DESIGN AND DEVELOPMENT OF WATER TUNNEL FOR FLOW VISUALIZATION STUDY ON MICRO-HYDROKINETIC TURBINE

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DESIGN AND DEVELOPMENT OF WATER TUNNEL FOR FLOW VISUALIZATION STUDY ON MICRO-HYDROKINETIC TURBINE

by

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ENDORSEMENT

I, Tong Poh Eng hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date:

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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.

____

(Signature of Student)

Date:

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DESIGN AND DEVELOPMENT OF WATER TUNNEL FOR FLOW VISUALIZATION STUDY ON MICRO-HYDROKINETIC TURBINE

ABSTRACT

A water tunnel is an experimental facility utilized for testing the hydrodynamic behavior of submerged bodies in flowing water. Water tunnel can be designed and developed to visualize a wide range of flow and one of its ability is to visualize the flow behavior over different objects and structures hence studying the phenomenon of boundary layer such as the vortex induced, flow separation, turbulence and the others. For the current project, a micro-hydrokinetic turbine model is to be placed in the test section of the water tunnel to visualize and study the flow behavior around the model. Hence a water tunnel that capable to mimic and simulate the Malaysia river flow velocity conditions (0 – 0.6 ms^{-1}) for the micro-hydrokinetic turbine model to be tested with generated range of mean water flow velocity of 0 – 0.7957 ms^{-1} at the test section of dimension of 0.25m × 0.25m × 0.85m (W × H × L) is designed, developed, fabricated and analyzed with maximum deviation of mean water flow velocity across the test section with 3.43% only. The design criteria of the components of the water tunnel are discussed in this thesis as well. From the quantitative analysis of the water tunnel, the best configuration of the components of the water tunnel consisting the components of inlet flow guide, exit flow guide, flow conditioning system and screen. The turbulence intensity level of the velocity profiles at the test section capable to reach low turbulence level (9.66%) at the mean water velocity of 0.3440 ms^{-1}. In addition, dye injection system is also designed and developed as the flow visualization technique to visualize the flow structures around the micro-hydrokinetic turbine model in the water tunnel designed and developed. The flow visualization experiment is conducted at mean water

velocity of 0.0250 ms^{-1}. The red dyes and blue dyes are founded have higher contrast level compare with both the water and yellow dyes. They capable to produce high pictorial representation of the flow behavior around the micro-hydrokinetic turbine model.

REKA BENTUK DAN PEMBANGUNAN TEROWONG AIR UNTUK KAJIAN VISUALISASI ALIRAN PADA MIKRO- HIDROKINETIK TURBIN

ABSTRAK

Terowong air adalah satu kemudahan eksperimen yang digunakan untuk menguji tingkah laku hidrodinamik badan terendam dalam air yang sedang mengalir atau dalam statik. Terowong air boleh direkabentuk dan dibangunkan untuk memvisualisasikan pelbagai jenis aliran. Salah satu keupayaannya adalah untuk menggambarkan tingkah laku hidrodinamik aliran ke atas objek dan struktur yang berlainan dengan itu mengkaji fenomena lapisan sempadan. Bagi projeck ini, model mikro hidrokinetik turbin akan diletakkan di bahagian uji terowong air untuk memvisualisasikan dan mengkaji kelakuan hidrodinamilk aliran di sekitar model tersebut. Oleh itu, satu terowong air yang bermampuan untuk mensimulasikan keadaan halaju aliran sungai Malaysia (0 – 0.6 ms^{-1}) untuk model mikro hidrokinetik turbin yang diuji dengan julat halaju aliran air purata yang dijana dari 0 - 0.7957 ms^{-1} dalam bahagian ujian dimensi 0.25m × 0.25m × 0.85m(W × H × L) telah direka dan dibuatan dengan sisihan maksimum purata halaju aliran air merentasi bahagian ujian dengan 3.43% sahaja. Kriteria reka bentuk komponen terowong air juga dibincangkan dalam tesis ini. Dari analisis kuantitatif terowong air, konfigurasi terbaik komponen terowong air untuk projek ini terdiri daripada komponen panduan aliran masuk, panduan aliran keluar, sistem penyaman aliran dan skrin. Tahap keamatan turbulensi profil halaju di bahagian ujian terowong air bermampuan untuk mencapai tahap pergolakan yang rendah (9.66%) pada halaju aliran air 0.3440 ms^{-1}. Di samping itu, sistem suntikan pewarna juga direka untuk menvisualisasikan tingkah laku hidrodinamik aliran air sekitar model mikro hidrokinetik turbin dalam terowong air yang direka dan dilakukan pada halaju air air

0.0250 ms^{-1}. Pewarna merah biru didapati mempunyai tahap kontras yang lebih tinggi berbanding dengan air dan pewarna kuning. Mereka mampu menvisualisasikan kelakuan hidrodinamik aliran air sekitar model mikro hidrokinetik turbin dengan gambar qualiti yang tinggi.

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LIST OF SYMBOLS

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

A water tunnel is an experimental facility used for the testing the hydrodynamic behavior of submerged bodies in flowing water (Kalyankar et al., 2015). For a water tunnel, the fluid inside the tunnel is restricted to water only. Water tunnel is paramount essential for the flow visualization study where it can conduct qualitative analysis on the model placed in water tunnel with high pictorial representation. One of the ability of water tunnel is visualization of the flow behavior over different objects and structures, studying the phenomenon of boundary layer such as the vortex induced, flow separation, turbulence and the others phenomenon (Kalyankar et al., 2015).

For the current project, a micro-hydrokinetic turbine model is to be placed in the water tunnel designed and developed in current project to study the flow behaviors around the model when the water flow passes through the model. Micro-hydrokinetic turbine is a new technology that extracts 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).Hence, the water tunnel designed and developed where the micro-hydrokinetic turbine model is placed should be capable in mimic the river flow conditions of the Malaysia's river where the micro-hydrokinetic will be placed in reality eventually.

Therefore, the studies of current project starts by investigating the specification of the test section of water tunnel required to be designed and developed based on the requirement of the micro-hydrokinetic turbine, the river water flow velocity of

Malaysia's rivers, and also the flow visualization technique used. Then, the rest of the components of the water tunnel is designed based on the standard design criteria based on the literature survey. The design of the water tunnel is finalized by modifying the preliminary design based on the constraints on the costs, resources and working space available in the wind tunnel laboratory provided. Flow visualization system of the water tunnel is developed where dye injection method is chosen the flow visualization techniques used in this project.

Once all of the components of water tunnel are fabricated and assembled, the velocity profile of the cross sectional area of the test section is measured and analyzed by varying the existence of different components of the water tunnel to understand the function of each components determine the best configuration of the components of water tunnel for current project. The capability of the range of water flow velocity of the water tunnel is also determined when the uniformity of the water flow of the test section is measured and analyzed. In the final stage of the experiment, dye injection system with 2 different diameter of injection tubes is used to analyze the quality of the flow visualization study on micro-hydrokinetic turbine model and the capability of the water tunnel to perform flow visualization.

At the end of this project, the capability of the range of flow velocity of the water tunnel, the best configuration of components of water tunnel designed and developed for current project, and also the capability of the water tunnel to perform flow visualization on micro-hydrokinetic turbine model are concluded. Future works for current project are also recommended.

1.2 Motivation

A water tunnel can be utilized to visualize a wide range of flow based on the purpose of designing and developing it. With proper flow visualization techniques used in the water tunnel, the flow behaviors of different kind of models that placed in the water tunnel can be visualized and studied. The design and development of a water tunnel that can simulate a controllable river flow conditions will aids in the development of high efficiency micro-hydrokinetic turbine. The developed micro-hydrokinetic turbine model can be tested directly in the water tunnel to study and analyze its performance at various river flow velocity mimicked by the water tunnel. The flow visualization study on the flow behavior of the fluid structures around the micro-hydrokinetic turbine model using the water tunnel designed also is essential to determine the design criteria of the micro-hydrokinetic turbine model to have greater efficiency and performance.

1.3 Objectives

The objectives of this final year project are

- To design and develop a water tunnel which capable to mimic the river flow conditions which is the water flow velocity of the river water flow of Malaysia's river suitable for the micro-hydrokinetic turbine model to be tested.
- To design and develop a water tunnel which capable to perform flow visualization study on micro-hydrokinetic turbine model.

1.4 Thesis Organization

This dissertation is categorized into 6 chapters which each of the chapter describing the details on the overall project for different aspect. In Chapter 1, the overview on the micro-hydrokinetic turbine 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. Moving on to the next chapter, literature review which including the relevant past studies and researches are discussed in detail to highlight the aspects which relevance to the current project. In the Chapter 3, the theories used for current project are discussed. In Chapter 4, the methodology of conducting the project from the design phase of the water tunnel and its components, the dye injection system for flow visualization study, and also the experiment set-up and method to conduct the experiment are described to provide a clear view on the method and technique that have been utilized in completing the project. Next, Chapter 5 will be presenting the results obtained from the experimental work which are supported by discussions and justification after analyzing the data recorded quantitatively and qualitatively. In Chapter 6, conclusion is made to summarize all the significant findings have been founded in this project with recommendation for the future works that can be implemented to study the current project deeper so that the research on water tunnel can be widened.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the past studies and relevant researches that have been carried out that related to the current project. Firstly, the survey on the type of water tunnels and their respective functions that have been designed and developed by the past researchers is discussed. Next, the general configuration and essential components for the conventional water tunnel design are discussed as well. This is followed by describing the role and design criteria of each components of the conventional water tunnel in order to determine their importance of existence in the water tunnel. The unconventional water tunnel designed by the past researchers is also studied to gather more resources on various kind of design of water tunnel. The flow visualization techniques used in the past researches also are discussed especially on the dye injection system used in water tunnel. After that, the requirements for the application of micro-hydrokinetic turbine in water tunnel are discussed. In order to mimic river flow conditions in the water tunnel designed for the micro-hydrokinetic turbine model to be tested, the survey on river flow conditions of Malaysia's rivers is also discussed. The method to analysis the velocity profile and uniformity of the test section of water tunnel designed conducted by past researches is also been surveyed. Lastly, the relevance of the literature review and the current project is discussed as well.

2.1 Water Tunnel

2.1.1 Water Tunnel's Components

Figure 2.1 shows the general configuration of a design of a water tunnel. For the components of the water tunnel designed, the most widely used configuration as shown in figure 2.1 for a water tunnel is in the form of three components connected in the sequence of inlet module, test section and the outlet module while the plumbing system will recirculate the water from to the inlet module from the outlet module through the motor and pump of the water tunnel (Kalyankar et al., 2015).

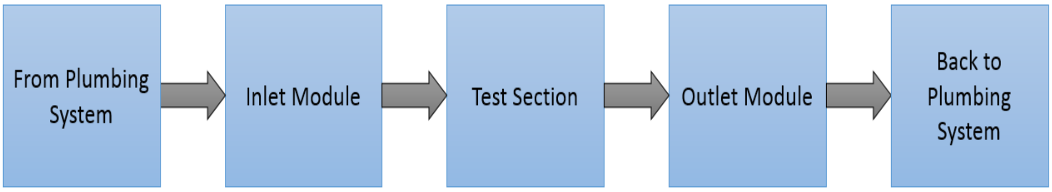


Figure 2.1: General configuration design of water tunnel components (Kalyankar et al., 2015).

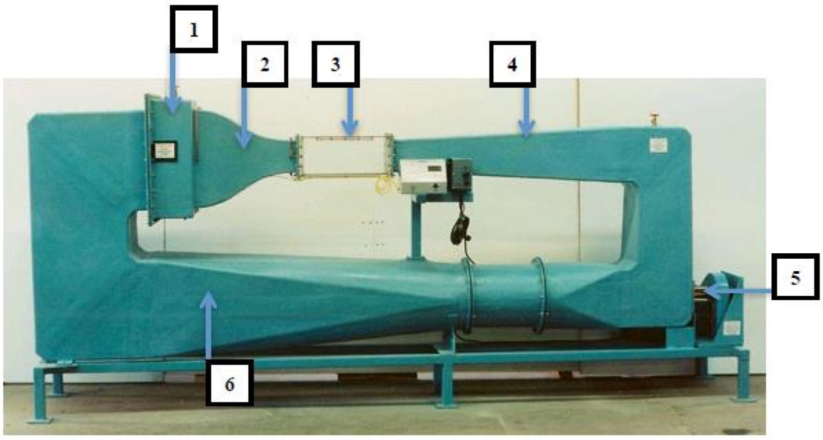


Figure 2.2: Typically commercially available water tunnel, 6×6 closed circuit water tunnel (Daniel, 2012).

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

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

The flow conditioning is needed to suppress the free-stream turbulence and creating flow straightening effect (Kalyankar et al., 2015)and (Daniel, 2012).

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

The convergent section will accelerate the flow and reduce the turbulence level of the fluid entering the test section (Kalyankar et al., 2015) and (Daniel, 2012).

3. **Test Section**

The test section is a platform or zone specially designed for conducting the experiments where flow visualization of micro-hydrokinetic turbine will be conducted at test section as well. The design of the test section will impact the quality of the desired flow quality of the flow stream (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015).

4. **Diffuser (Outlet Module)**

The diffuser is developed to slow down the flow and regain the pressure of the flow stream (Daniel, 2012, Daniel et al., 2015).

5. **Motor and Pump**

Motor and pump are also a significant component in order to provide the required pressure differential to drive the water through the whole water tunnel loop system (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015). The motor and pump normally used impeller in order to drive the water.

6. **Return Leg Piping.**

Return leg piping and their sizing are determined by the integration requirements with other components, drain locations, and also for the avoidance of flow separation (Daniel, 2012, Daniel et al., 2015).

All of the primary components mentioned here are normally needed by most of the conventional water tunnel. The water flow mechanisms in conventional water tunnel as usually are pumped by the motor and pump through the flow conditioning section followed by the contraction section, the test section, the diffuser, return leg piping and eventually back to the motor and pump to be recirculated again in the water tunnel. During the designing and development phase of a water tunnel, it is important to focus on the significance and the key decisions of each primary components of water tunnel (Kalyankar et al., 2015) so that the water tunnel designed can meet the objectives of the project.

2.1.2 Design Criteria of Conventional Water Tunnel and Its Components

Based on the studies on water tunnel designed by (Kalyankar et al., 2015) and (Daniel, 2012), no matter the water tunnel is designed to performed on low Reynolds number or high Reynolds number of water flow velocity in the tunnel, generally 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 will 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 decision criteria for each of it are essential for determining the capability of the water tunnel. The baffle, inlet plenum, convergent section, and flow conditioning are the inlet module while the diffuser and outlet plenum are the outlet module as shown in figure 2.3.

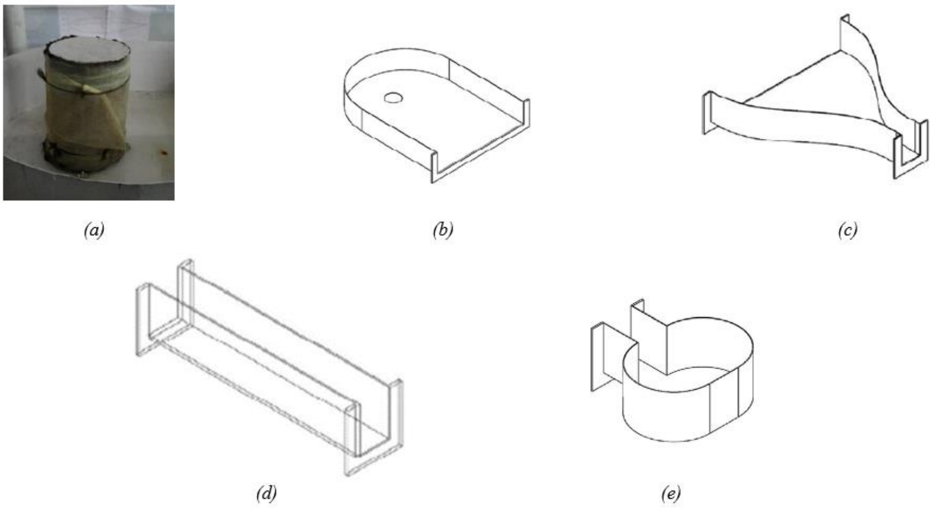


Figure 2.3: (a) Baffle (b) Inlet plenum (c) Convergent section (d)Test section (e) Outlet plenum design of water tunnel (Kalyankar et al., 2015).

2.1.2.1 <u>Baffle</u>

Baffle is used to cover the inlet delivery point for safety purpose, mitigate the possibility of spillage or even overflow of water during the pumping of water from the delivery system into the inlet plenum (Kalyankar et al., 2015). Baffle usually is designed as a hollow cylinder with the top end closed and wrap up with cotton cloth so that the turbulence energy of the incoming water from the delivery system pumped from the motor and pumping system can be reduced. In addition, nylon net or cotton cloth normally will be added to act as a flow conditioner to the incoming water through the baffle to reduce the turbulence energy as well.

2.1.2.2 <u>Inlet Plenum</u>

Inlet plenum is a component that located before the convergent section and after the baffle. It receives the water from the delivery system through baffle and delivers to the convergent section with a settling chamber. According to (Kalyankar et al., 2015), there are few design criteria when designing an inlet plenum. The inlet plenum must be able to provide a tank like feel effect by having a large water containing volume. This design factor aims in dampening the turbulence created from the water pumping and delivery systems. 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 will be placed. From the design of the inlet plenum of water tunnel of (Kalyankar et al., 2015), the inlet plenum is made circular at the part surrounding delivery hole to reduce the corner flow effects. The semicircular design of the inlet plenum will guide the flow coming out from the baffle towards the settling chamber and hence reducing the turbulence of water through the circular junctions.

2.1.2.3 Flow Conditioning System

As the flow about to enter the test section, it is likely to have significant swirl and turbulence in the flow due to the pump as well as 90 degree bend of the delivery piping system (Daniel, 2012, Daniel et al., 2015). Flow conditioning system is essential for reducing the turbulence of the incoming water from the inlet plenum and entering the test section area and also straightening the flow as well. It consists of the honeycomb sections, screens and settling chamber (Daniel, 2012, Daniel et al., 2015). There are two types of turbulences which are the longitudinal and lateral turbulence. Screens will reduce the longitudinal components of turbulences while honeycomb sections reduce the lateral parts and straightening the flow (Kalyankar et al., 2015). The ratio of the length of the honeycomb section to the diameter of the honeycomb pipe shall be within 5 to 10 for safety considerations. However, in the flow conditioning system design of water tunnel by (Kalyankar et al., 2015), 33.87 ratio is used because the higher the ratio, the more effective the performance of the honeycomb in straightening the flow.

2.1.2.4 Convergent Section

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. According to (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015), the contraction ratio of the contraction section must be in between 6 to 10 and a higher contraction ratio will damp the flow perturbations (C.Weiselsberger, 1925). In addition, the design of the contraction geometry of convergence section is based on the 5th degree polynomial curve (Bell and Mehta, 1988). The width to length ratio of the contraction length also must be range in between 0.667 to 1.79 because too short length will result in reducing the turbulence damping performance while too long 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 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 needed to be optimized to damp the turbulence created by the piping system and 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 same as the width of the inlet of the convergent section.

2.1.2.5 Test Section

According to (Kalyankar et al., 2015) and (Daniel, 2012, Daniel et al., 2015), the length of the test section cannot be too long or else the boundary layer thickness at the downstream of the test section will be thicker, alter the main flow stream behavior, and subsequently affect the quality of the flow visualization experiments. However, the length of the test section also need to have enough length so that the flow visualization of 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 happened to be at the downstream of the test section and the boundary later thickness can be calculated. The other considerations is that 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 (Daniel, 2012, Daniel et al., 2015). The maximum ratio (downstream of test section) of the boundary layer thickness to the height of the test section of (Daniel, 2012, Daniel et al., 2015)used is 0.146 where the boundary layer thickness is 22mm within a 0.152m height 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 and (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 Wide Angle Diffuser

Wide angle diffuser is one of the components of the outlet module of the test section. It is needed 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 important parameter in designing wide angle 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 important 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 and (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 occur and subsequently produces unsteadiness in the flow which will eventually resulting the flow propagates back to the test section.

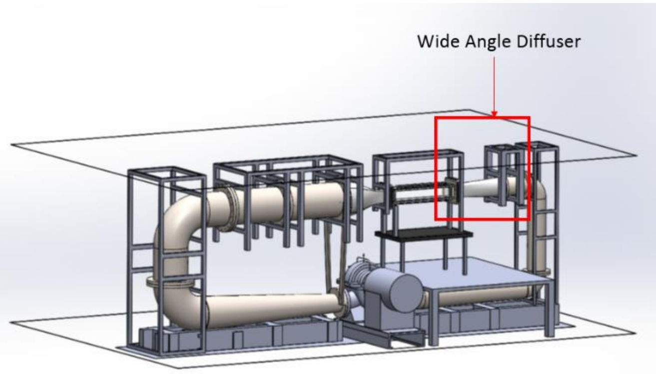


Figure 2.4: Wide angle diffuser design of the water tunnel (Daniel, 2012, Daniel et al., 2015).

2.1.2.7 Outlet Plenum

According to (Kalyankar et al., 2015), outlet plenum connects the whole setup with the piping systems. The main design criteria of the outlet module design is its geometry since any irregularities will result a back pressure and flow reversal back into the test section causing the flow in the test section is disrupted.

2.1.2.8 Motor and Pumping System

The main purpose of the pump and motor is to supply a pressure differential sufficiently large to overcome the pressure losses throughout the entire loop at desired volume flow rate. The pump and motor size is selected such that the pressure differential of the pump overcomes the total pressure losses throughout the loop at the desired volumetric 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). Hence, the criteria of the selection of pump is based on the test section cross-sectional area, flow speed range within the test section and the total pressure losses throughout the water tunnel system.

2.1.2.9 Return Leg Piping System

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

2.1.3 Design of Unconventional Water Tunnel

The conventional water tunnel designed usually leads a water tunnel with large dimensions even for low Reynolds number water flow water tunnel due to their design criteria of their components. Hence, the design of unconventional water tunnels are been studied due to their smaller dimensions compare to the conventional water tunnel. For the unconventional water tunnel, some of the primary components in the conventional water tunnel design will not be used such as the convergent section and the diffuser. Figure 2.5 shows the exploded view of the unconventional water tunnel designed and developed by (Zahari and Dol, 2015) where there are no convergent section and diffuser is used. However, two polyvinyl chloride (PVC) flow guide is used to direct the water stream from the pump to the central channel which is the test section and provide a steady flow within it.

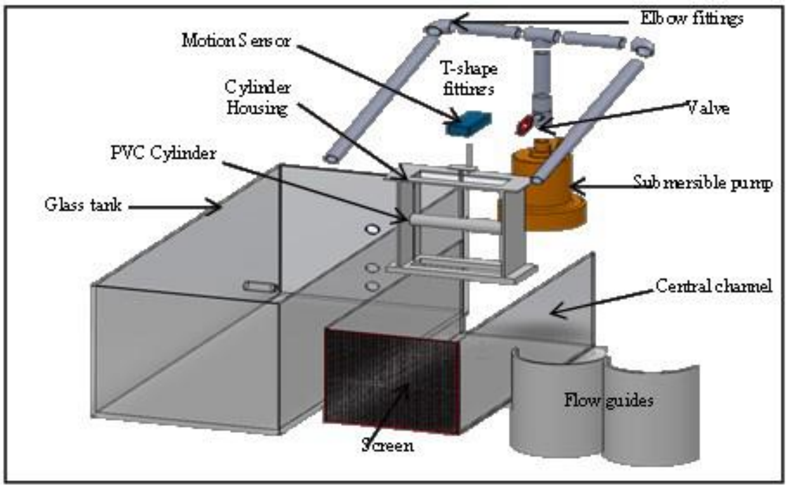
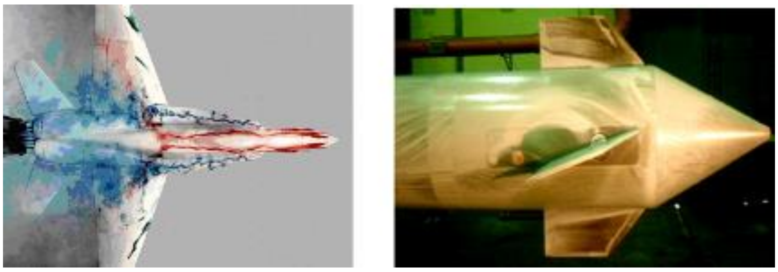


Figure 2.5: Exploded view of the unconventional water tunnel designed (Zahari and Dol, 2015).

2.2 Flow Visualization Techniques in Water Tunnel

Flow visualization is the process of making different phenomenon of the fluid flow visible (Kalyankar et al., 2015) and play an important role to assist the researcher in understanding the flow behavior by providing the overall picture of the flow field (Ristić, 2007a) and formulating more consistent theories regarding the particular flow. It simplifies the steps by making the analysis of the flow structures around the micro-hydrokinetic turbine into qualitative analysis instead of quantitative analysis (Kalyankar et al., 2015). A flow visualization survey has been conducted by (Kalyankar et al., 2015), the flow visualization techniques are categorized into three broad categories as shown in table 2.1.



(a) *(b)*

Figure 2.6: Flow visualization method (a) Off-the-surface flow visualization using food dye, (b) Surface flow visualization using oil firm (Ristić, 2007a).

Table 2.1: Flow visualization techniques survey conducted (Kalyankar et al., 2015).

Visualization Techniques	Application Medium	Flow Regime
Dye injection	Water	Low speeds (water tunnels)
Smoke visualization	Air	Low subsonic speeds (M<0.3)
Particle Image Velocimetry	Water	Low speeds
Pressure sensitive paint	Air	High speeds
Wake imaging	Air – Water	Low to moderate speeds
Shadow graphs	Air	Compressible flow
Schlieren Imaging	Air	Supersonic speeds

From the table 2.1, dye injection method is chosen as the flow visualization techniques in current research project instead of particle image velocimetry method due to its low cost of apparatus, simplicity, ease of setup procedure, and high quality of pictorial representation (Kalyankar et al., 2015).

2.2.1 Dye Injection System

During the flow visualization experiment using dye injection system, dye will be injected in a tested flow either from a small ejector tube placed at a desired position or from small orifices, that setup on the wall of the model, without the components perpendicular to the model surface (Ristić, 2007a). The dye also can be generated in the flow without disturbing the flow by placing the ejector of the dye at the upstream of the test section (Ristić, 2007a). Figure 2.6 (a) shows the flow visualization using dye injection system by ejecting the dye through the ejector tube placed inside the aircraft model and eject through small orifices made on the aircraft model surface. There are 2 main parameter that needed to be emphasized when performing flow visualization using dye injection system in water tunnel which are the water velocity or Reynolds number of the water flow stream and also the type of dye used in the system in order to have a clear pictorial representation of the flow visualization.

2.2.1.1 Flow Velocity of the Water Stream in Water Tunnel

In a study of flow visualization of scaled X-31 aircraft model (Cobleigh and Frate, 1994), dye injection method is used to visualize the flow structures around the model. During the flow visualization experiment, the fluid flow is set to be at low velocity and low Reynolds number. The test is typically performed at approximately velocity of 0.0762ms^{-1}. The velocity profile at this rate may vary at ±0.004572 ms^{-1}. This lead to the turbulence intensity at the test section has less than 1%. Visualization with dyes injection method is not suitable with turbulent flow as the filaments of the dyes will decay and mix up with the surroundings immediately and hence flow visualization test cannot be conducted (Ristić, 2007a). In the design of water for flow visualization study by (Kalyankar et al., 2015), a water tunnel that use dye injection method to perform flow visualization is designed and developed and perform its flow visualization test at water flow velocity of 0.08 ms^{-1}.

2.2.1.2 Dye Used in Dye Injection System

According to (Ristić, 2007a) and (W.Merzkirch and K.Gersten, 1987), a dye used for flow visualization of filament of line is called as ideal tracer when the dye fulfill several criteria which are good stability with respect to diffusion of the dyes in water, same specific weight as the working fluid (neutral buoyancy) and high contrast which give good visibility to ensure a high quality pictorial representation of the flow visualization around the model to be tested. In a rotating flow, it is very essential to make sure that the dye solution has the same specific weight with the working fluid (neutral buoyancy) (Ristić, 2007a). Neutral buoyancy can be attained by mixing the dye material with a fluid whose specific weight is lower than that of water such as alcohol.

There are few selection for the dyes that used in flow visualization in water tunnel which are food coloring dyes, ink, potassium permanganate, rhodamine, and fluorescein where they can be mixed in milk or alcohol. The fattiness of the milk retards the diffusion of the filament of the dye solution into water and give high contrast to the dye's filament line by improving the reflectivity of the dye (Ristić, 2007a) and (W.Merzkirch and K.Gersten, 1987). The dye layers also can be stabilized by a weak saline stratification in the tank because the time scale for diffusion of dye layers into stratified salt water is large compared to the time needed for one test run (W.Merzkirch and K.Gersten, 1987). One of the weakness when using dye injection method in a closed circuit water tunnel is the water of the water tunnel will increasingly contaminate the water, hence the tunnel has to be emptied and refilled after each experiments.

2.3 Application of Micro-Hydrokinetic Turbine in Water Tunnel

Water tunnel is capable to perform various kind of experiment in order to study the hydrodynamic behavior of the model to be studied that placed in the test section of the water tunnel. The model can be car model, aircraft model wing model, cylinder model and even micro-hydrokinetic turbine model and the others. However, the water tunnel design and specification must meet the requirement by the micro-hydrokinetic turbine model so that the experimental work can be conducted. The requirements by 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 river flow velocity of Malaysia's river where the micro-hydrokinetic turbine will be placed which defined the range of water flow velocity of water tunnel required.

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

Micro-hydrokinetic turbine is a new technology that extracts 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 2.7 (Kaur and R.P.Saini, 2016).

(a) *(b)*

Figure 2.7: (a) Open channel water tunnel (b) Straight bladed squirrel cage Darrieus vertical axis micro hydrokinetic turbine model (Kaur and R.P.Saini, 2016).

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

The micro scale of hydrokinetic turbines generally have smaller dimensions (diameter of 15 - 25cm for micro-hydrokinetic turbine) compare to the normal hydrokinetic turbines which in turn give less cost for fabrication and hence giving much smaller impact to the environment (Khan et al., 2008). During the development of the hydrokinetic turbine in the past researches, a micro scale hydrokinetic turbine model with diameter of 15cm is designed, fabricated and tested as shown in figure 2.7 (b) (Kaur and R.P.Saini, 2016).

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

One of the researches shows that 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 2.8. In addition, the research also founds 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 2.9 for River Senggai (Hin et al., 2008).

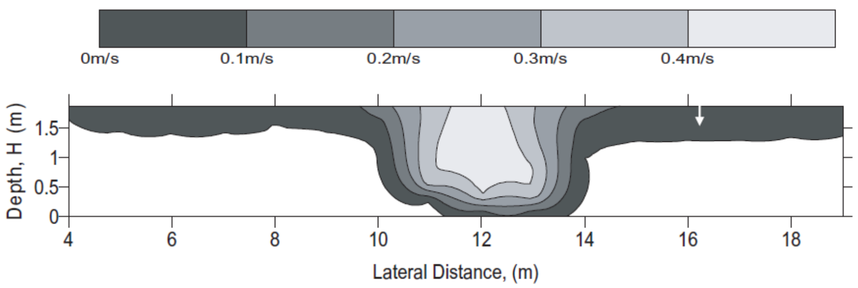


Figure 2.8: Velocity distribution of river Senggai (Hin et al., 2008).

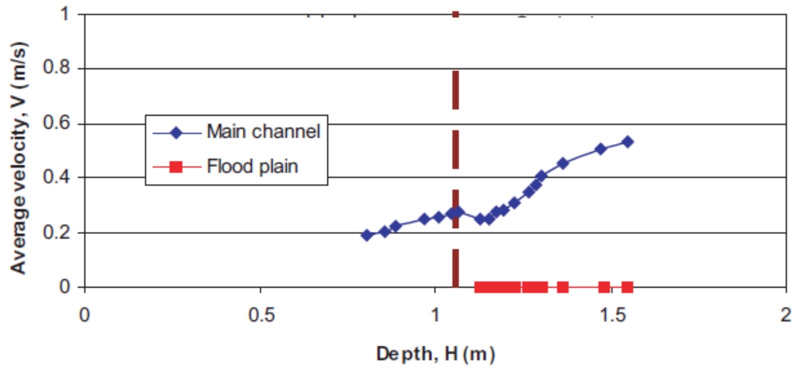


Figure 2.9: Average Velocity of River Senggai, Sarawak (Hin et al., 2008).

Furthermore, one of the many researches inspects the river flow conditions and dynamic state analysis of Pahang rivers in which 17 river cross section stations of Pahang rivers are selected. The hydrologic sampling data collected on 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 2.10 shows the average velocity of river flow stream of the hydrologic sampling data collected from Pahang river.

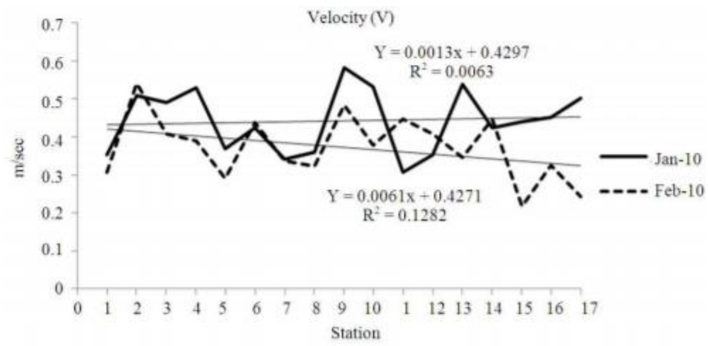


Figure 2.10:Average velocity of river flow stream of hydrologic sampling data collected from Pahang river (Gasim et al., 2013).

2.4 Relevance between Literature Review and Current Project

One of the significance of the literature reviews carried out on the past researches and studies is the design criteria of the components of the preliminary water tunnel model 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 preliminary water tunnel model is further 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.

Furthermore, 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 are aiming 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.

Literature surveys also conducted on the design criteria of the components of water tunnel that capable to conduct flow visualizations as one of the objectives of current project is to study the flow behavior of the micro-hydrokinetic turbine model when water passes through it. The surveys on the method used to perform flow visualizations in water tunnel which is dye injection method are performed to understand the factors needed to be concerned when conducting flow visualization. The factors included by the dye injection method are the type of dyes used and also the flow velocity of the water tunnel when flow visualization experiment is conducted. The flow velocity required to perform flow visualization also crucial when determining the capability of the water tunnel on the range of water flow velocity of the water tunnel when designing its components. In summary, the current project will be focusing on the aspects as listed below:

1. The criteria of the components of water tunnel are designed based on the literature survey done 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 criteria of the components of water tunnel are designed in order to perform flow visualization study on micro-hydrokinetic turbine model in water tunnel using dye injection method.

3. 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}), minimum river flow velocity required by micro-hydrokinetic turbine model to generate electricity, and the flow velocity of water tunnel suitable to perform flow visualization.

4. 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.

5. The capability of the water tunnel designed to perform flow visualizations on static micro-hydrokinetic turbine model using dye injection method.

CHAPTER 3

FUNDAMENTAL THEORY

In this chapter, the fundamental theory that related to the current research especially the factors that affect the behavior of the fluid in the water tunnel which be discussed. The factors are including the Reynolds number, boundary layer, uniform velocity profile, uniform flow and turbulence intensity of the fluid will be discussed. The mathematical equation involved are also presented.

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 while the property of an object to continue its position or motion at a constant velocity unless exerted by an external force is known as inertia. For inertia, an object with small inertia can be started and stopped almost instantaneously when external force is applied on it and vice versa for the object with larger inertia. Meanwhile, viscosity cause drag to the. In summary, the inertia will keep the fluids continue its motion either stationary or flowing while the viscosity will resist the fluid from flowing. In this project, the calculation of Reynolds number is based on the external flow. External flow is a flow which mainstream has no district boundaries is alike to internal flow that also has a transition regime. The Reynolds number in this project can be calculated mathematically by using equation as following:

$$\mathrm{Re} = \frac{\rho v x_c}{\mu} \tag{3.1}$$