubah suai. Kajian ini juga merangkumi analisis kuantitatif pada profil halaju dan keseragaman aliran air. Ini dilakukan dengan mengumpul data halaju pada setiap titik di bahagian silang dalam pengaliran air. Hasilnya kemudiannya digunakan untuk plot graf keseragaman dan untuk mengira intensiti pergolakan di bahagian uji terowong air. Keamatan pergolakan di bahagian ujian dengan semua perubahan dan komponen baru yang dipasang menghasilkan minimum sebanyak 6.77%. Reka bentuk sebelumnya menghasilkan peratusan intensiti pergolakan sebanyak 9.66%. Oleh itu, intensiti pergolakan dalam terowong air dapat dikurangkan sebanyak 29.92%.

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Greek Symbols

ρ	: density of fluid (water)
μ	: dynamic viscosity of the fluid (water)
δ	: boundary layer thickness

Roman Symbols

H	: height of test section
He	: exit width
Hi	: inlet width
$I_{turbulent}$	: turbulence intensity
l	: contraction length
L	: length of test section
n	: total number individual velocities of the cross section of the test section where the fluid passed through
Re	: Reynolds number
Re_{xc}	: Reynolds number of the flow at a distance of $x_c$from the leading edge of the plate
V	: velocity of fluid (water)
v	: individual velocity at certain point of the cross section of the test section where the fluid passed through

v_{mean} : mean flow velocity of the cross section of test section

v_{RMS} : root-mean-square velocity of the velocity fluctuations of the cross section of test section

W : width of test section

x : x-coordinate of geometry shape in 5th degree polynomial curve along x-axis

x_c : distance from the upstream of test section

y : y-coordinate of geometry shape in 5th degree polynomial curve along y-axis

Abbreviations

CFD : Computational Fluid Dynamics

CAD : Computer-Aided Drawing

DC : Direct Current

MATLAB : Matrix Laboratory

2D : Two dimensional

3D : Three dimensional

CHAPTER 1

INTRODUCTION

1.1 Overview

Water tunnel is an experimental facility used for the testing of the hydrodynamic behavior of submerged bodies in flowing water (Kalyankar et al., 2015). Water tunnel is identical to a wind tunnel but fluid inside the tunnel is restricted to water. Water tunnel is important for investigating the phenomena of boundary layer such as the vortex, flow separation, turbulence and also flow visualization (Kalyankar et al., 2015, Dehghan Manshadi, 2011).

The aim of this project is to improve on an already existing water tunnel in terms of its turbulence intensity for the application of a Micro-hydrokinetic turbine. Micro-hydrokinetic turbine is a new technology that extracts the kinetic energy from the flowing water current of river to generate electricity instead of the potential energy of falling water from the dam and reservoir required by micro-hydro power generation (Abd Rahim et al., 2010). Hence, the water tunnel designed and developed where the micro-hydrokinetic turbine model will be placed should be capable in mimicking the river flow conditions of Malaysia.

One way to investigate the flow in the water tunnel is by monitoring the turbulence intensity of the flow. Turbulence Intensity is a scale characterizing turbulence expressed as a percent. Turbulence intensity must be low because high turbulence will cause the water flow shift from laminar to turbulent flow on the model surface significantly upstream of its actual location (Dehghan Manshadi, 2011). This triggers an unfavorable transition in the desired measurements such as lift and drag may be inaccurate (Dehghan Manshadi, 2011). Idealized air flow with no fluctuations have a turbulence intensity of 0% and this is impossible to be achieved on earth.

Thus, with minimum turbulence intensity in the water tunnel, the fluctuations can also be minimized. This directly translates into a better performance of the water tunnel as the flow is more uniform along the test section. Turbulence intensity can be reduced by making improvements to the design of the components such as flow conditioning system, propeller size, etc. The purpose of this project is to improve the performance of the water tunnel by reducing the turbulence intensity.

1.2 Motivation

In an emerging country like Malaysia, energy poverty and lack of electricity in the rural areas worsens the living condition of the poor people. 3.8% of Malaysians are stricken by poverty and a huge majority of them live in the rural areas (Rahman et al., 2017). The rate of electrification in Peninsular Malaysia is around 99.7% while in Sabah and Sarawak it is around 77% and 67% respectively (Abd Rahim et al., 2010).The electrification of the regions which are facing inadequate clean and affordable energy is vital for the growth of Malaysia. As a response to this matter, the kinetic energy in the flow of a river can be harnessed into a sustainable energy source by means of a hydrokinetic turbine. Before installing a hydrokinetic turbine into rivers, there are several aspects of the hydrokinetic turbine that are needed to be studied. This is where the implementation of the water tunnel plays a significant role. Submerging the hydrokinetic turbine in the water tunnel would provide the necessary insights of the hydrodynamic behavior which can be used later to fine tune the design of the turbine.

By reducing the turbulence intensity in the test section of the water tunnel, the results produced on the submerged body would be highly accurate. Thus, it is important to have a water tunnel which could display the performance and output of the hydrokinetic turbine more accurately as it contributes to the ultimate goal.

1.3 Objectives

The objectives of this final year project are

- To improve on the design criteria for each components and the performance of the water tunnel that was previously developed for the flow visualization study on micro-hydrokinetic turbine by turbulence intensity reduction and improvement in flow uniformity.
- To conduct quantitative analysis on the velocity profiles and uniformity of the water flow at the test section.

1.4 Thesis Outline

This dissertation is categorized into 5 chapters with each chapter describing the details of the overall project in different aspects. In Chapter 1, the overview on water tunnel and the reason of designing and developing of the water tunnel, project motivation and objectives are described to provide a general insight on the current project investigation. In Chapter 2, literature review which includes the relevant past studies and researches are discussed in detail to highlight the related topics to the current project. In Chapter 3, the methodology of conducting the project from the design phase of the water tunnel and its components, the experiment set-up and method to conduct the experiment are described to provide a clear view on the methods and techniques that have been utilized in completing the project. Next, Chapter 4 presents the results obtained from the experimental work which are supported by discussions and justification after analyzing the data recorded quantitatively. In Chapter 5, conclusion is made to summarize all the significant findings in this project with the challenges faced throughout this project.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the past studies that have been carried out that are related to the current project are explained in detail. Firstly, examples of water tunnels, their components and respective functions that have been previously designed and developed researchers are discussed. Then, the standard configuration and vital components for the water tunnel design are discussed by describing their role and specific design criteria of each components of the conventional water. Besides, the importance of turbulence intensity in a water tunnel is also discussed. After that, the requirements for the application of micro-hydrokinetic turbine in water tunnel are discussed. A survey on river flow conditions of Malaysia’s rivers is performed in order to mimic river flow conditions in the water tunnel designed for the micro-hydrokinetic turbine model to be tested. Analysis method of velocity profile and uniformity at the test section of water tunnel designed is also surveyed. Lastly, the relevance of the literature review to the current project is discussed as well.

2.1 Water Tunnel

Water tunnels are a possible alternative to small low-speed wind tunnels for an expanded range of aerodynamic testing. An assessment was made by (Ol, 2012) regarding the extent to which water tunnels can be used for such testing. For conventional tests on aircraft, such as force and moment measurements, it is unfavorable due to a mismatch in Reynolds numbers for similar sized wind tunnels. Water tunnels are more suited to carrying out fundamental research than they are for applied aerodynamics testing. However, they are very useful as part of a large research program, by helping to create the testing schedule for large wind tunnels (Ol, 2012). In flow situations that are insensitive to Reynolds number, or where a test Reynolds number is close to that of a full-size vehicle, water tunnels should be regarded as the preferred option for experimental aerodynamics. Such examples include micro air vehicles, high-rate dynamic testing, and high-sweep sharp-edge configurations. Water tunnels are also very useful for providing validation data for computational-fluid-dynamics analyses of a flow (Ol, 2012).

2.1.1 Components of a Water Tunnel

The general configuration of a water tunnel is shown in Figure 2.1 where the water tunnel is made up of three major components connected in the sequence of inlet module, test section and the outlet module while the plumbing system will repump the water back to the inlet module through the motor and pump of the water tunnel (Kalyankar et al., 2015)

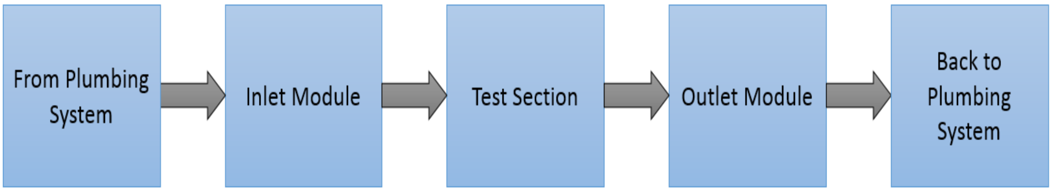

Figure 2. 1: General configuration design of water tunnel components (Kalyankar et al., 2015).

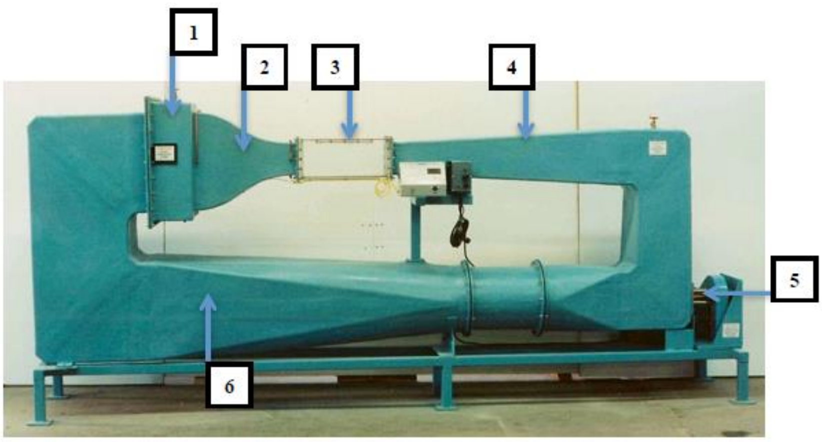

Figure 2. 2: Commercially available water tunnel, 6×6 closed circuit water tunnel (Daniel, 2012).

Figure 2.2 shows a commercially available conventional water tunnel (Daniel, 2012) with the primary components labelled:

1. **Flow Conditioning (Inlet Module)**

   - Flow conditioning is vital to suppress the free-stream turbulence and producing flow straightening effect by eliminating the swirl in the flow(Kalyankar et al., 2015) and (Daniel et al., 2015)

2. **Convergent Section (Inlet Module)**

   - Convergent section accelerates the flow speed and minimizes the turbulence level of the fluid entering the test section of the water tunnel (Daniel, 2012).

3. **Test Section**

   - The test section is a zone designed for conducting the experiments where the turbulence intensity studies of micro-hydrokinetic turbine will be performed. The design of the test section will impact the flow quality of the stream (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015).

4. **Diffuser (Outlet Module)**

   - The diffuser is developed to reduce the flow speed and regain the pressure lost in the test section (Daniel, 2012, Daniel et al., 2015).

5. **Motor and Pump**

   - Motor and pump are a significant component which provides the required pressure differential to force the water through the water tunnel loop system (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015). The motor and pump normally use impeller to drive the water.

6. **Return Leg Piping.**

- Return leg piping are determined by integrating with requirements from other components, drain locations, and also to avoid flow separation (Daniel, 2012, Daniel et al., 2015), (Kalyankar et al., 2015)

The primary components stated previously make up the water tunnel. The flow mechanism in the water tunnel are usually driven by pump through the flow conditioning section to the contraction section, the test section, the diffuser, return leg piping and back to the motor and pump to be recirculated again in the water tunnel. During the modification phase of the water tunnel, it is vital to focus on the significance of each primary components of water tunnel (Kalyankar et al., 2015) so that objectives of the project are successfully met.

2.1.2 Design Criteria of Water Tunnel and Its Components

Referring to the studies on water tunnel designed by (Kalyankar et al., 2015) and (Daniel, 2012), regardless of the water tunnel designed is to performed on low Reynolds number or high Reynolds number, the primary components of the water tunnel consists of convergent section, flow conditioning system, test section, motor and pump, inlet plenum, outlet plenum, and also return leg piping system. All of these components usually circulate the water flow in a closed loop with sequence of baffle, inlet plenum, flow conditioning, convergent section, test section, diffuser, outlet plenum and then eventually back to inlet plenum again through the water pump. The design criteria for each of components are essential for determining the capability of the water tunnel.

- Baffle,

- Inlet Plenum,
- Convergent Section/Contraction Zone
- Test Section
- Flow Conditioning System
- Diffuser
- Outlet Plenum

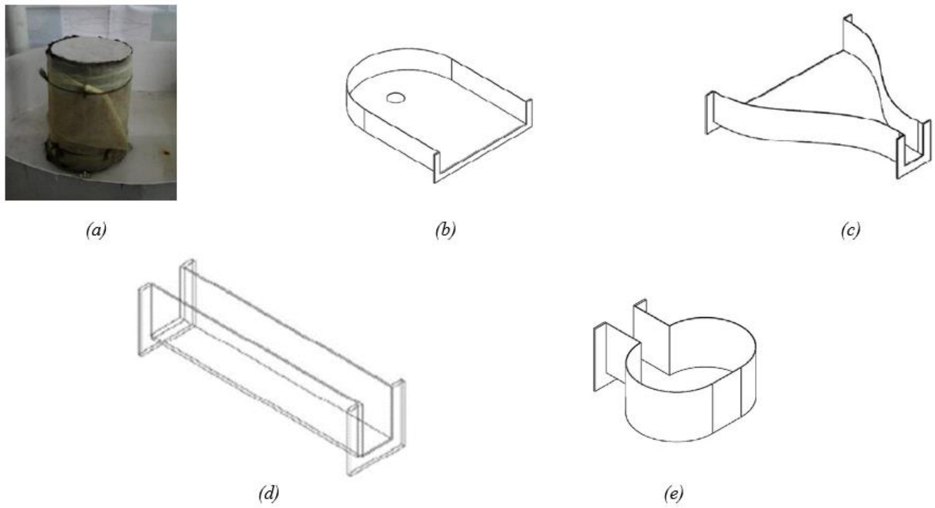

Figure 4.3: (a) Baffle (b) Inlet plenum (c) Convergent section (d)Test section (e) Outlet plenum design of water tunnel (Kalyankar et al., 2015).

2.1.2.1 Baffle

Baffle acts as the inlet delivery point for safety purpose, which prevents the overflow of water during the pumping of water from the delivery system into the inlet plenum (Kalyankar et al., 2015). Baffle is usually designed as a hollow tube with the top end closed and wrapped up in a cotton cloth so that the turbulence energy of the incoming water pumped from the motor and pumping system can be minimized. Often times, nylon net or cotton cloth is integrated to provide flow conditioning of the incoming water through the baffle to reduce the turbulence.

2.1.2.2 Inlet Plenum

Inlet plenum receives the water through baffle and delivers it to the convergent section with a settling chamber. Referring to (Kalyankar et al., 2015), there are several design criteria needed to be taken into consideration when designing an inlet plenum. The inlet plenum should acts as a tank by having a large water storing volume. This is to provide dampening of the turbulence created from the water pumping and delivery system. Next, it must have the ability to act as a storage to accommodate the flow conditioning system and also have a suitable delivery point from the piping system which is also the location of the baffle. From the design of the inlet plenum of water tunnel of (Kalyankar et al., 2015), the inlet plenum is designed to be circular surrounding the delivery hole to reduce the corner flow effects. The semicircular design of the inlet plenum will assist in guiding the flow coming out from the baffle towards the settling chamber and hence reducing the turbulence of water at circular junctions.

2.1.2.3 Flow Conditioning System

As the flow enters the test section, it has significant swirl and turbulence in the flow due to the pump and the 90 degree bend of the piping system (Daniel, 2012, Daniel et al., 2015). Flow conditioning system is important for reducing the turbulence of the incoming water from the inlet plenum. It is generally made of the honeycomb sections, screens and settling chamber (Daniel, 2012, Daniel et al., 2015).

There are two types of turbulences; longitudinal and lateral turbulence. Screens reduces the longitudinal components of turbulences while honeycomb sections reduce the lateral parts and straightens the flow (Kalyankar et al., 2015). The ratio of the honeycomb section length to the diameter of the honeycomb pipe should be within 5 to 10.

2.1.2.4 Convergent Section/Contraction Zone

A well designed contraction should speed up the flow, decrease turbulence intensity and create a uniform flow, while avoiding separation (Nedyalkov, 2012). Convergent section are designed to accelerates the flow of water to the test section and reduce the turbulence levels at the upstream of the test section (Daniel, 2012, Daniel et al., 2015). In the design of convergent section of water tunnel of (Kalyankar et al., 2015), two dimensional convergent section design is used because it is simpler in manufacturing and has less probability of errors and also does not require a closed top design although a top may be used if required.

Contraction ratio is the ratio of the width of the inlet of the convergent section from inlet plenum to the width of the convergent section near to the test section. The width to length ratio of the contraction length also must be range in between 0.667 to 1.79 because any shorter length will result in reducing the turbulence damping performance while longer length will cause the growth of the boundary layer thickness along the contraction section as mentioned by (Bell and Mehta, 1988) and also causing the boundary layer separation (Kalyankar et al., 2015). Before the water is delivered to the convergent section from the inlet plenum, the water flow is required to go through the settling chamber.

Settling chamber is a chamber where the water is guided to the convergent section and also reducing the flow velocity and turbulence intensity by providing space for water molecules. According to (Daniel, 2012, Daniel et al., 2015), the length of the settling chamber must optimized to damp the turbulence created by the piping system and to prevent the growth of boundary later thickness as well. In the design of water tunnel by (Daniel, 2012, Daniel et al., 2015), the width of the settling chamber is optimized by equaling its width to be the same as width of the inlet of the convergent section.

2.1.2.5 Test Section

Referring to (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015), the length of the test section cannot be too long as the boundary layer thickness at the downstream of the test section will be thicker, which alters the main flow stream behavior, and subsequently affect the quality of the experiments. However, the length of the test section also need to have enough length so that extended flow effects such as the wakes and vortices can be visualized.

The settling distance and the distance for the wake and vortices visualization must be about 5 times the characteristics length of the model (Kalyankar et al., 2015). The thickest boundary layer will occur at the downstream of the test section and the boundary later thickness can be calculated. According to (Daniel, 2012, Daniel et al., 2015) the other consideration includes the boundary layer thickness need to be smaller relative to the height of the test section so that the boundary layers from the wall will not merge with the test section within the test section.

The test section height should be at least 10 times the boundary layer thickness (Daniel, 2012, Daniel et al., 2015). Rectangular shape test section are commonly used based on the study on the test section design of (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015). The material used for both test section are acrylic due to its high transparency and hence providing a high optical access to the test section during experiments (Daniel, 2012, Daniel et al., 2015). The velocities of the fluid flow in the test section is determined by the volume flow rate by the pump throughout the whole water tunnel loop and the cross-sectional area of the test section.

2.1.2.6 Diffuser

Diffuser is a component of the outlet module of the test section. It functions to reduce the flow speed of water from the test section before entering the outlet plenum thereby regain the pressure in the system of the water tunnel. There are two major specifications in designing diffuser which are the area ratio of the outlet width of the diffuser to the inlet width of the diffuser and the diffuser angle and (Daniel, 2012, Daniel et al., 2015). These parameters are necessary to achieve a uniform and smooth expansion when the water is delivered to the outlet module. From the past studies on design of water tunnel by (Daniel, 2012, Daniel et al., 2015), the area ratio of the inlet width of the diffuser to the outlet width of the diffuser should be less than 4 or else flow separation may which will lead to unsteadiness in the flow and the flow eventually propagate back to the test section.

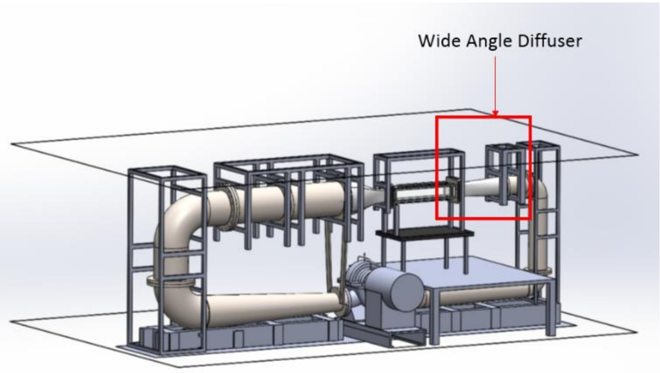

Figure 2.4: Wide angle diffuser design of the water tunnel (Daniel, 2012, Daniel et al., 2015).

2.1.2.7 Outlet Plenum

Based on (Kalyankar et al., 2015), outlet plenum connects the whole setup with the piping systems. The main design criteria of the outlet module design are the geometry of the outlet plenum since even the minor irregularities can lead to a back pressure and flow will be reversed back into the test section causing disruption of the flow in the test section which increases the turbulence intensity in the test section.

2.1.2.8 Motor and Pumping System

Pump and motor is to supply a pressure differential large enough to overcome the pressure losses throughout the loop at desired volume flow rate. The desired volume flow rate of the pump is determined by the cross-sectional area of the test section and the required flow speed range within the test section (Daniel, 2012, Daniel et al., 2015).

2.1.2.9 Return Leg Piping System

The sizing and design of the return leg piping system is dependent on the requirements with other primary components of the water tunnel, drain locations, avoidance of flow separation. Integration with the primary components yeilds the diameter of the piping systems (Daniel, 2012, Daniel et al., 2015).

2.2 Application of Micro-Hydrokinetic Turbine in Water Tunnel

Water tunnel can be used to perform various experiments in order to study the hydrodynamic behavior of the model that is placed in the test section of the water tunnel. In this case, the water tunnel design and specification must meet the requirement of the micro-hydrokinetic turbine model so that the experimental work can be conducted. The requirements of the water tunnel to test the micro-hydrokinetic turbine model involved are the minimum water flow velocity required by the micro-hydrokinetic turbine model to generate electricity, the size of the micro-hydrokinetic turbine model which defined the size of the test section of water tunnel required, and also the general range of Malaysia's river flow velocity of where the micro-hydrokinetic turbine will be placed.

2.2.1 Minimum Water Flow Velocity Required by Micro-Hydrokinetic Turbine in Water Tunnel

Micro-hydrokinetic turbine is a new technology that uses the kinetic energy from the flowing water current of the river to generate electricity instead of the potential energy of falling water from the dam and reservoir required by micro-hydro power generation (Khan et al., 2008). A minimum velocity of 0.5m/s is required to generate electricity by the vertical axis micro-hydrokinetic turbines and most of the micro hydropower generating unit producing components calculate velocity of the stream up to 3 m/s (Hoq et al., 2011). In the design and development research of micro-hydrokinetic turbine by (Kaur and R.P.Saini, 2016), the average velocity of the open channel water tunnel used to test his micro-hydrokinetic turbine model is varied between 1.0 – 2.5 m/s as shown in figure 2.5 (Kaur and R.P.Saini, 2016).

(a)

(b)

Figure 2.5: (a) Open channel water tunnel (b) Straight bladed squirrel cage Darrieus vertical axis micro hydrokinetic turbine model (Kaur and R.P.Saini, 2016).

2.2.2 Size of Test Section of Water Tunnel Required for Micro-Hydrokinetic Turbine Model

The micro scale of hydrokinetic turbines have smaller dimensions (diameter of 15 - 25cm for micro-hydrokinetic turbine) compared to the normal hydrokinetic turbines which in turn give less cost for fabrication and hence giving lesser effect to the surrounding environment (Khan et al., 2008). In the past researches of the hydrokinetic turbine, a micro scale hydrokinetic turbine model with diameter of 15cm was designed, fabricated and tested (Kaur and R.P.Saini, 2016).

2.2.3 Range of River Flow Velocity of Malaysia's Rivers Required by Water Tunnel for Micro-Hydrokinetic Turbine Model

The velocity distribution of River Senggi located in Kuching, Sarawak of Malaysia has a range of velocity from 0m/s to 0.6m/s as shown in figure 2.7. In addition, the research also stated that the average velocity of the River Senggai, River Senggi and the River Batu in Sarawak ranged between 0.2m/s – 0.6m/s, 0.2m/s – 0.35m/s and 0.3 – 0.5m/s as shown in the figure 2.6 for River Senggai (Hin et al., 2008).

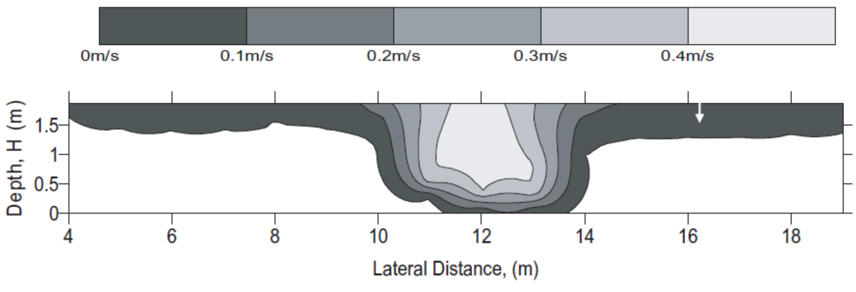

Figure 2. 6: Velocity distribution of river Senggai (Hin et al., 2008).

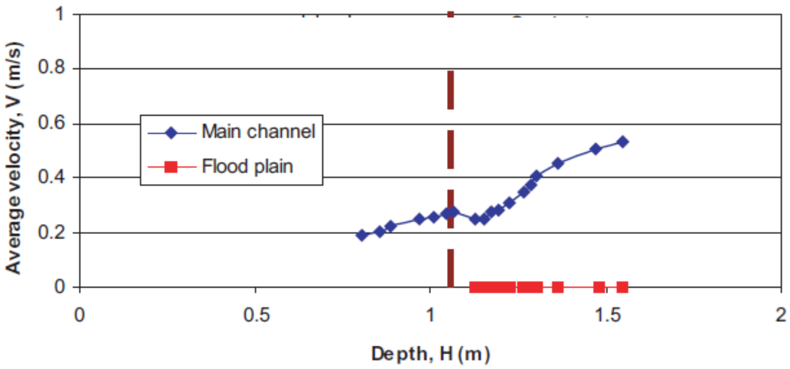

Figure 2. 7: Average Velocity of River Senggai, Sarawak (Hin et al., 2008).

On top of that, one of the many researches inspected the river flow conditions and dynamic state analysis of Pahang rivers in which 17 river cross section stations of Pahang rivers were selected. The hydrologic sampling data collected in January year 2010 and February year 2010 indicate that the velocity of the river ranged from 0.308m/s – 0.582m/s and 0.217m/s – 0.484m/s (Gasim et al., 2013). Figure 2.8 shows the average velocity of river flow stream of the hydrologic sampling data collected from Pahang river.

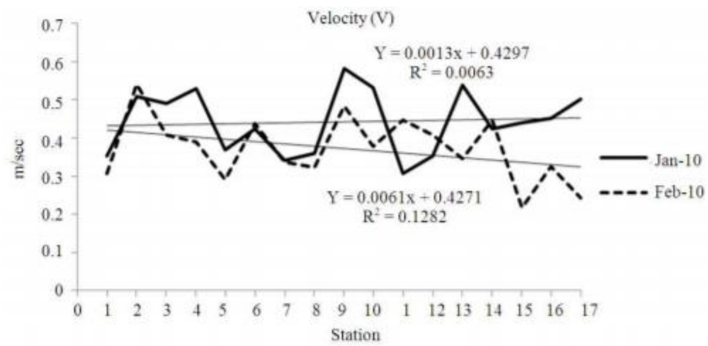

Figure 2. 8:Average velocity of river flow stream of hydrologic sampling data collected from Pahang river (Gasim et al., 2013).

2.3 Fundamental Theories

In this section, the fundamental theories that are related to the current research especially the factors that affect the behavior of the fluid in the water tunnel are discussed. The factors kare Reynolds number, uniform velocity profile, uniform flow and turbulence intensity of the fluid are discussed. The mathematical equations involved are also presented.

2.3.1 Reynolds Number

The Reynolds number, Re is a dimensionless quantity which is the ratio of the inertial force to viscous flow of a fluid. Viscosity is the resistance of a fluid acting to the flow under the influence of an external force. Inertia is the property of an object to continue its position or motion at a constant velocity unless exerted by an external force(Nedyalkov and Wosnik, 2013). In summary, the inertia keeps the fluids in its state of motion, either stationary or flowing while the viscosity resists the fluid from flowing. In this project, the calculation of Reynolds number is based on the external flow. The Reynolds number in this project can be calculated mathematically by using equation as following:

$$Re = \frac{\rho v x_c}{\mu} \qquad (2.3.1)$$

where

x_c : distance from the upstream of test section

μ : dynamic viscosity of water, $8.90 \times 10^{-4} \mathrm{kg/m.s}$

ρ : density of water, $1 \times 10^{3}\ \mathrm{kg/m^3}$

V : velocity of fluid (water)

The Reynolds number is essential to determine the type of the flow in the test section (Nedyalkov and Wosnik, 2013). For an external flow such as the flow in the test section of water tunnel, a low Reynolds number with range of, $\mathrm{Re} < 5 \times 10^{5}$ is considered as laminar flow region while high Reynolds number with range of, $5 \times$

$10^5 < \mathrm{Re} < 10^7$ indicates a turbulent flow region. A region with laminar flow in the test section gives a smooth and regular streamlines flow while a turbulent region causes the flow to be irregular and broken streamlines flow.

2.3.2 Uniform Velocity Profile

A velocity profile is the variation in velocity along a line perpendicular to the general direction of the flow. It is a profile that shows not only the magnitude of the velocity but also the characteristics of the flow like direction, and even increase and decrease in the velocity magnitude across the test section in which the fluid passed through. In this project, the uniformity of the velocity profile means the constant magnitude of velocity across the cross sectional area of the fluid passed through. The uniformity of the velocity profile in this project is important to ensure the magnitude of the velocity across the cross-sectional area of the test section is uniform.

2.3.3 Uniformity of Water Flow

The flow is defined as uniform flow when in the flow field, the velocity and other hydrodynamic parameters remained unchanged from point to point at any instant and time. In this project, the uniform flow also can be defined as the flow of a fluid in which each particle moves along its line of flow with constant speed at all the cross-sectional area of the test section. The uniform flow is important in this project and can be assessed by determining deviation of the mean water velocity of the flow across each different cross-sectional area of the test section.

2.3.4 Turbulence Intensity

The turbulence intensity, $\mathrm{I_{turbulent}}$ is defined as the ratio of the root-mean-square of the velocity fluctuations, $\mathrm{v_{RMS}}$ to the mean flow velocity, $\mathrm{v_{mean}}$. In the current project, it is important to determine also the turbulence intensity of the cross-sectional area of the test section in order to know the turbulence level in the test section. The mathematical equation representing the root-mean-square of the velocity fluctuations v_{RMS}, root-mean-square of the velocity fluctuations v_{mean} and turbulence intensity, $I_{turbulent}$ are as following:

$$v_{mean} = \frac{v_1 + v_2 + v_3 + \ ... + v_n}{n} \tag{2.3.4}$$

where

v_{mean}	: mean flow velocity of the cross section of test section
$v_1, v_2, v_3, \dots, v_n$	: individual velocities at each point of the cross section of the test section where the fluid passed through
n	: total number individual velocities of the cross section of the test section where the fluid passed through

$$v_{RMS} = \sqrt{\frac{v_1^2 + v_2^2 + v_3^2 + \cdots + v_n^2}{n} - {v_{mean}}^2} \tag{2.3.5}$$

where

v_{RMS}	: root-mean-square velocity of the velocity fluctuations of the cross section of test section

$$I_{turbulent} = \frac{v_{RMS}}{v_{mean}} \tag{2.3.6}$$

where

$I_{turbulent}$: Turbulence intensity of the flow at the cross section of the test section where the fluid passed through

2.4 Relevance between Literature Review and Current Project

Literature reviews was carried out on the past researches of the design criteria of components of the water tunnel. The models designed and developed in current project is based on the design criteria used by the water tunnel designed by (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015). However, the design criteria of the components of previous water tunnel model is modified based on the constraints in term of resources, working space available in the wind tunnel laboratory and also the requirement from the micro-hydrokinetic turbine model.

Besides, the literature reviews conducted on the micro-hydrokinetic turbine size are essential when making decision on the design of the size of the test section of the water tunnel. In addition, the surveys conducted on the minimum river flow velocity to generate power by the micro-hydrokinetic turbine model and the range of river water flow velocity of Malaysia's rivers which aims on determining the capability of the water tunnel on the range of water flow velocity of the water tunnel as one of the current project objectives is to design and develop a water tunnel capable to mimic the river flow conditions of Malaysia's rivers where the micro-hydrokinetic turbine model will be placed. In summary, the current project focuses on the aspects as listed below:

1. The criteria of the components of water tunnel are designed based on the literature survey carried out in order to mimic the river flow conditions of Malaysia's rivers where the micro-hydrokinetic turbine model will be placed and tested.

2. The capability of the range of water flow velocity of the water tunnel required and compromised between the requirement from river flow velocity conditions of Malaysia's rivers (river flow velocity of Malaysia ranged from 0 - 0.6 ms^{-1}) and the minimum river flow velocity required by micro-hydrokinetic turbine model to generate electricity.

3. The analysis on the results of velocity profile and uniformity of the water flow stream in the test section of water tunnel designed and developed based on the design criteria and existence of the components when designing the water tunnel in current project.

CHAPTER 3

METHODOLOGY

This chapter presents the design, fabrication of the water tunnel and each of its components, experimental set-up for the analysis of water tunnel. For this project, only quantitative analysis was performed. The quantitative analysis method is used to analyze the uniformity of the velocity profile, flow, and also turbulence intensity. The overview of this chapter is illustrated in *Figure 3.1*.

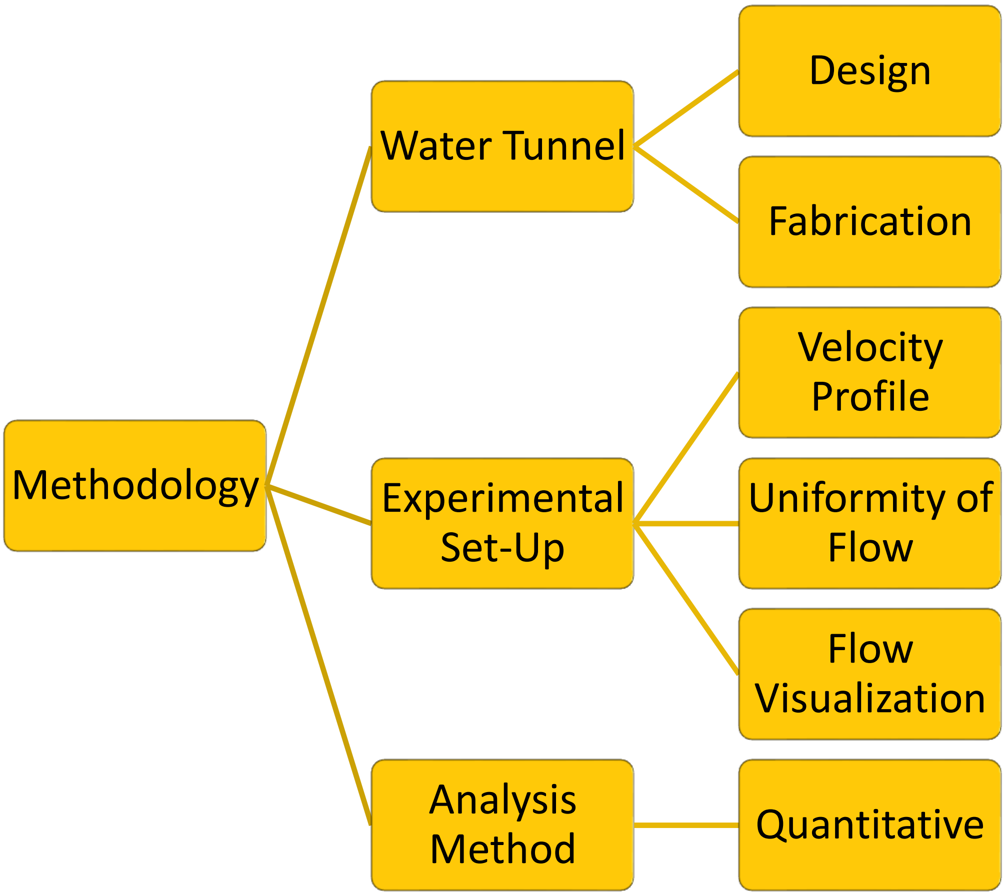

Figure 3.1: Overview of methodology in this project

3.1 Water Tunnel Design

Since the main objective of the project is to improve the performance of the previous water tunnel that must be capable to mimic a controllable river flow conditions of Malaysia's rivers to conduct test on the micro-hydrokinetic turbine model, hence for the first section of the methodology, the design criteria of the water tunnel and its component required to achieve the objective of the project is discussed. The design of water tunnel and its components are categorized into few stages which are the previous design, modified design and eventually come to finalized design. After the design of water tunnel is finalized, the fabrication method of the water tunnel is explained as well. In summary, the finalized design of the water tunnel consists of few primary components which are the frame, the contraction zone, diffuser, and honeycomb inlet flow guide, exit flow guide, test section, X crosspiece, flow conditioning system, water propeller with motor and also the support jig to hold the water propeller with motor. The modification that was performed to the flow conditioning system is also discussed.

3.1.1 Previous Water Tunnel Design

As the primary objective of this project is to modify the existing water tunnel to reduce the turbulence intensity, the CAD design of the existing model(pre-modification) is shown in the diagram below.