PERFORMANCE EVALUATION OF AN IN-PIPE HYDROPOWER SYSTEM WITH VERTICAL AXIS PARALLEL TURBINE

AIMA MARIATY BINTI AHMAD

FACULTY OF ENGINEERING
UIVERSITI MALAYA
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AIMA MARIATY BINTI AHMAD

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ABSTRACT

The performance evaluation of an in-pipe hydropower system with vertical axis parallel turbines prototype in a pipeline has been investigated in order to generate renewable energy. This is because the excess pressure, kinetic energy, and potential energy in flowing water can be used to generate electricity when water is used rather than wasted.

Therefore, this study led to the development of a new design of an in-pipe hydropower prototype called prototype 40 (P40). This prototype is designed by dividing the water flow into two parts, namely the main water channel and the power generation (PG) channel. The PG channel contains a turbine on the side of the pipe. The flow of water in the PG channel is controlled by valves located in the inlet and outlet channels. If service and maintenance work needs to be done, the valves on the PG line can be closed to stop the water flow. This will not affect the water flow on the main channel as the water flow works normally. With the division of this water flow, it will not interfere with the water supply to consumers, which has become the main concern for water suppliers.

An experiment was conducted on a laboratory scale to determine the increased power and efficiency of the prototype. The proposed method includes theoretical design, building a prototype, testing its performance, and analysing the data that was collected.

Based on the findings, the prototype has worked according to the intended design. It allows most of the water to flow while using some of the water pressure for power generation. Therefore, the prototypes should be recommended for real-world implementation towards Technology Readiness Level (TRLs) 6 or higher.

Keywords: Hydropower, in-pipe hydropower generation, performance test, turbine efficiency, vertical axis parallel turbine system.

ABSTRAK

Penilaian prestasi sistem kuasa hidro dalam paip dengan prototaip turbin selari paksi menegak dalam saluran paip telah disiasat untuk menjana tenaga boleh diperbaharui. Ini kerana lebihan tekanan, tenaga kinetik, dan tenaga potensi dalam air yang mengalir boleh digunakan untuk menjana elektrik apabila air digunakan dan bukannya dibazirkan.

Oleh itu, kajian ini membawa kepada pembangunan reka bentuk baharu prototaip kuasa hidro dalam paip yang dipanggil prototaip 40 (P40). Prototaip ini direka bentuk dengan membahagikan aliran air kepada dua bahagian iaitu saluran air utama dan saluran penjanaan kuasa. Saluran penjanaan kuasa mengandungi turbin di sisi paip. Aliran air dalam saluran penjana kuasa dikawal oleh injap yang terletak di saluran masuk dan keluar. Sekiranya kerja servis dan penyelenggaraan perlu dilakukan, maka injap pada saluran penjanaan kuasa boleh ditutup untuk menghentikan aliran air. Ini tidak akan menjejaskan aliran air pada saluran utama kerana aliran air berfungsi seperti biasa. Dengan pembahagian aliran air ini, ia tidak akan mengganggu bekalan air kepada pengguna yang menjadi kebimbangan utama oleh pembekal air.

Satu eksperimen telah dijalankan pada skala makmal untuk menentukan peningkatan kuasa dan kecekapan prototaip. Kaedah yang dicadangkan termasuk reka bentuk teori, membina prototaip, menguji prestasinya, dan menganalisis data yang dikumpul.

Berdasarkan penemuan, prototaip telah berfungsi mengikut reka bentuk yang dimaksudkan. Ia membolehkan kebanyakan air mengalir sambil menggunakan beberapa tekanan air untuk penjanaan kuasa. Oleh itu, prototaip ini disyorkan untuk pelaksanaan dunia sebenar pada Tahap Kesediaan Teknologi 6 atau lebih tinggi.

Kata kunci: Kuasa hidro, penjanaan kuasa hidro dalam paip, ujian prestasi, kecekapan turbin, system turbin paksi selari secara menegak.

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Symbols	Meanings
ρ	Density
Q	Flow rate
g	Gravitational acceleration
H	Height
π	Pi
P	Pressure
A	Surface area
τ	Torque
v	Velocity

Abbreviations	Meanings
AAIBE	Akaun Amanah Industri Bekalan Elektrik
CI	Cast iron
FiT	Feed-in tariff
GPRV	Generating pressure reducing valve
GRP	Glass-reinforced pipes
HDPE	High-density polyethene
IHGS	In-line hydroelectric generating system
Inc	Incorporated
IPSH	In-pipe hydropower system

Ltd	Limited
MDPE	Medium- density polyethene
MESTECC	Ministry of Energy, Science, Technology, Environment and Change
PAT	Pump as turbine
PG	Power generation
PLA	Polylactic acid
PRV	Pressure-reducing valves
PSH	Pumped storage hydro
PVC	Polyvinyl chloride
ROR	Run-of-river
RPM	Rotational speed per minute
SEB	Sarawak Energy Berhad
SEMS™	Sustainable Energy and Monitoring Systems
SESB	Sabah Electricity Sendirian Berhad
TNB	Tenaga Nasional Berhad
TRLs	Technology Readiness Level
UM	Universiti Malaya
WDN	Water distribution network

CHAPTER 1: INTRODUCTION

1.1 General Introduction

Energy is one of the world's most essential components that affect a country's economic growth. Generally, there are two categories of energy resources that are non-renewable sources such as fossil fuels, nuclear resources, and renewable resources (Yah *et al.*, 2017). However, since the early stages of electrification, fossil fuels such as natural gas, coal, and oil, have become the leading world's primary energy source due to their availability and high calorific value (Abbas *et al.*, 2019). However, emerging electricity-generating practices based on fossil fuels can harm the environment. Global warming, air pollution, ozone depletion, energy security, and rising fuel prices have become significant societal concerns. In addition, the increased use of fossil fuels has become a health risk for humans (Panwar *et al.*, 2011). Consequently, the increased use of fossil fuels in these energy sources has diminished reserves in recent years (Khan *et al.*, 2016).

Due to the increase in global demand for energy, the environmental implications of conventional energies, climate conservation, and sustainable growth concepts, many countries seek an alternative to energy resources (Berrada *et al.*, 2019). As a result, numerous people contemplate expanding renewable and clean energy resources. These include the current national policies and international understanding and treaties as a priority goal for environmental sustainability that does not endanger the natural resources of future generations. Therefore, to meet the rising demand and protect energy resources and the environment, it is essential to move toward the use of renewable energy (Bujang *et al.*, 2016).

Renewable energy is derived from naturally replenished energy sources. Renewable energy may be derived directly from the sun (helio chemical, helio thermal and helio electrical), indirectly from the sun (wind, hydropower, and photosynthetic energy stored in biomass), or from other natural environmental movements and mechanisms (such as geothermal) (Ellabban *et al.*, 2014). The interpretation of renewable energy excludes energy resources derived from fossil fuels, waste products from fossil sources, and waste products from inorganic sources. Figure 1.1 illustrates a general overview of renewable energy sources.

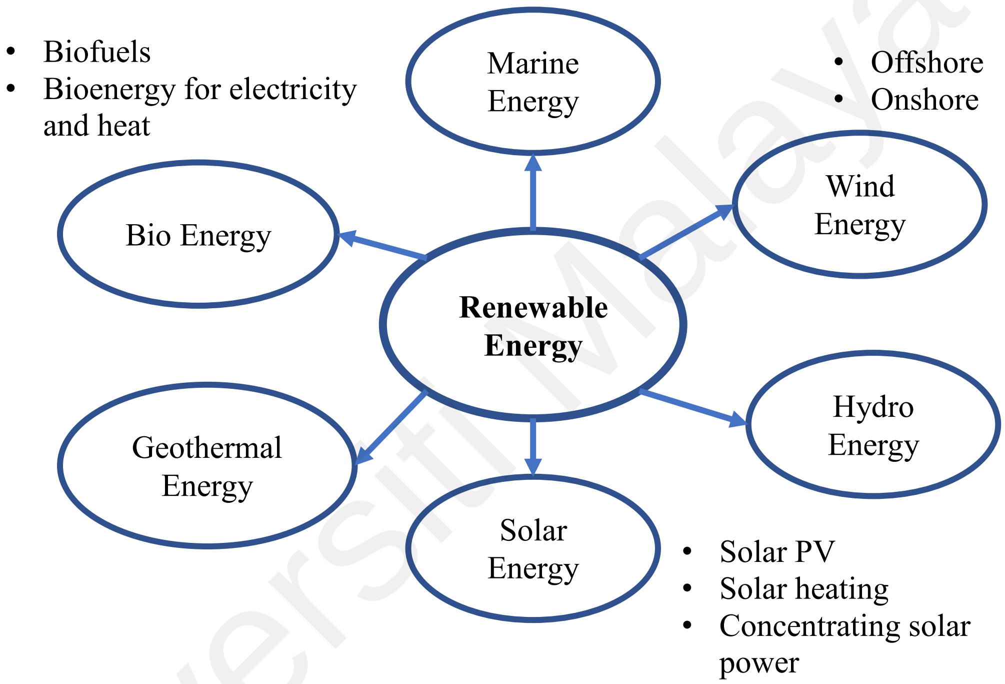


Figure 1.1: Overview of renewable energy sources (Ellabban *et al.*, 2014).

Renewable energy supplies hold enormous promise because, theoretically, they will massively meet global energy demand. As a result, they can play an essential role in the future global energy portfolio, focusing on expanding its renewable energy resources pool (Ellabban *et al.*, 2014). Global power consumption from renewable energy sources is expected to increase 2.7 times between 2010 and 2035. According to the Renewable 2020 Global Status Report (REN21, 2020), renewable energy has increased three times faster than fossil fuels and nuclear energy over the last five years. However, it has accounted for less than a third of total final energy consumption growth. Meanwhile, according to Hydropower Status Report 2019 (IHA, 2019), it is clear that non-renewables now supply the majority of the world's energy demand with fossil fuels, and nuclear fuels generate 74.4% of electricity generation, with renewables accounting for the remaining 25.6%. This can be shown in Figure 1.2.

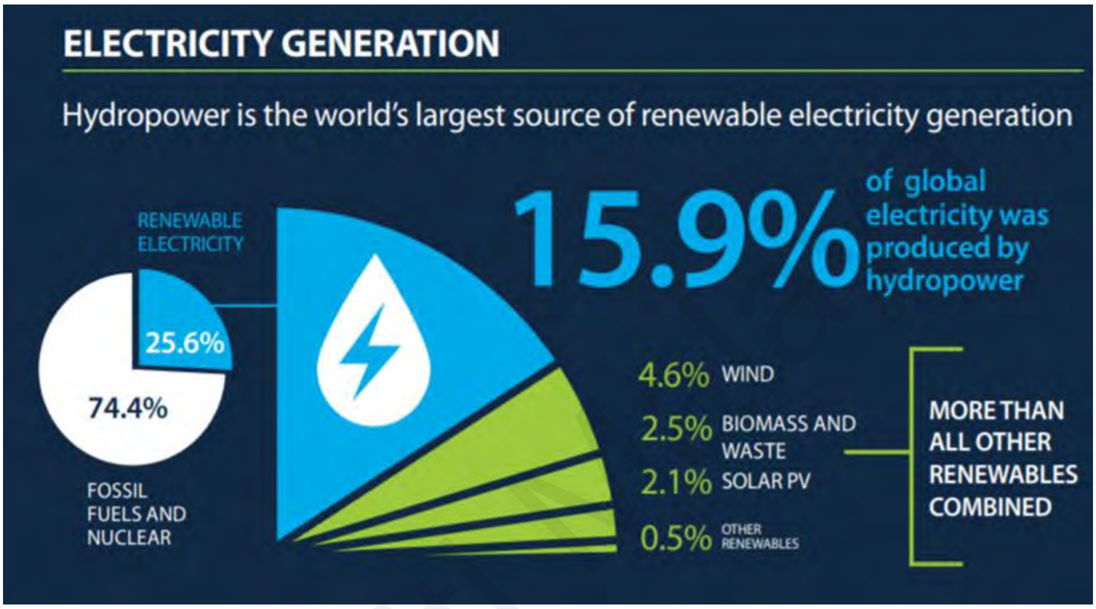


Figure 1.2: Production of global electricity (IHA, 2019).

Currently, hydropower is the most important alternative energy source in the world. Its generation costs are frequently much lower than the current costs of solar, nuclear, thermal, and wind power. Hydropower is one of the most desirable regulatory forces for the electricity industry because it is easily controlled by adjusting the dam gates (Huang *et al.*, 2014). In 2019, renewable energy sources generated approximately 4,305 TWh of hydropower generation. A total of 15.6 GW of hydropower capacity was added, bringing the global production capacity to 1,308 GW (IHA, 2019). As a result, hydropower has emerged as one of the most significant and active renewable energy sources (Razan *et al.*, 2012). Therefore, a shift to renewable energy was expected to meet rising demand while protecting energy supplies and the environment (Bujang *et al.*, 2016).

Hydropower, also known as water power, generates electricity using flowing water. Hydropower is widely regarded as the safest, most reliable, and most effective renewable energy source (Zimny *et al.*, 2013). It is a well-established technology adopted by most nations worldwide (Casila *et al.*, 2019). In contrast to non-renewable sources, hydropower would be more cost-effective and appealing, particularly when considering external costs (S. Karimov *et al.*, 2013). It has become the most environmentally friendly renewable energy source (Idsø, 2017), where it is classified as green energy (Didik *et al.*, 2018). This energy source can eliminate secondary emissions and is sustainable for current and future social needs (Yah *et al.*, 2017). Hydroelectric energy systems have numerous advantages over alternative energy sources (Vyas *et al.*, 2015). It stabilises demand-supply fluctuations to support the instability of other renewable energy sources, such as wind and photovoltaic power, proliferating globally (Casini, 2015). This matter also attracts the interest of developing nations that lack the infrastructure to effectively and reliably manage electricity demand because it decentralises the production and storage of energy (Strang, 2017).

The Ministry of Energy, Science, Technology, Environment, and Climate Change (MESTECC) was tasked with green technology-related responsibilities by the Malaysian government in 2009 when it emphasised the significance of sustainable energy. The ministry is responsible for increasing the nation's proclamation of biodiversity and sustainable alternatives. It has made an earnest goal to attain a greater penetration of renewable energy in the Malaysian energy mix. It also has set a 31% renewable energy target in the energy mix by 2025 and up to 40% in 2035 (*MyRER – Renewable Energy Malaysia*, n.d.) (Chan & Sopian, 2022). In the hydropower sector, Malaysia has installed a total capacity of 6,094 MW, generating 15,66 TWh. However, hydropower production in Malaysia is low because fossil fuels continue to play a significant role in the country's electricity generation (Firdaus *et al.*, 2019).

The objective of all hydropower plants is to generate electricity as efficiently as possible. A conventional hydropower system requires damming a water supply, dam in an advantageous location to create a head of water with accumulated potential electricity. A pipeline connects the dam to a lower area with a turbine generator, allowing water pumped from a high position to flow into the turbine. The water's potential energy drives the turbine to generate mechanical energy, which drives the generator to produce electricity. However, numerous studies have been conducted in recent years to apply the concept of hydropower to existing water supply systems.

Researchers have looked into the feasibility of using a pump-as-turbine (PAT) to generate electricity in the water distribution network (Du *et al.*, 2017). Most of the studies appear to be focusing on the use of pumps as turbines without investigating the benefits of turbines in water network energy production. There are numerous advantages to using turbines over PAT, such as increasing the volume of micro-hydro turbines in industries and better overall efficiency. It also does not interfere with normal pipeline flow and has a shorter payback time (Coelho & Andrade-Campos, 2018).

There is a small but expanding effort to examine the viability of producing micro hydropower from the high-pressure water that flows through the city's water supply and feeds the national grid every day (Ramos *et al.*, 2010). This includes a turbine that generates energy by rotating in response to the water flow in these pipelines (Aqel *et al.*, 2018). Similar research has increased significantly due to the substantial advantages of pressure control in the water system, such as reduced leakage, pipe burst incidents, and water consumption (Vicente *et al.*, 2016).

In water supply systems, installing in-pipe turbines is gaining interest (Samora *et al.*, 2016). Nevertheless, the major challenge in generating hydropower in water supply pipelines is selecting or designing appropriate turbines to meet the water supply requirements (Jiyun *et al.*, 2018). The turbines incorporated into the system have been verified to contribute to energy quality improvement and the resolution of leakage issues (Corcoran *et al.*, 2013). For example, LucidPipe, a corporation based in the United States, has developed and patented a spherical in-pipe hydropower turbine that generates electricity without losing all friction or interfering with water delivery. However, this integrated in-pipe hydropower turbine has limitations; if maintenance is required, the water supply must be shut off.

1.2 Project Background

This research presents reconstructed research based on a novel design concept for an in-pipe hydropower system (IPHS). The novel IPHS product description (Filing number: PI2019007588) is shown in Figure 1.3.

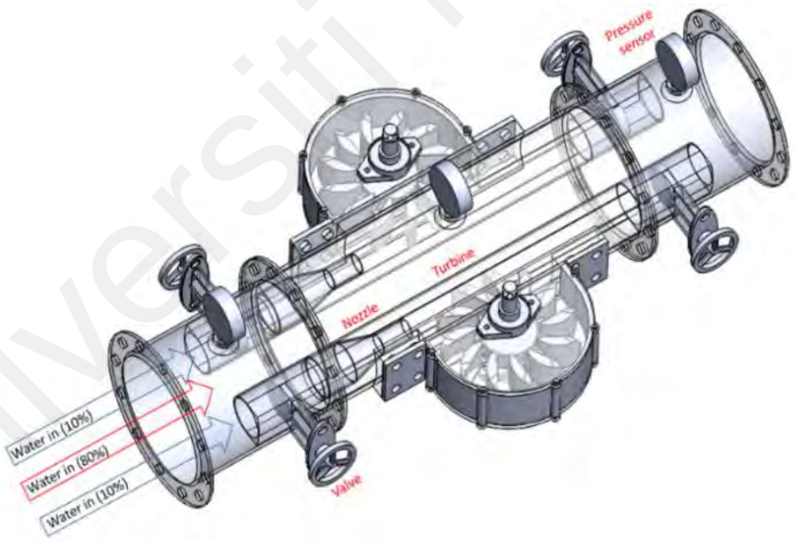


Figure 1.3: IPSH (Abdullah *et al.*, 2021).

The IPHS is designed to divide the water flow into the main water channel and two power generation (PG) channels, each of which contains a turbine on one side of the pipe. Water flow in the PG channels is controlled by valves located at the channels' inlet and outlet. It was estimated that 20% (10% each) of the water flow would flow through the prototype's PG channels. It would optimally harness the energy of flowing water in a pipe without obstructing or diverting the primary water flow. Water can still flow through the main water channel even if the PG channel is closed for maintenance and repair. This will ensure that the water supply is not interrupted, as it would not be necessary to shut down the entire system.

Meanwhile, an extended and reconstructed prototype is proposed in this study. Previous research by Abdullah *et al.* used a PG 20, but this research has been improved with a PG40. The percentage of water diverted into the PG channel is indicated by the number shown after PG. In this research, 40% of the water inlet will be diverted to the PG channel (20% on each side), with the remaining 60% flowing through the main channel. 40% was selected because it was the maximum diameter that can fit into the main pipe.

Therefore, this research focuses on the performance evaluation of an in-pipe hydropower system with a vertical axis parallel turbine of a new IPHS based on PG40. Based on this research and the available data, it is hoped that a new source of sustainable and functional renewable energy will be introduced and promoted in Malaysia. The application is proposed to the initiative's key players, most likely the water operators. The electricity generated can be used for both grid and off-grid applications.

1.3 Problem Statement

During the last 50 years, Malaysia's electricity demand has increased significantly to meet the needs of the domestic and industrial sectors. Energy demand has increased significantly due to the proliferation of residential, commercial, and agriculture operations to meet consumer demands. As a result, global primary energy demand is anticipated to increase by 1.6% between the year 2009 to 2030 (Chua & Oh, 2011). Due to rapid population growth, industrialisation, and modernisation, more energy is required than ever before (Anaza *et al.*, 2017). This is one of the critical issues faced by the European Union in ensuring energy security through competitive and "clean" energy, despite rising global energy demand and an uncertain future in terms of access to energy resources (Moldoveanu *et al.*, 2017).

The water industry is one of the significant electricity consumers since water is a basic human need. Industrial water can generate energy by incorporating hydropower into its water distribution networks. In urban areas, increased water demand has necessitated a 24-hour water industry. When water is transported through a pipe from one location to another, it generates pressure that exceeds what is required (Amjadi *et al.*, 2020). Due to the elevated pressure, this excess energy may cause pipeline damage at specific locations (Muhsen *et al.*, 2019). This has prompted many water supply system managers to implement a pressure control strategy involving installing Pressure Reducing Valves (PRVs) in the networks to limit leaks and pipe breaks and reduce water resource losses (Postacchini *et al.*, 2020). Typically, this excess pressure, kinetic and potential energy in the flow is dissipated into the atmosphere by PRVs (Ramos, 2010; Fecarotta, 2014; Corcoran, 2016). It leads to inefficient energy usage in water treatment plants and piping systems, as the kinetic energy produced by the flow can be utilised rather than wasted.

In recent years, hydropower turbines integrated into water-supply networks, also known as in-pipe hydropower, have been a viable source of electricity generation (Corcoran *et al.*, 2013; Karadirek *et al.*, 2016). Although water supply networks are not used for energy generation, the infrastructure and network allow full participation in PG scenarios. However, another issue raised by current in-pipe hydropower is the disruption of water supply to consumers (Sari *et al.*, 2018). It is critical that the water supply system not be disrupted while hydropower is installed in it (Kral *et al.*, 2019). Furthermore, energy harvested from the water supply system at locations with excessively high flow or pressure should not impact the level of service provided to customers.

In a previous study done by Abdullah *et al.*, his research focused on the conceptual design and preliminary experiments of a novel in-pipe hydropower vertical axis parallel turbine using PG20. The preliminary laboratory-scale evaluation of the prototype yielded a positive result in its workability and performance. However, due to fabrication issues, the flow of PG channels and the valves' workability were not assessed. Also, the pressure at the PG channel and the flow rate after the nozzle were not calculated. The increase of percentage from 20% to 40% is done with an estimation that more power will be generated. According to Power *et al.* (2015), higher power output can be generated when a higher resistance force (torque) is applied to the turbine as the turbine size increases.

It is hoped that this research will aid in generating green energy and energy conservation because it can provide valuable electricity for both grid and off-grid electrification. Consequently, it can improve the sustainability of the water distribution network while not interfering with or neglecting the water supply service. Micro-hydropower energy is considered renewable, clean energy, and a reliable energy source (Samora *et al.*, 2016), which will help to reduce carbon gas emissions.

1.4 Objective

The study's objectives are as follows:

a) to design an in-pipe hydropower prototype with PG40,

b) to investigate the performance of an in-pipe hydropower prototype with PG40 based on water flow, water pressure, turbine rotational speed, and torque, and

c) to evaluate the efficiency in terms of mechanical power generated and pressure loss inside the pipe of an in-pipe hydropower prototype with PG40 towards the readiness of Technology Readiness Level (TRLs) 6 in the appropriate environment.

1.5 Scope of Work

This research determined the amount of energy harvested by PG40 in-pipe hydropower. Before the product can be utilised in the real world, a prototype must be developed to measure its dependability. Hence, an IPSH prototype known as an in-pipe hydropower vertical axis parallel turbines prototype with PG40 was invented in the university laboratory. The development of the prototype or model (full scale) was demonstrated to achieve TRLs 6, where the prototype's performance was investigated and evaluated. The prototype was fabricated by machining and joined together by welding.

In this research, two conditions of water flow were investigated. The first condition was where the control condition water flows without a prototype installed; this is when the pipe is fully opened and closed. The second condition was water flows with two prototypes installed, one with an open valve and another with a closed valve. Only water pressure and two water flows from different locations were recorded for the first condition. For the second condition, six water pressure readings were taken, three before and three after the water flowed into the turbine. Aside from that, each turbine's rotation speed and torque were measured while the valve was open.

Data was collected to calculate the value of water flow, water pressure, turbine rotational speed and torque, and performance in terms of power generated and turbine efficiency. The significance of the research lies in the fact that, if successful, it will be able to persuade relevant industries to grant this research permission to be applied in their place.

1.6 Thesis Outline

This dissertation is divided into five chapters. It is organised in the following sequence.

Chapter 1: This chapter introduces the dissertation, focusing on the background, problem statement, goal to be achieved, and scope of work in this research. It also includes the overall design of an in-pipe micro-hydropower device.

Chapter 2: This chapter provides an overview of the hydropower sector in Malaysia and in general. This chapter discusses the benefits, size, and type of hydropower. Previous experiments and studies into the micro-hydropower in-pipe system in the water distribution network are included in this chapter. It also describes the formula and the components of an in-pipe micro hydropower system.

Chapter 3: This chapter will discuss the methods used in this study. It explains how the research will be carried out and what data will be collected to analyse it.

Chapter 4: The details of the experimental results and the study's analysis will be covered in this chapter. This chapter will determine how much renewable energy can be harvested using this in-pipe vertical hydropower system. The pressure loss inside the pipe is also discussed in this chapter. It is based on the information gathered during the experiment.

Chapter 5: This chapter summarises the research findings and makes recommendations for future research.

CHAPTER 2: LITERATURE RESEARCH

2.1 Introduction

Energy plays an essential role in advancing universal socio-economics in modern civilisation in all nations, where it has become one of society's basic needs. It is closely related to critical elements of sustainable sustainability, where energy consumption per capita is one of the essential components and an indicator of economic growth (Bhandari *et al.*, 2018). It is also required in all commercial and human activity areas, where it improves productivity, livelihoods, and the quality of living. Consequently, the energy demand has increased tremendously due to the expansion and advancement of many industrial, domestic, and agricultural activities (Yah *et al.*, 2017) in response to consumer demands for developed and developing nations (Palakshappa *et al.*, 2019). Therefore, it is necessary to increase the capacity so that enough electricity can be generated to meet the needs of consumers.

However, most of today's energy consumption is due to fossil fuels. Increasing daily energy demand necessitates more diverse energy generation and production sources. The use of non-renewable energy has a devastating effect on the environment, resulting in carbon emissions, ozone depletion, global warming, and pollution in our fragile ecosystems. In turn, this may affect global human health (Yüksel, 2010). Due to increased exposure to environmental issues, the rising cost of non-renewable resources, and government incentives to promote renewable energy sources, PG derived from renewable energies has attracted considerable attention (Soffia *et al.*, 2010). As a result, there is a growing awareness of using renewable energy resources, making it the most practical approach.

2.2 Hydropower

Hydropower, hydraulic power, or water power is derived from the force or energy of flowing water. Thus, it can be said that water plays a vital role in the global energy production portfolios. Hydropower is produced by converting the kinetic energy of moving water into mechanical energy, then used to generate electricity (Hatata *et al.*, 2019). This can be explained as shown in Figure 2.1.

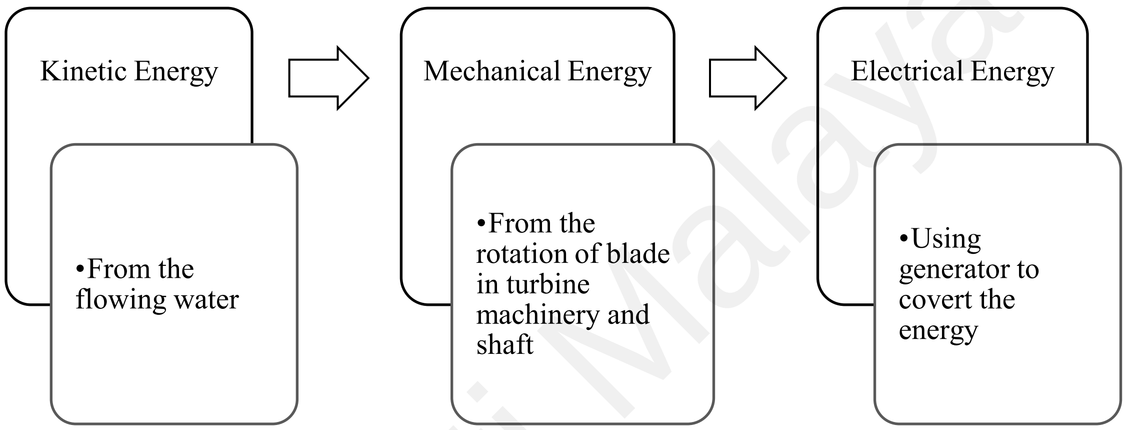


Figure 2.1: Energy conversion in hydropower.

Among all the different forms of renewable energy, the hydropower plant stands out for its feasibility, which plays a significant role in electricity production (Pérez-Sánchez *et al.*, 2017). Hydropower generation systems are one of the world's most well-known renewable energy sources (Aqel *et al.*, 2018) and a viable renewable energy source due to their low cost (Suman *et al.*, 2020). It is one of the earliest forms of renewable energy, inexpensive, viable, and environmentally friendly (Comino *et al.*, 2020). The golden era of hydropower was during the first half of the 20th century, before the influence of oil on the energy supply's controlling power.

However, it is a well-established technology that countries worldwide have used. Compared to a fossil-fuel-based power plant, the current hydro system is approximately 85% efficient, whereas a typical fossil-fuel-based project is only about 50% efficient

(Akpinar, 2013; Barelli *et al.*, 2013). Consequently, hydropower development can also substantially impact the operational management of natural and artificial water supply systems (Novara *et al.*, 2019).

In 1882, the first hydropower plant was built in Appleton, Wisconsin, using running water from the Fox River (Jawahar & Michael, 2017). It generates 12.5 kilowatts of electricity, enough to power two paper mills and two homes. Meanwhile, in Malaysia, the Sempam Hydroelectric Power Station in Raub, Pahang, was constructed in the early 1900s by the Raub Australian Gold Mining Company and is the country's oldest hydropower facility. Nowadays, hydropower has become an essential service for the present and the future. As the world's leading renewable energy source, hydropower ensures that global decarbonisation goals are met while complementing intermittent renewables with flexibility and storage.

China has the world's largest hydropower installation (356.40 GW) among all nations. It demonstrates that China leads the world in installed hydropower capacity. China also has the highest installed hydropower capacity globally. However, it has developed engineering and technological expertise, demonstrating a globally unique dimension of growth and dynamic development in the hydropower industry. Meanwhile, the country with the second-highest hydropower installation (109.06 GW) after China is Brazil. The United States has the third-highest hydropower installation (102.75 GW), behind Canada (81.39 GW), India (50.07 GW), and other nations. The details of hydropower installation capacity worldwide by country are shown in Figure 2.2.

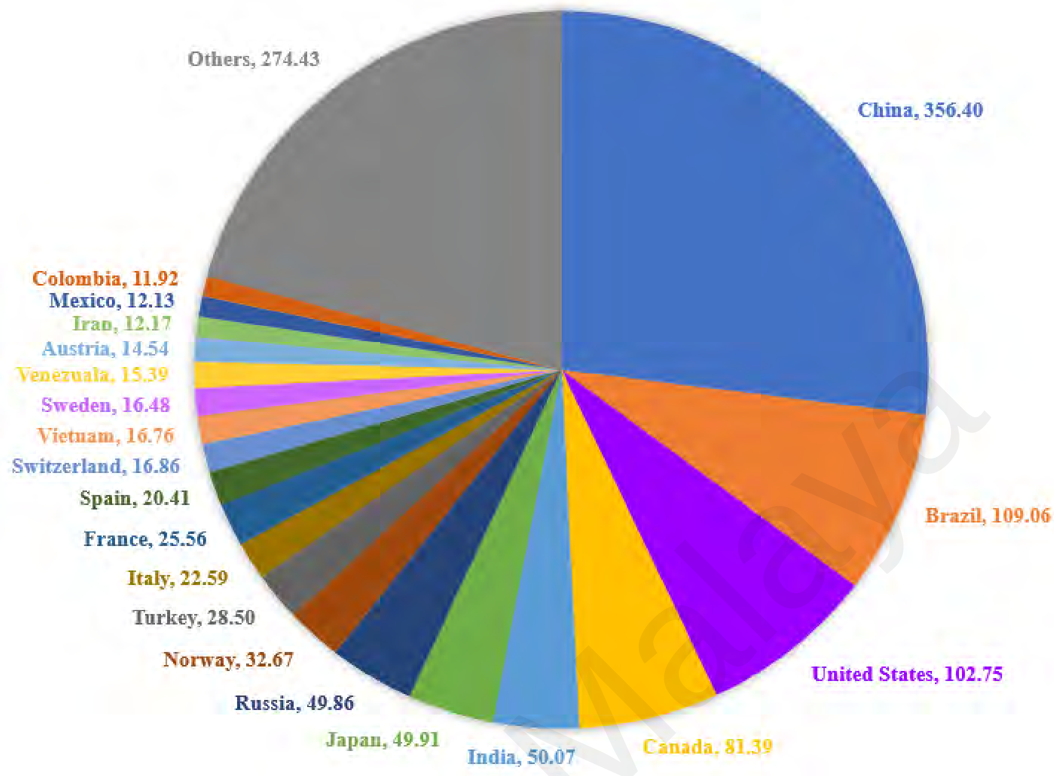


Figure 2.2: Global hydropower installed capacity (unit GW) - modified from (IHA, 2020).

Between 2015 and 2019, the cumulative installed capacity increased by 2.1% annually for five years. In 2019, the growth rate was 1.2%, and it appeared to be the world's leading producer of renewable energy sources, with numerous additional non-power benefits. The increase in hydropower installed capacity from 2015 to 2019 is depicted in Figure 2.3.

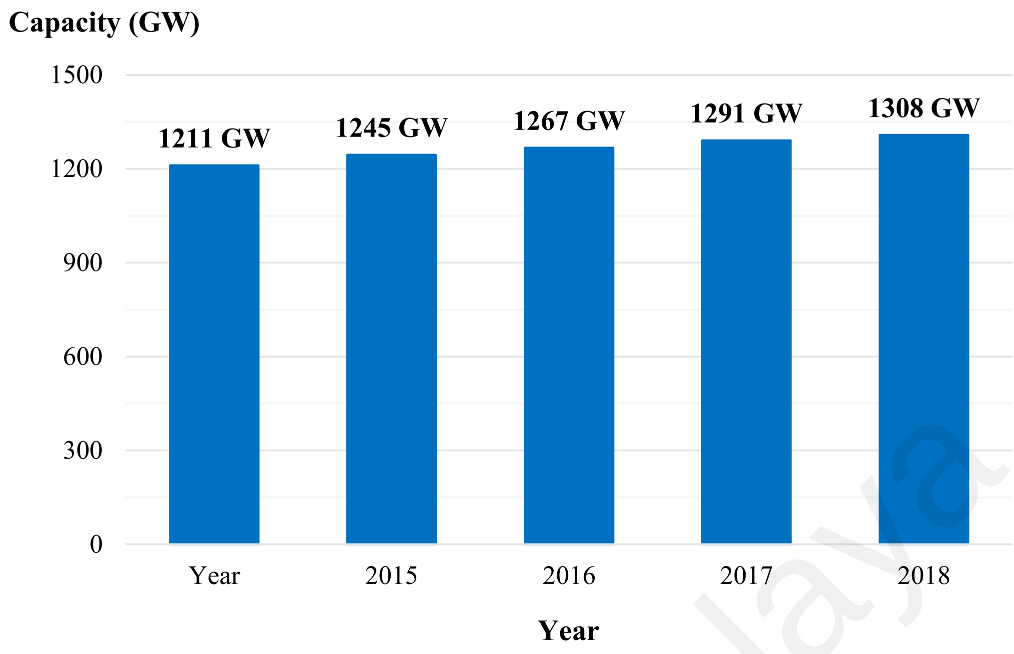


Figure 2.3: Hydropower installed capacity growth (2015-2019) - modified from (IHA, 2020).

Nevertheless, in its Transforming Energy Scenario (IRENA, 2018), IRENA reported that global hydropower capacity must increase by 25% by 2030 and 60% by 2050. This is to limit global warming to within 2 °C above pre-industrial temperatures. A 2% annual increase in total hydropower capacity is required to meet the 2050 target. On the other hand, annual installed capacity development can differ significantly depending on new hydropower projects, which can take years to construct before becoming operational. However, this emphasises the need for significant hydropower production over the next decade.

2.2.1 Hydropower in Malaysia

Malaysia has an abundance of renewable energy resource bases (Hossain *et al.*, 2018). Malaysia is fortunate in that it already has access to large amounts of water due to its geographical location and high annual rainfall, allowing hydropower to thrive (M. Faizal *et al.*, 2017), benefiting the hydropower sector. The country's climate is characterised by high humidity and supporting terrain, with Peninsular Malaysia receiving an average of 2,500 mm of rainfall per year. On the other hand, East Malaysia receives 5,080 mm of rain per year, making it ideal for hydropower projects. Aside from that, the hilly terrain covering the entire country's broad and long-range and many streams flowing to the foothills increase the potential suitability of hydropower for small hydropower plants significantly (JUNIDO & ICSHP, 2013). Moreover, Malaysia has an abundance of water resources. There are 150 rivers in Peninsular Malaysia and 50 more in Sabah and Sarawak (Borhanazad *et al.*, 2013), covering 41% of the total land area (S. Ahmad & Tahar, 2014).

Malaysia has over 30 million people and an area of 329,847 km^2. The electricity demand is rising in tandem with the global population. As a result, the annual global primary energy consumption growth is 1.6% between 2009 and 2030 (Chua & Oh, 2011). Malaysia's government has prioritised hydropower development to ensure a prosperous and environmentally sustainable energy future (Fairuz *et al.*, 2013). As a result, hydropower is poised to play an increasingly important role in achieving Malaysia's energy and environmental objectives. This will contribute to Malaysia's goal of increasing renewable energy installed capacity from 217 MW in 2011 to 11.5 GW by 2050 (Bekhet & Ivy-Yap, 2014). According to the National Energy Balance (NEB, 2018) report, Malaysia's total installed electricity generation capacity was 33,991 MW in 2018. It was also reported that the peak demand, or the point at which energy consumption is at its highest in a given day, is 18,338 MW for Peninsular Malaysia, 3,504 MW for Sarawak, and 955 MW for Sabah. The total gross electricity generation was 163,415 GWh, a 5.1% increase from 155,456 GWh in 2017.

Hydropower is the leading source of installed renewable energy capacity in Malaysia compared to other renewable sources, although natural gas is still predominant, as stated in Malaysia Energy Statistic Handbook 2019 (Malaysia Energy Statistic, 2019).

As of 31 December 2017, Malaysia had a total installed capacity of 6128.1 MW, with Peninsular Malaysia contributing 2580 MW, Sarawak 3459.5 MW, and Sabah 88.6 MW. Hydropower potential exists in almost all Malaysian states, with Peninsular Malaysia, Sarawak, and Sabah having annual average rainfalls of 2420, 3830, and 2630 mm, respectively (F. Ahmad *et al.*, 2017). Due to its high rainfall and geography, Sarawak has contributed the most to hydropower, making it an ideal location for hydropower station installations. Table 2.1 displays the source's breakdown of available capacity, including renewable and non-renewable sources. Figure 2.4 displays the installed capacity of significant hydropower stations in Malaysia.

Table 2.1: Installed capacity as of 31 December 2017 (Unit: MW) - modified from (Malaysia Energy Statistic, 2019).

	Peninsular Malaysia	Sabah	Sarawak	Total	**Total (%)**
Natural Gas	12,681.6	1,2314	983.6	14,896.6	**43.6%**
Coal	10,066.0	0.0	480.0	10,546.9	**30.9%**
Hydro	2,580.0	88.6	3,459.5	6,128.1	**17.9%**
Diesel / MFO	478.2	801.6	126.6	1,406.4	**4.1%**
Bio mass	403.2	295.5	49.5	748.2	**2.2%**
Solar	318.1	39.0	0.5	357.6	**1.0%**
Bio gas	51.1	18.4	0.5	70.0	**0.2%**
Other	25	0.0	5.1	30.1	**0.1%**
Total	**26,603.2**	**2,474.5**	**5,105.2**	**34,182.9**	**100.0%**

Aside from the large-scale hydropower mentioned earlier, Malaysia also has small hydroelectric power in several rivers and dams that can generate approximately 500 MW (Kadier, 2018). The government supports the adoption of small hydro in Malaysia via the feed-in tariff (FiT). The installed capacity of mini-hydro in Malaysia as of 31 December 2014 was 72.2 MW, with a total generation of 1,82,063 MWh in 2014 contributed by Tenaga Nasional Berhad (TNB) (9.327 MW), Sarawak Energy Berhad (SEB) (7.297 MW), Sabah Electricity Sendirian Berhad (SESB) (8.0 MW), mini-hydro feed-in tariff (FiT) holder (15.7 MW), mini-hydro IPP (20 MW), and others (11.90 MW) (Sovacool & Bulan, 2012) Figure 2.5 shows the location of small hydropower in Malaysia as of December 2014, as operated by TNB, SEB, and SESB.

Figure 2.4: Installed capacity of significant hydropower stations in Malaysia - modified from (M. Faizal *et al.*, 2017)

Figure 2.5: Location of a small hydropower plant in Malaysia - modified from (Hossain et. *al.*, 2018)

2.2.2 Advantages of Hydropower

Hydropower has its advantages. The following are the most significant advantages of hydropower relative to other technologies:

a) Hydropower generation is an inexpensive and reliable source of energy. With a global weighted average cost of USD 0.05 per kWh for new hydropower projects, it is the cheapest source of electricity generation in many markets (IRENA, 2018). The cost of average electricity in a hydropower station with more than 10 MW capacity is between 3 to 5 cents/kWh (Cobb & Sharp, 2013; D. Yan *et al.*, 2017).

b) Hydropower plants can be quickly rehabilitated or upgraded using recent hydro technology advances. Rehabilitating or upgrading existing hydropower schemes allows cost-effective capacity expansion (IRENA, 2012; Kougias *et al.*, 2019).

c) Hydropower is renewable because it does not deplete water resources and does not require fuel. This helps reduce pollution and emissions, whereas hydropower is a low-carbon technology that helps offset the carbon emissions and pollutants caused by fossil fuels. Compared to fossil fuel-powered plants, the hydropower station emits few greenhouse gases because there is no direct waste (Suman *et al.*, 2020). In 2011, hydropower saved three billion tonnes of carbon dioxide compared to fossil fuels to generate the same amount of electricity.

d) In most cases, hydropower is a cost-effective renewable energy source that will be used more extensively in the future (Muhsen *et al.*, 2019). It supports the growth of variable renewables such as wind and solar, which meet demand when these sources are unavailable (IHA, 2019). Furthermore, storage hydro helps meet peak demand or accommodate other power plants in the grid (primarily solar and wind), which can experience sudden fluctuations in power production.

e) Hydropower uses domestic water supplies to gain supply stability instead of fuel or other minerals, where demand volatility can be controlled (Hossain *et al.*, 2018). Furthermore, it is unaffected by market fluctuations, promoting price stability (Porkumaran *et al.*, 2017).

f) Hydropower systems are relatively stable in power production over time, where the flow may vary by tens of seconds and can be measured reasonably in advance (Kral *et al.*, 2019). It also provides operational stability because it can be quickly ramped up or shut down, generating the potential for rapid response to fluctuations in energy demand.

g) Constructing reservoirs also makes it easier to manage freshwater responsibly (IHA, 2019). Stored water is an essential tool for safely managing freshwater and supplying water to homes, businesses, and agriculture. This reduces the risks posed by climate change, such as extreme weather events, which help to reduce human vulnerability to floods and droughts.

2.2.3 Types of Hydropower

Hydropower is a mature technology with highly effective and dependable solutions. Hydropower accounts for eight of the world's ten largest power plants in generation capacity. Hydropower generation systems are typically classified into five types: run-of-river (ROR) hydropower, storage (reservoir) hydropower, pumped storage hydropower, in-stream (hydrokinetic) hydropower, and gravitational vortex hydropower (Yaakob *et al.*, 2014).

2.2.3.1 ROR Hydropower

ROR hydropower, also known as diversion hydropower, uses flowing water in a river to spin a turbine through a canal or penstock. Typically, a ROR scheme will have little or no storage capacity. ROR has a continuous supply of electricity (baseload), with some operational variations due to daily fluctuations in demand caused by the plant's water flow management. This hydropower could be advantageous because it does not necessitate rehabilitation or harm the environment, as its turbines are spun by a rapid flow of water (Singh & Singal, 2017). Typically, this type of hydropower plant is employed for small-scale hydroelectric generation. Figure 2.6 shows the diagram of a typical ROR hydropower system.

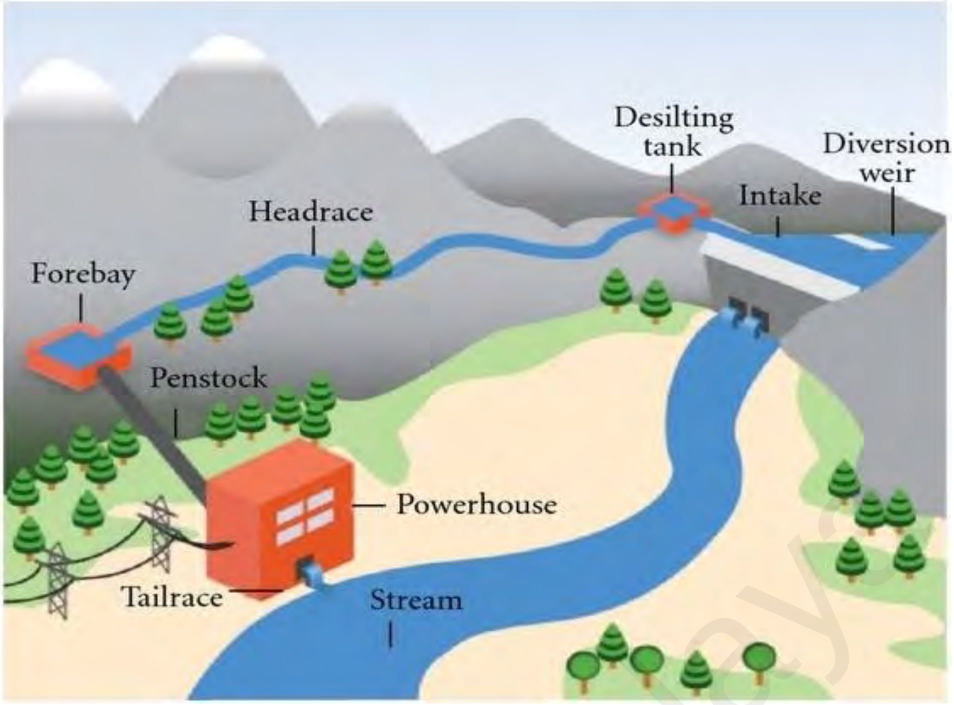


Figure 2.6: Diagram of a typical ROR hydropower system (Simon & Harbunou, 2019).

2.2.3.2 Storage Hydropower

Storage hydropower, also known as hydropower dams, is an extensive system that uses a dam to store water in a reservoir for later use by conserving water during the high-flow season (spring and rainy seasons) and releasing water during the low-flow season (winter, dry season) (Bujang *et al.*, 2016). The electricity is generated by releasing high-kinetic-energy water from the reservoir through a turbine, which activates a generator. Storage hydropower provides a baseload and the ability to quickly shut down and restart in response to device demands (peak load). It has enough storage space and allows the hydropower plant to operate independently, responding appropriately to demand profiles in the short term (hours, days) or seasonally. Figure 2.7 shows the diagram of a storage hydropower system.

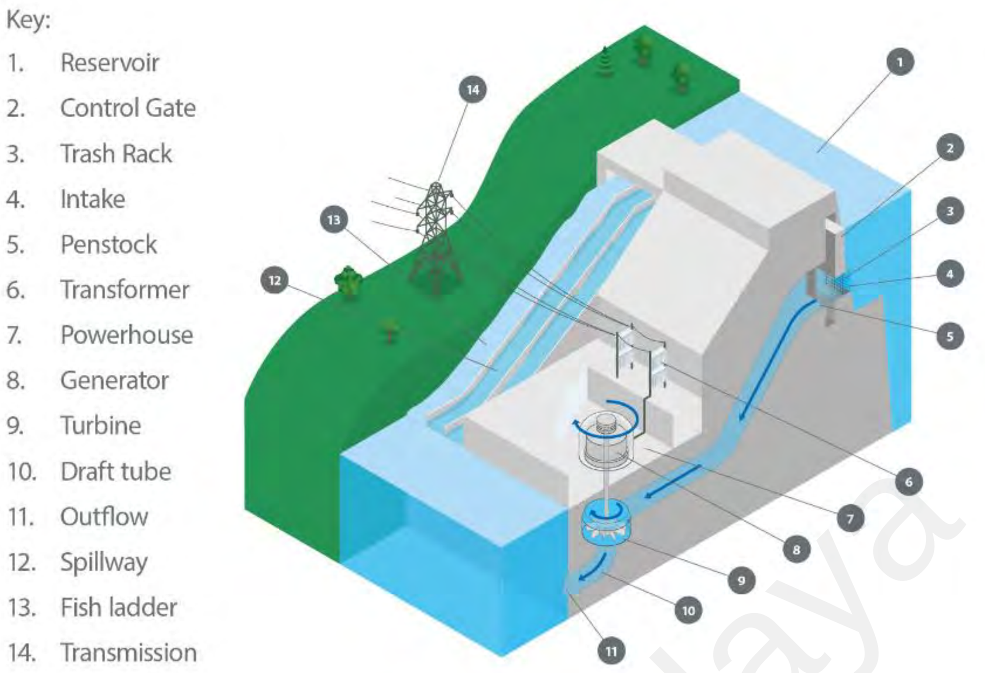


Figure 2.7: Diagram of a storage hydropower system (*Types of Hydropower*, n.d.)

2.2.3.3 Pumped-storage Hydropower

Reversible power plants comprise pumped-storage hydropower plants. This system provides a peak load supply by pumping water between upper and lower reservoirs or tanks at a more significant elevation. The system's excess non-peak energy is utilised during periods of low energy demand. However, when demand is high, water will be released back into the lower reservoir to generate electricity via the turbine. Figure 2.8 shows the diagram of a pumped-storage system.

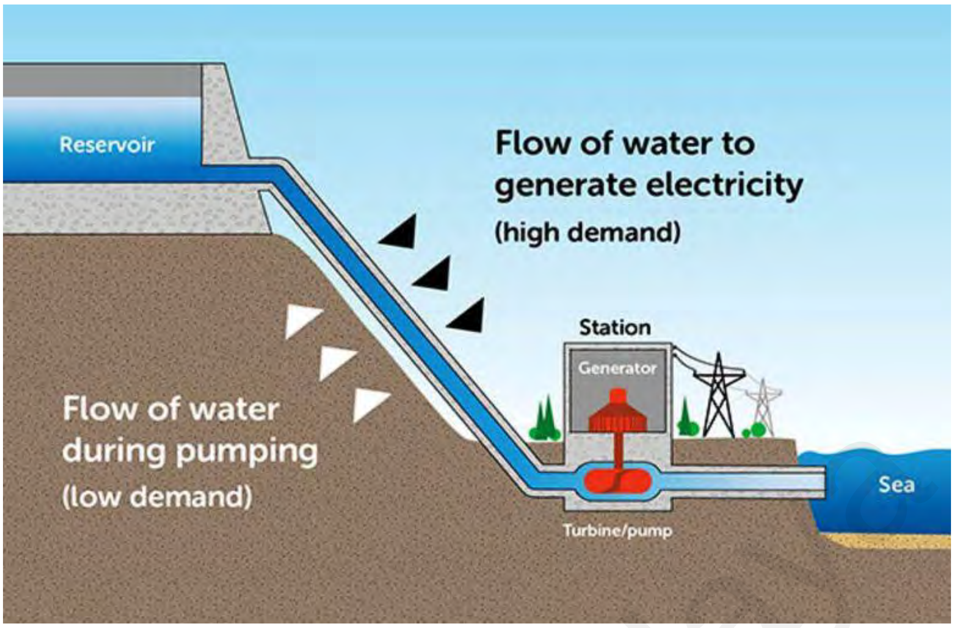


Figure 2.8: Diagram of a pumped-storage hydropower system (*Seawater Pumped Hydro*, n.d.).

2.2.3.4 In-stream Hydropower

This system is less common and well-known than the others. However, it intends to add rivers and canals to future hydropower generation sites. It would be capable of generating energy directly from flowing water instead of the hydraulic head supplied by dams or other control systems. Figure 2.9 shows the diagram of the in-stream hydropower system.

Figure 2.9: Diagram of an in-stream hydropower system (Simon & Harbunou, 2019).

2.2.3.5 Gravitational Vortex Hydropower

This hydropower utilises the energy available in a vortex motion. Typically, a vortex is produced in a circular basin with a tangential inlet and a central outlet. A turbine with a vertical axis is positioned at the center of the vortex, where the rotational speed is at its maximum (Power *et al.*, 2015). The turbine rotates with the whirling flow, generating mechanical energy that can be transformed into electrical energy by a generator. Figure 2.10 shows the gravitational vortex turbine. This system is suitable for generating power from low water heads (Rahman *et al.*, 2017). This type of power plant is therefore appropriate for river areas.

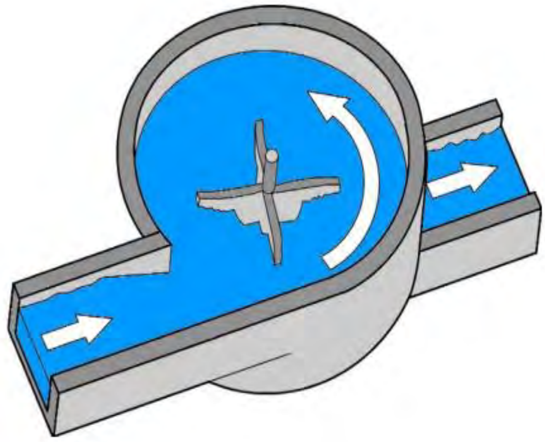


Figure 2.10: Gravitational vortex turbine (W. I. Ibrahim *et al.*, 2021).

2.2.3.6 Hydropower in Water Distribution Network (WDN)

WDN are infrastructures for the production, transportation, treatment, reserving, and distribution of a valuable economic good, water for human consumption. They are physical infrastructures planned, built, operated, and maintained by managing entities to provide consumers with satisfactory quality service. Population growth has resulted in increased distances between populations and water sources, resulting in rapid expansions of several water networks. Water demand is expected to fluctuate in the long run due to rising population and economic activity (Anaza *et al.*, 2017). Consequently, the immediate consumer supply has resulted in efficient operating systems, increasing the energy costs for water supply and distribution.

Previously, in a more traditionalistic approach, the managing entities of water supply systems, whether public, private, or mixed, were solely concerned with economic aspects that guaranteed the quality and quantity of water to users (Ramos & Mello, 2009). Decision-makers must now consider factors other than economics when making decisions, such as performance analysis, reliability improvements, and operational cost savings. At the same time, water companies must be concerned about ensuring good service levels throughout the system's life cycle and environmental concerns. This reflects the need to rationalise natural resources, particularly water and energy. The supply must follow the quantity and quality requirements of the water distribution network (Nogueira Vilanova & Perrella Balestieri, 2014).

Frequent fluctuations in water lines caused by high water demand caused significant pressure variations in water line networks. This could result in massive water losses due to water supply leakage and pipe fracturing. In the worst-case scenario, it could destroy the entire water line system (Kral *et al.*, 2019). Therefore, variations in pressure and flow in the water supply network due to fluctuations in water requirements throughout a typical day, week, or yearly season (McNabola *et al.*, 2014) must be considered. In some systems, PRV is commonly used to alleviate excess pressure to circumvent these issues. PRV helps water supplies maintain pressure following some demands, thereby minimising leakage in the water distribution system. The PRV will release substantial pressure and excessive energy content in the flow consumed during water pumping. However, the dissipated energy regarded as wasted energy can be harvested and utilised because it is regarded as renewable energy.

Consequently, several studies have demonstrated significant hydropower potential in the existing water distribution networks. This is because water and energy are intrinsically linked within the pipeline. Improving energy efficiency in water distribution networks and implementing a hydropower potential must be vital given current concerns regarding sustainable development (Coelho & Andrade-Campos, 2014). Furthermore, energy and water are indispensable to humans and inseparable from all aspects of their lives. These indicate that the two fundamental sources are closely associated with human growth and development.

Thus, micro-hydro generation is anticipated to significantly contribute to future energy supplies (Bavishi & N.K, 2017). Studies have demonstrated the practicability and economic viability of mini and nineteen micro hydropower plants for municipal water distribution networks (Soffia *et al.*, 2010). The concept of energy production from water distribution systems stems from energy dissipation devices, such as PRVs, to reduce operationally necessary excess pressures. Hence, most studies aim to recover this lost energy via a mini or micro hydropower plant.

Moreover, because the system operates efficiently throughout the day and year, energy can be harvested continuously. Several studies have been conducted to assess the interdependence of water availability, electricity generation, and demand (Kucukali, 2011). A remarkable sum of energy can be harvested from the kinetic energy in water flow at the point of high excess pressure in the water supply, allowing potential power to be produced. Micro hydropower in water distribution networks consumes very minimal space and has an insignificant impact on land use.

Energy recovery within the water distribution network has been the subject of numerous published works. Ibrahim *et al.* (2019) conducted a study on introducing micro-hydropower systems and preliminary calculations of the anticipated energy harvesting from three different locations: the shopping mall, residential building, and water plant or station. According to the calculations, it is possible to harvest substantial energy from the pipelines under various operating conditions or applications. Casini (2015) conducted a study that provides an overview of the different types of in-pipe hydro systems that are commercially available, highlighting their potential applications at the urban and building scales, as well as the electricity production advantages gained in comparison to other systems.

Meanwhile, Ma *et al.* (2018) developed a novel in-line hydroelectric generating system (IHGS) to harness the energy contained in the site's water flow and power the primary water pipeline data monitoring system. In this study, a drag-type turbine for a medium-sized pipeline and a lift-type turbine for a large-sized pipeline was designed. In addition, a hybrid energy storage system combining batteries and supercapacitors was developed to store excess energy and stabilise the power supply for the off-grid IHGS. A control system with remote monitoring software was also developed to operate the entire system. Findings indicate that this innovation can resolve the power supply issue for data monitoring systems. However, numerous research opportunities exist, including cost-benefit analyses, long-term device monitoring, and evaluation.

Moreover, Bhargav *et al.* (2016) proposed and investigated the extraction of electricity from high headwater in a building's pipelines. In the study, a 15-meter-tall building was chosen to examine the viability of producing electricity with a low-cost turbine. A microturbine with a 135 mm diameter and a 12 V DC generator was utilised in the experiment. A light-emitting diode and resistors were used in conjunction with numerical results derived from computational fluid dynamics simulation to verify the outcome. Exergy analysis was also performed to quantify the irreversibility of the system's process.

Muhsen *et al.* (2019) investigated the effect of the utilised turbine design of the internal system and reaction turbines for energy harvesting from in-pipe systems. There were four distinct turbine designs with varying numbers of blades. The outcome of the proposed turbine was verified and analysed using a prototype to compare and evaluate the performance of the design. At a water distribution network in Amman, Jordan, a case study was conducted to identify potential sites that would benefit from installing the in-pipe system with the investigated turbines. The experiment demonstrated that micro-hydro systems with the most extended lifespan are the most efficient, ecological, and resilient technology for renewable electrification (Paish, 2002).

2.3 In-pipe Hydropower

Water is a critical component in many global energy development portfolios. A thermal power plant (whether it operates on fossil fuels or nuclear fission) requires a large amount of water to cool the operating fluids and run thermodynamic cycles successfully (O. S. Abdullah *et al.*, 2021). That makes hydropower the most frequently used alternative energy source on the planet. Moreover, abundant hydropower inside the pipeline appears very attractive to provide sufficient and safe power for the monitoring system (Chen *et al.*, 2013a). The monitoring system's power requirements can be met by using an excess water head or a tiny portion of kinetic hydropower inside the pipeline. On the other hand, water providers require a lot of energy to offer their consumers a clean, dependable, and ecologically responsible water source.

Waterpower can be utilised in numerous ways. In recent years, small or micro-hydropower turbines with highly advanced technology have been designed in various alternate ways based on their applications. Water is an up-and-coming and secure medium for energy treatment. Consequently, there is a growing interest in utilising water from drinking or irrigation pipelines to generate energy (Pérez-Sánchez *et al.*, 2017). As a result, power generation systems incorporate in-pipe hydropower. It is one of the most promising methods for energy collecting that can be installed on any structure (Kumano *et al.*, 2018). With multifunctional hydro systems, the current infrastructures of the water supply network can contribute significantly to energy generation.

The concept has grown increasingly appealing, especially in metropolitan settings, where energy may be harvested from residential, commercial, and agricultural water supply systems. There will be an excellent potential to generate power anyplace as long as there is extra head pressure in the water infrastructure (Vincent Denis & Punys, 2012). Integrating the micro hydropower system into the water distribution system has numerous advantages, as it is a green facility that emerges from the reuse of existing infrastructure (Berrada *et al.*, 2019). Compared to other renewable sources, the energy generated by water networks is continuous and easy to estimate the power that could be generated from the system (Okedu *et al.*, 2020). Aside from that, the infrastructure for an average hydro plant is typically less expensive because it does not require a dam or substantial civil works. The installation of micro-hydropower turbines within water distribution networks will also ensure that the critical reliability of the water supply is not compromised.

2.3.1 IPHS

Generally, this in-pipe hydropower can be divided into two main designs: internal and external systems (Casini, 2015).

2.3.1.1 Internal System

Figure 2.11 depicts the IPHS's internal system. The runner is entirely enclosed within the pipe section, whereas only the generator protrudes from the pipe. Internal structures benefit from being smaller in size, making them better suited to smaller applications, but not limited to them. Power performance ranges from 5 to 10W, which is sufficient to power self-powered water meters or control devices, to 100 kW, sufficient to power more demanding applications. The internal mechanism consists of impellers and turbines with horizontal axes parallel to the water flow.

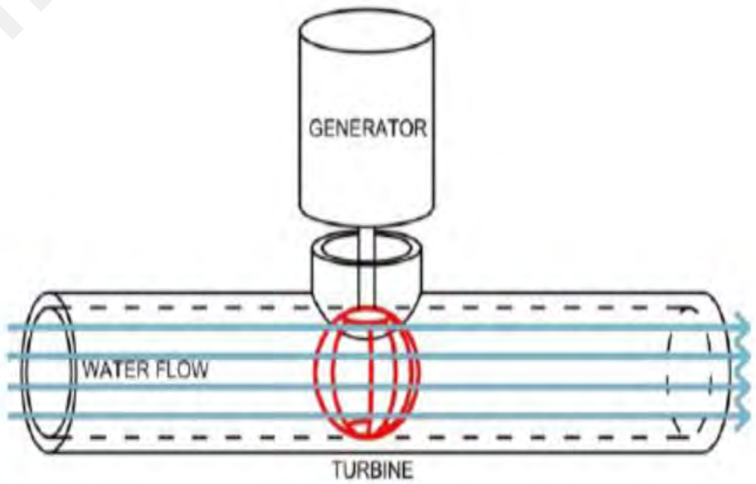


Figure 2.11: Internal design of IPSH (Casini, 2015).

2.3.1.2 External System

Figure 2.12 depicts the external system of the IPHS, in which the runner is confined in a secondary that bypasses the primary. Since the runner is enclosed within the dedicated pipe, external devices are not constrained by pipe size, allowing for much greater versatility. Nonetheless, this method is unsuited for retrofitting existing water facilities since massive vaults are required to store the turbine and generator components. This system is often constructed to match the present pipe capacity, with the turbine and generator varying according to the quantity of available water energy.

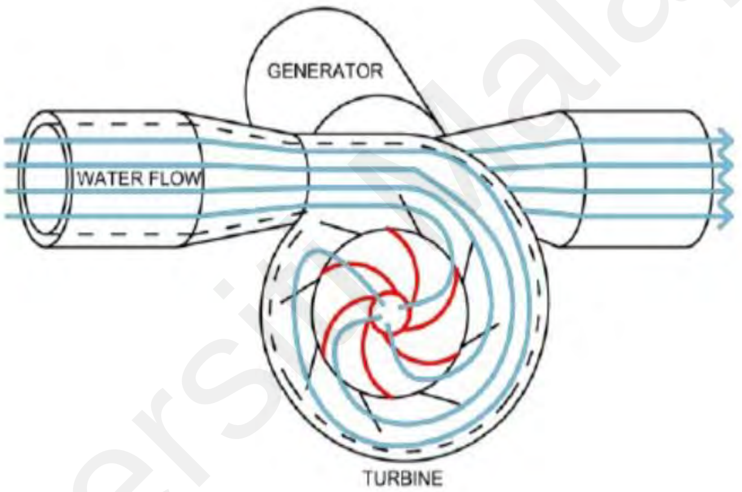


Figure 2.12: External design of IPSH (Casini, 2015).

2.3.1.3 Vertical Axis Parallel System

A new design concept for in-pipe hydropower generation using vertical axis parallel turbines was recently introduced (Abdullah *et al.*, 2021). Figure 2.13 depicts the new vertical parallel turbine system design. It has two vertical turbines installed symmetrically side-by-side in parallel on a water-transporting pipe. The water flowing via the main pipe has been separated into PG channels where energy will be captured. The objective of this design is to address service and maintenance difficulties. When service or maintenance is required, gate valves will be used to close the PG channel and prevent water from entering. Therefore, the water will continue to flow uninterruptedly via the main pipe.

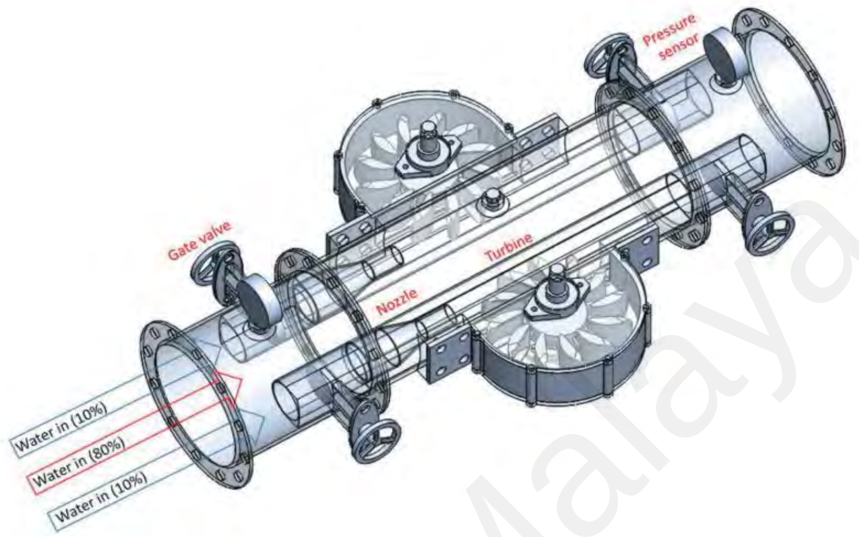


Figure 2.13: New design of vertical parallel turbine system (Abdullah *et al.*, 2021).

2.3.2 In-pipe Hydropower in Industries

IPHSs are gaining popularity because they require neither additional infrastructure nor a substantial initial expenditure. The market for in-pipe hydro systems is anticipated to be driven by a higher emphasis on renewable energy generation and increasing demand for efficient PG in commercial and industrial applications.

2.3.2.1 Lucidpipe Energy

Lucid Energy is the first firm in the United States to develop an in-pipe turbine generator for hydropower pipelines. They have patented a hydro pipeline turbine that operates within the pipe. Figure 2.14 depicts the design of the Lucidpipe power system.

The LucidPipe Energy System consists of spherical turbines installed within a large-diameter (24 – 1500 mm) gravity-fed water distribution conduit. This new generation of impulse conduit turbines can be installed directly at high-pressure locations in pressurised systems (Itani, 2020). It demonstrates that the system can operate directly within the pipe without circumventing the piping system. The system can generate up to 100 kW per turbine with a minimum flow rate of 1 m^3/s and a maximum flow rate of 5.6 m^3/s (*LucidEnergy.Com*, n.d.).

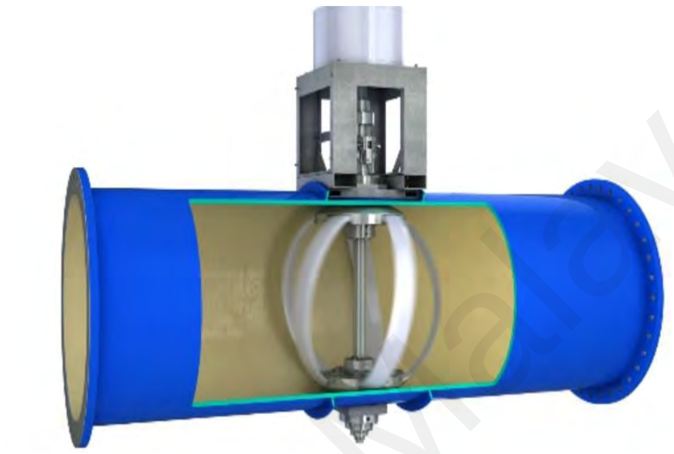


Figure 2.14: Lucidpipe power system (LucidEnergy.Com, n.d.).

The Portland Water Bureau erected a Lucidpipe power system capable of producing 1100 MWh per year in 2015 (Suman *et al.*, 2020). They have become one of the first utilities to implement Lucid Energy's innovative in-line turbine technology. As seen in Figure 2.13, the turbine is integrated within the pipe, which is a constraint as it must halt the water delivery for repair.

2.3.2.2 Leviathan Energy Hydroelectric Limited (Ltd)

Leviathan Energy Hydroelectric Ltd is another company that has developed an in-pipe turbine. As seen in Figure 2.15, this in-pipe hydropower is known as Benkatina and employs the pump as the turbine (PAT). It turns water flow and pressure into energy while keeping downstream pressure constant and achieves excellent efficiency even with changing flows (*In-Pipe Hydroelectric - Leviathan Energy*, n.d.).

Figure 2.15: Benkatina^{TM} in-pipe hydropower (Bekatina.Com, n.d.).

Benkatina^{TM} in-pipe hydropower has the benefit of being user-friendly and suited for installation in all municipal and transportation water systems, water tanks, piping systems, and remote reservoirs. This hydropower is a viable option for rural electricity due to its small size and ease of installation. This notion, on the other hand, is inappropriate for pipes and other systems where water flow rates vary (depending on the time of day and season of the year, among other factors), and pressure downstream from the turbine must be managed in order for the water system to function. This is because the system must be able to generate power efficiently across a wide range of changing water flow rates.

2.3.2.3 SOAR hydropower

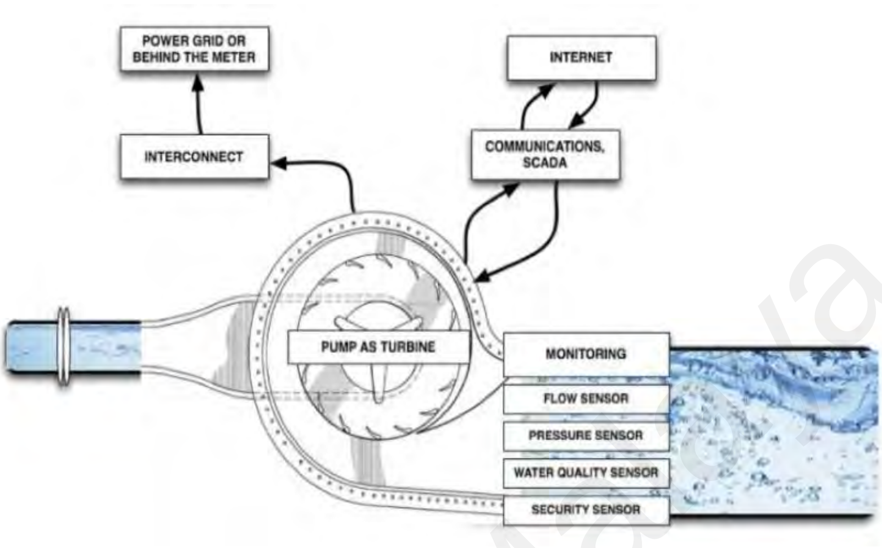
Figure 2.16 depicts SOAR Hydropower's Generating Pressure Reducing Valve (GPRV®) turbines. It is typically implemented in conjunction with existing pressure-reducer valves in water systems. Its operation is similar to that of a Francis turbine in that water flows straight through the turbine, spinning a runner and producing electricity while also releasing pressure. (*SOAR Hydropower*, n.d.).

Figure 2.16: SOAR GPRV hydro turbine (SOAR Hydropower, n.d.).

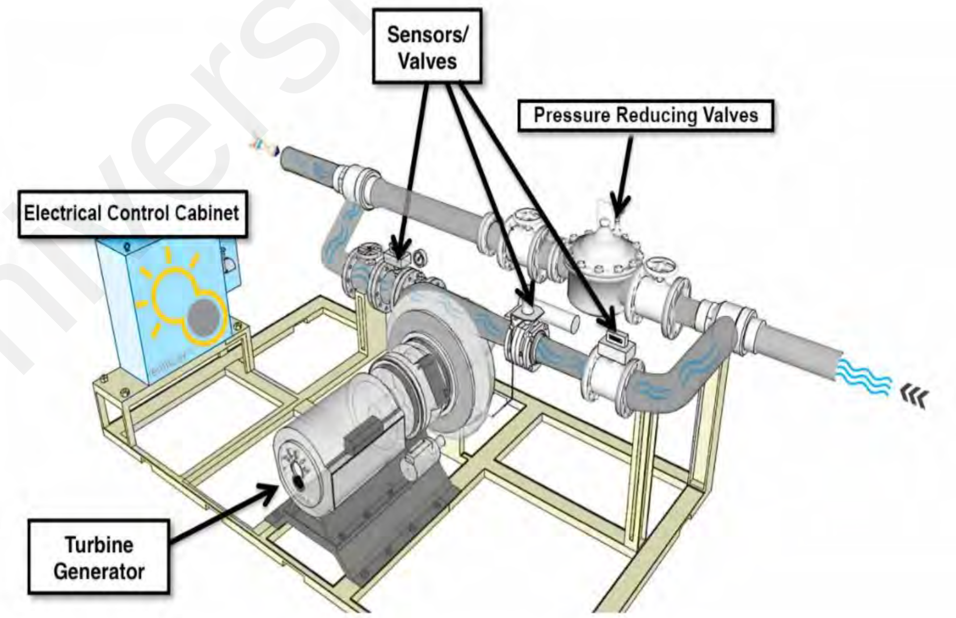
2.3.2.4 Rentricity Incorporated (Inc)

Another US company, Rentricity Inc., has developed a method for harvesting excess pressure generated by water operations and using it to generate clean electric power. Rentricity is an intelligent IPHS that employs supervisory control and data acquisition integration technologies. They offer tailored information services that monitor system performance in real-time, monitoring flow, pressure, incursion, and pollution while optimising operating efficiencies (Rentricity Home: Rentricity, n.d.). The technology generates power by employing the PAT, which reduces R&D expenses (Motwani *et al.*, 2013).

Rentricity has developed two Flow-to-Wire^{TM} in-pipe hydro energy recovery systems for 30 kW to 350 kW or more applications. The most recent product is plug-and-play Sustainable Energy and Monitoring Systems (SEMS^{TM}), or a 5 kW to 30 kW application. Figure 2.17 depicts the Renciticy products. Additionally, the company has completed its first installation of 360 kW-generating tree turbines within an irrigation system within the Utah distribution network of the Richmond Irrigation Company (Rentricity Completes First Irrigation In-Pipe Hydropower Energy Recovery System, n.d.).



(a) Flow-to-Wire Systems™



(b) SEMS™

Figure 2.17: Rentricity in-pipe hydropower product (Rentricity Home: Rentricity, n.d.).

2.3.2.5 Natel Energy Inc

As depicted in Figure 2.18, Natel Energy Inc. has developed HydroEngine, a hydroelectric turbine with a Pelton-style turbine. The HydroEngine linear drivetrain comprises two parallel shafts joined by carbon fiber belts to create a horizontal loop. Crossbars are used to attach two parallel rows of cups resembling Pelton turbine cups to the belts. Later, the flat nozzle will inject water from the middle into the two rows of cups. The parallel cups will move to transmit rotation to the electricity-generating machine. The increase in rotational speed is positioned to improve input by enhancing output.

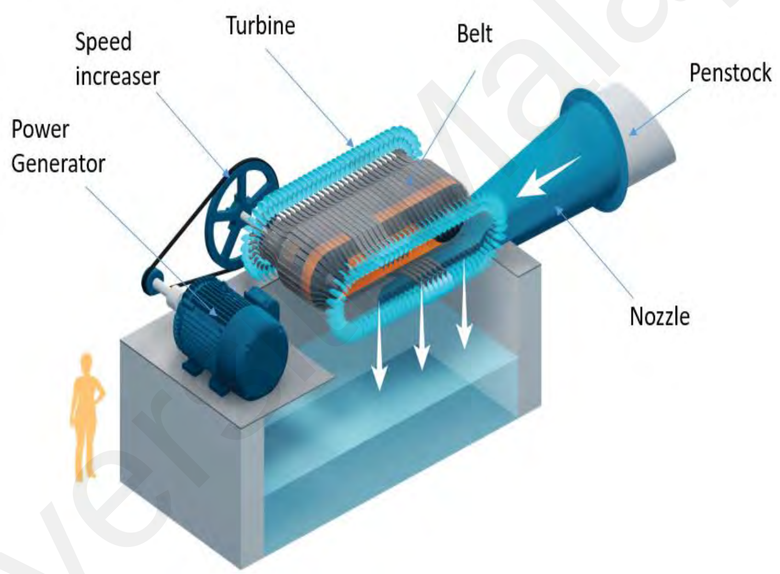


Figure 2.18: HydroEngine (Natel Energy – Distributed, Baseload, Renewable Hydropower, n.d.).

HydroEngine has a low civil cost, is available at less than 6 m head, is anti-cavitation constructed, and is fish-friendly when installed along a river. It produces the same amount of electricity as a Kaplan or Archimedes turbine but is smaller and less expensive.

2.4 Hydropower Generation System

This section provides an overview of the essential components involved in computing and building a typical hydropower plant. The primary focus is on the interconnecting core elements of the typical hydropower device.

2.4.1 Head

The water runs into streams with varied gradients, resulting in various potential head formations. As demonstrated in Figure 2.19, the power capacity is proportional to the head and flow rate. Consequently, water power is the product of the head and flow. Both are required to generate power.

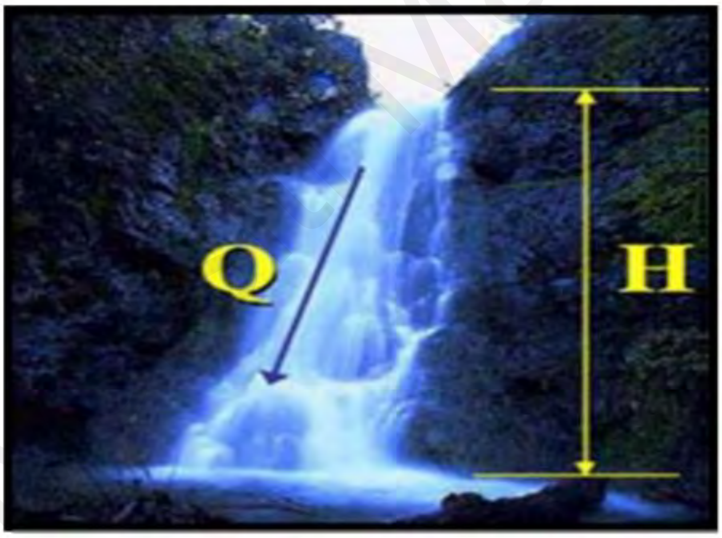


Figure 2.19: Description of flow rate, Q and head, H of a stream.

The hydropower plant's available head is equal to the difference between the water levels in the forebay and the tailrace. Its measured value is dependent on the site's topography and the location of the powerhouse concerning the forebay (Kaunda *et al.*, 2014). H also referred to the water pressure caused by the difference in altitude between the water intake and the turbine (Bavishi & N.K, 2017). It can be expressed as a vertical distance, typically measured in feet or meters, or as a pressure, measured in pounds per square inch (psi) or pascal (Pa).

The net head is the pressure of the turbine when the water is running, and it is frequently lower than the average pressure when the water is turned off (static head) due to friction and turbulence between the pipe and the water. When choosing a hydro location, the site's topography with the most significant fall over the shortest distance is advantageous to the system (Zukhrufiyati *et al.*, 2019). A higher head is usually favoured because power equals the sum of head output and flow. With a taller head, the turbine can operate at higher speeds. This ensures that electricity may be generated even in low-flow circumstances.

The head drop (gross head) value at each point in a water network might vary due to differences in the reservoir or tank water levels and a head loss between particular tanks or reservoirs and each site. There are two sorts of heads to consider when determining the head: gross and net head. The net head is the gross head minus friction and turbulence pressure losses. Reduced pipeline length and twisting in the pipeline can help to avoid pressure losses. However, all water supplies to the home area will be routed through a PRV before delivering to the user. As a result, the pressure head from the meter point (direct) ranges from 25 to 40 m across Malaysia (T. C. Yan *et al.*, 2011). For estimating purposes, the head's mean value should be employed as the construction head.

Since pressure gauges are typically measured in psi or bar, it is necessary to convert to the heads commonly used in pump curves, such as feet or meters. H is the altitude at which a column of water density of 1000 kg/m^3 can be elevated to a specified pressure. Consequently, it is calculable using Equation (2.1),

$$\rho\, h = 1\, bar = 10^5\, Pa \tag{2.1}$$

where ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), and h is the net available head (m). Therefore, in a pipeline, the value of pressure in a bar can be converted to a meter to determine the value of the head, allowing potential energy to be estimated.

2.4.2 Flow Rate

The flow rate (Q) is the amount of water that flows through the system in one unit of time. It is one of the parameters that influence the amount of energy produced. The flow is determined by the hydrology of the reservoir region, which is regulated by climate, temperature, and meteorological conditions. Although flow can be computed from hydrological data, an actual measurement should confirm the anticipated flow for system design purposes. The following techniques are used to quantify the flow quantity in a river as an application: a float, a bucket, salt dilution, and a weir (Kaunda *et al.*, 2014).

Flow is a quantitative measurement of water that is expressed in terms of "volume per time" such as cubic feet per second (ft/s), cubic meters per second (m^3/s), or liters per minute (l/m). The maximum flow for which the hydro system is designed is design flow. Like the net head, the design flow is usually lower than the maximum flow in the streamflow (primarily during monsoon season) but more than the lowest flow, and a compromise between the potential electricity generated and system expenses. As a result, hydropower's potential depends on the flow of water from particular heights in sufficient quantity to operate the turbine and generate electricity from the kinetic energy of water.

The generated power is proportional to the pressure head and water flow rate. The more power generated, the higher the head of water or the faster the water flows through the pipe. The water flow rate is the amount of water that moves across a particular surface per time. Equation (2.2) can be used to calculate it.

$$Q = Av \tag{2.2}$$

where Q is the flow rate (m^3/s), A is the surface area (m^2), and v is the fluid velocity (m/s). As a result, increased water usage would increase the quantity of power generated. There is continuity of flow if steady flow exists in a channel, and the theory of conservation of mass is applied to the system. The Continuity equation is written as:

$$Q = A_1 v_1 \ = \ A_2 v_2 \tag{2.3}$$

where Q is the flow rate (m^3/s), A is the surface area (m^2), and v is the fluid velocity (m/s).

2.4.3 Pipeline

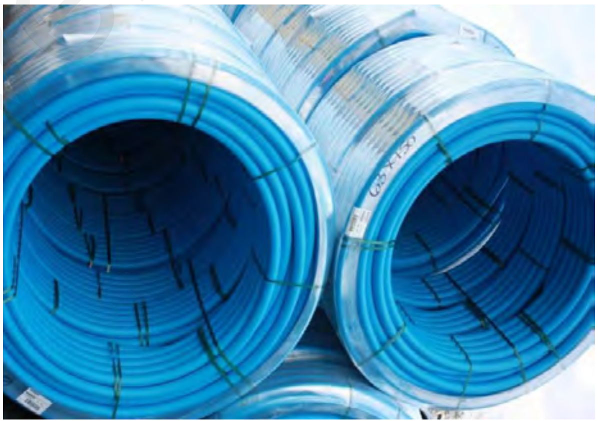
Pipes are one of the most important parts of water networks (for distribution and transportation) since they transfer water from point A to point B to the final consumer. The diameter of the pipes will shrink as the consumption point approaches. The water supply pipeline in a micro hydropower system is in charge of supplying water to the turbines in the system. The vertical drop creates pressure at the lower end of the pipeline, from which the pressured water drives the turbine (Ching *et al.*, 2011). As a result, the pipeline has a significant influence on the pressure of the head. The greater the vertical drop, the greater the concentration of water at the pipeline's rim, where the turbine is installed.

Pipes can be built of various materials and have varying diameters, service connections, and valves. Consequently, the efficiency of the pipeline is also strongly dependent on it. However, the pipe specifications are determined by the ultimate use. A bigger pipeline diameter causes less friction, allowing more power to be transferred to the turbine, even if the cost is too expensive. Pipe sizes are also affected by the location of the water source.

Aside from piping size, another factor is the pipe's material. During the design phase, the pipe's material must be carefully selected. Rust can emerge due to material choices such as steel pipes as they age. As a result, the pipe's conceivable materials are cast iron (CI), steel, polyvinyl chloride (PVC), and glass-reinforced pipes (GRP). Mild steel, high-density polyethylene (HDPE), PVC, and medium-density polyethylene (MDPE) are commonly used piping materials in small conduit hydropower generation systems. Figure 2.20 depicts a description of some distinct pipe materials.


(a) (b)


(c) (d)



(e)

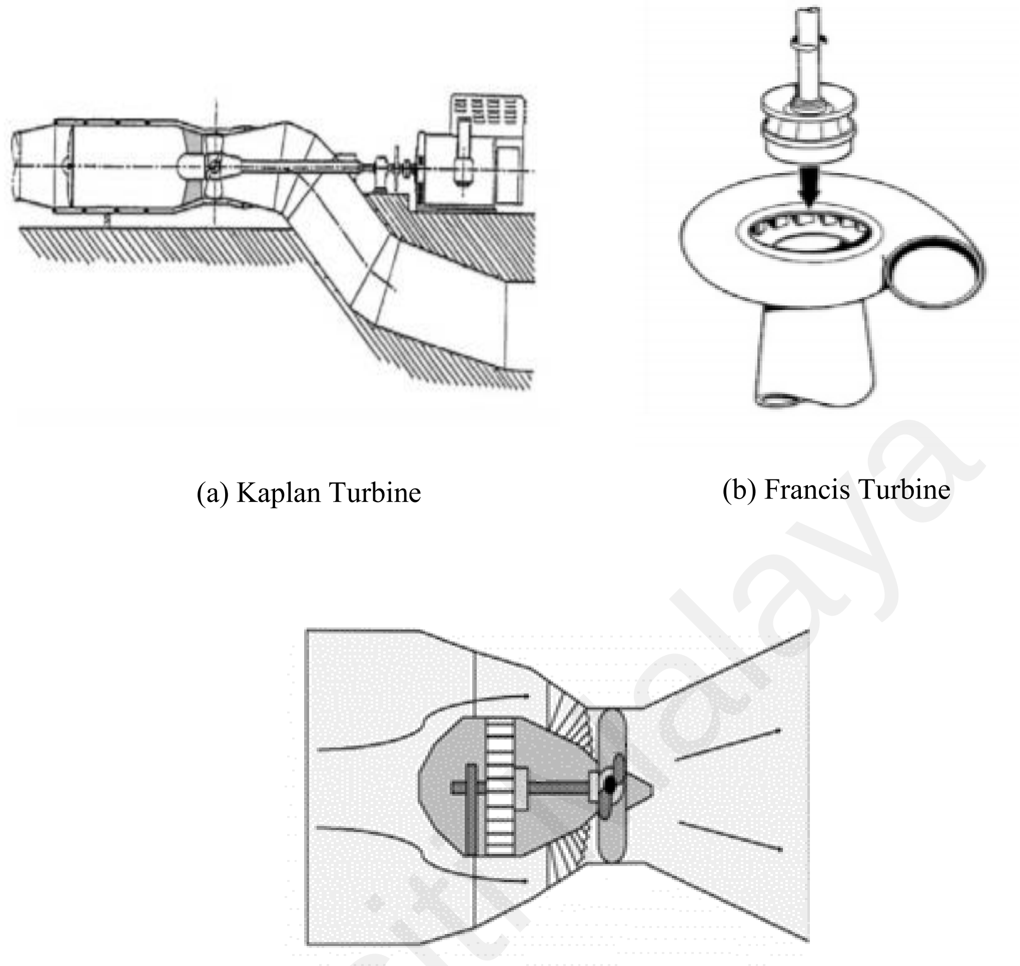
Figure 2.20: Different pipe materials. (a) CI pipe (*C.I Pipes*, n.d.) (b) PVC pipe (*PVC Pipes*, n.d.) (c) GRP pipe (*GRP Pipes*, n.d.) (d) HDPE pipe (*HDPE Pipes*, n.d.) (e) MDPE pipe (*MDPE Pipes*, n.d.).

2.4.4 Turbine

The turbine is the main component of the micro-hydro PG system. It converts water power into rotational force, which drives the generator. Depending on the speed required by the generator, the turbine is either directly connected to it or via gears, belts, and pulleys (Anaza *et al.*, 2017). The turbine is chosen based on the significant characteristics of the head and flow available (Bavishi & N.K, 2017) and the cost of the powerhouse, generating equipment, and relative advantages of energy generation (Yah *et al.*, 2017). A turbine is classified as either a reaction or an impulse turbine, whose various physical principles and properties define it.

A reaction turbine is a vertical or horizontal wheel that runs with the wheel fully immersed, which reduces turbulence. It is propelled by kinetic energy and water pressure created by the head. Although current turbines appear to bear no resemblance to their predecessors, these could be considered the successor of a backshot or overshot wheel. A typical modern reaction turbine is enclosed in a casing, with water coming around from the edges of the casing and entering tangentially from all sides. The casing that feeds the water into the turbine is spiral-shaped to allow twirling to activate the turbine. As the water reaches the turbine, the pressure on the blades reacts, causing them to rotate.

Based on the blade's geometry, the water is thus forced to depart axially. Water is delivered into a conduit known as the draft tube to increase suction to the forces operating on the turbine rotor, allowing more energy to be transferred to the machine. The most common form is reaction turbines. There are several types of turbine reactions, one of which is seen in Figure 2.21. The Francis turbine is the most common, accounting for 80% of all hydraulic turbines. Kaplan turbines are preferred for shallow head cases because they may be employed in practically all conditions.



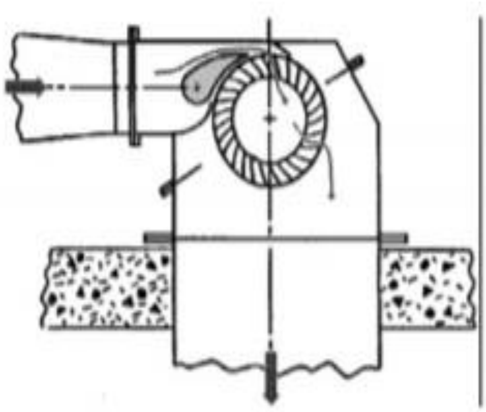
(a) Kaplan Turbine

(b) Francis Turbine

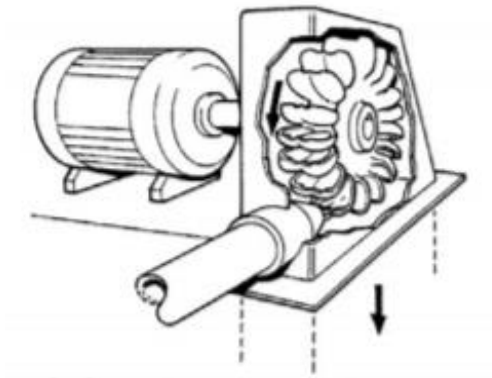
(c) Bulb Turbine

Figure 2.21: Various reaction turbines (Paish, 2002; Sari *et al.*, 2018).

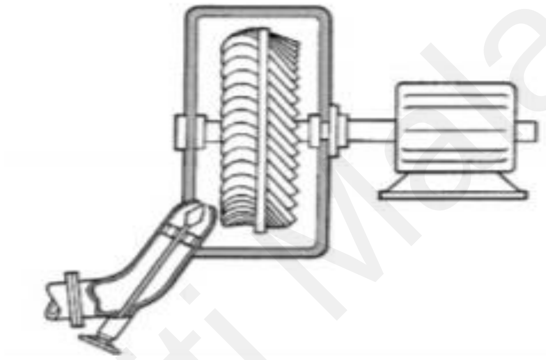
An impulse turbine is another type of turbine that directs high-pressure water to a nozzle and extends it to atmospheric pressure. The developing jet impacts the turbine blades (or buckets), resulting in the required torque and power output. This type of turbine converts energy into kinetic energy before it is transformed into the rotor, making it more suitable for applications requiring a high head and low power. An impulse turbine simply requires a chase to control splashing and guard against mishaps. Because no specific pressure chase is required, this turbine type is typically less expensive than reaction turbines. The Pelton turbine, Turgo turbine, and Crossflow turbine are examples of impulse turbines, as shown in Figure 2.22.



(a) Crossflow Turbine



(b) PeltonTurbine



(c) Turgo Turbine

Figure 2.22: Various impulse turbines (Paish, 2002).

The selection of a turbine for a particular setting is mainly influenced by the head and water flow rate at which it operates (Nasir, 2014). One of the essential parts of hydro turbine planning is the turbine's specific speed. The turbine application chart, shown in Figure 2.23, is typically used to identify a turbine type. As a result, determining the head and flow numbers is critical in determining the appropriate type of turbine to be assigned at the chosen site.

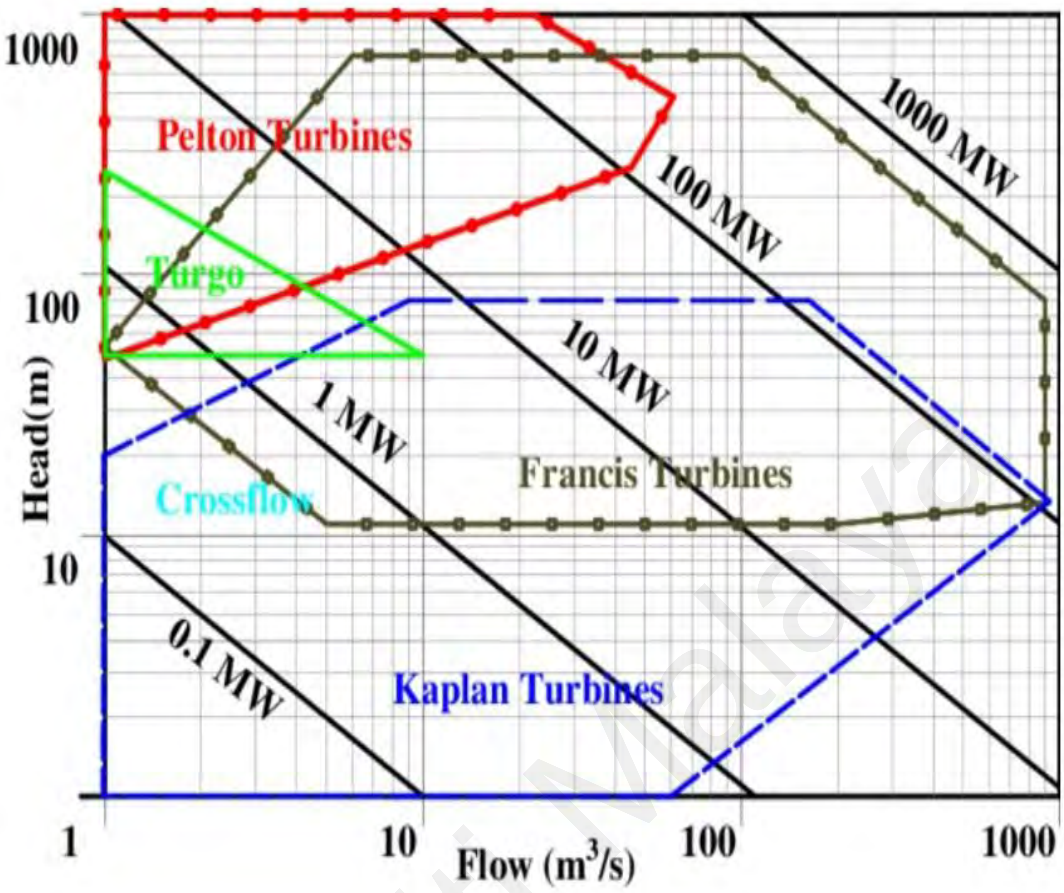


Figure 2.23: Turbine application chart (Chen *et al.*, 2013).

2.4.5 Generator

Following the selection of the turbine type, an appropriate generator must be chosen. A generator is a device that transfers mechanical (rotational) energy provided by the turbine into electric power for an external load (Reyna *et al.*, 2019). The generator's rotor spins as the turbine blades turn, and an electric current is formed as magnets rotate inside the fixed-coil generator to generate electricity (IRENA, 2012).

The selection of a generator depends on several factors, including the form of electricity production, such as frequency, AC/DC, and voltage, the amount of usable electricity, and the cost of the generator. In hydropower, generators convert the kinetic energy of a water turbine's rotation into electricity. It also results in an improvement in efficiency. Nevertheless, well-designed generators can attain an acceptable level of performance with the aid of current technologies.

Two kinds of generators are synchronous and asynchronous generators suitable for hydropower applications, especially on a small scale (Hatata *et al.*, 2019). The synchronous generator's armature winding (usually a three-phase winding on the stator) produces an alternating current. In contrast, the field winding is excited by direct current (generally on the turbine). The primary benefits of the synchronous generator are that it may operate in both grid-connected and independent modes and can provide reactive electricity in any quantity. It is typically favoured for large hydropower units over smaller hydropower facilities.

Meanwhile, asynchronous generators are made up of unwinding turbines. Induction from the stator windings produces the current that travels through it. On average powers, an asynchronous generator is easier to implement, lighter, and less expensive than a synchronous generator, and it is easier to connect with the network. Thus, the system's potential energy, the kind of delivery system, the type of electrical load (fixed or variable), market availability of generation capacity, and the most cost-effective generator all influence the choice of hydropower generators.

2.5 PG Concept

The energy efficiency law will assist in explaining the process of producing energy from water. The flowing water's potential energy is transferred to kinetic energy. The turbine blades will then be rotated by kinetic energy and converted into mechanical energy. Eventually, the turbine shaft will rotate the generator, which will provide electrical energy (Singh & Singal, 2017).

Bernoulli's equation, named after its discoverer, the Swiss scientist Daniel Bernoulli (1700–1782), quantitatively describes the relationship between pressure and fluid velocity. According to Bernoulli's equation, for an incompressible, frictionless fluid, the following sum is constant,

$$P_1 + \frac{1}{2} \rho v^2 + \rho g H = constant \tag{2.4}$$

where P is the absolute pressure, ρ is the fluid density, v is the fluid velocity, H is the height above some reference point, and g is the acceleration due to gravity. If the fluid volume is small along its path, the volume's various values may change, but the volume remains constant. Points 1 and 2 can be referred to as any two points along a path travelled by a bit of fluid, which causes the Bernoulli equation (Qin & Duan, 2017) to become as follows:

$$P_1 + \frac{1}{2} \rho v_1^2 + \rho g H_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g H_2 \tag{2.5}$$

Meanwhile, pressure gauges are often used to measure pressure in a pipeline that gives value in psi or bar. It is essential to convert the heads widely used in pump curves, such as feet or meters. Hence, it can be determined using the previously described Equation (2.1). Their available power can be used to evaluate the hydropower resources. The hydropower potential can be calculated by multiplying the head by the total available flow and a conversion factor. The most effective turbines can achieve hydraulic efficiencies of 80 to 90% (more significant than most other primary movers); however, this decreases with increasing size (Paish, 2002). Microhydro systems are typically 60 to 80% efficient (Chae *et al.*, 2015), while current modern turbines extract 90% of the available energy (Akpinar, 2013). Therefore, the following equation can be used to compute the hydraulic power produced by the water flow:

$$W_{Hy} = \rho g Q H \ (Watt) \tag{2.6}$$

where W_{Hy} is hydraulic power (Watt), ρ is water density (1,000 kg/m^3), g is gravity acceleration (9.81 m/s^2), Q is the flow rate (m^3/s), and H is meter head (mH) or pressure.

Aside from hydraulic power, mechanical power also needs to be considered. The rate at which work may be performed is mechanical power. The mechanical power can be calculated using the turbine's rotation per minute and torque. This equation is used to determine mechanical power:

$$W_{Mech} = \frac{2\pi N\tau}{60} \tag{2.7}$$

where W_{Mech} is mechanical power (Watt), τ is torque (Nm), and N is turbine rotational speed (RPM).

According to the formula, the quantity of energy generated is dependent on the water's height and the volume of water flowing each second. Therefore, the greater the water velocity in the turbine, the more energy is generated. Newton's equation states that the hydropower generation system will create no electricity if these two components are absent. Therefore, it can be stated that water power comprises two key elements: head and flow. Multiplying the generated power by the projected number of operating hours yields the annual electricity output (Patro *et al.*, 2020). Therefore, the value of a hydropower plant's annual energy production can be computed using the following formula:

$$P = Et \tag{2.8}$$

where E is the energy generation (kWh/year), and t is the operating hours in a year.

2.6 TRLs

TRLs are a system developed by NASA in the 1970s to assess the maturity of technologies throughout the programme acquisition phase. TRLs provide consistent and uniform dialogues about technical maturity across numerous forms of technology (Héder, 2017). A Technology Readiness Assessment (TRA) examines programme concepts, technology needs, and demonstrated capabilities to determine the TRLs. TRLs are ranked from 1 to 9, with 9 signifying the most advanced technology. The summary level of hydropower in TRLs is shown in Table 2.3.

Table 2.2: Hydropower level in TRLs (Rose *et al.*, 2017).

Level	Guidance	Description
1	Basic principles observed	Basic research. Principles are postulated and observed, but no experimental proof is available
2	Technology concept formulated	Technology formulation. Concept and application have been formulated
3	Experimental proof of concept	Applied research. First laboratory tests complete; proof of concept
4	Technology validated in lab	Small scale prototype built in a laboratory environment ("ugly" prototype)
5	Technology validated in lab	Large-scale prototype tested in the intended environment
6	Technology demonstrated in a relevant environment	Prototype system tested in an intended environment close to expected performance
7	System prototype demonstration in the operational environment	Demonstration system operating in the operational environment at the pre-commercial stage
8	System complete and qualified	First of a kind commercial system. Manufacturing issues solved
9	The actual system is proven in the operational environment	Complete commercial application, the technology available for consumers

2.7 Summary

Emphasis on the study of hydropower, especially in-pipe hydropower was discussed. There are important elements that need to be considered in the hydropower system to ensure that energy can be generated optimally. Some existing technologies related to in-pipe hydropower that involve industry and water suppliers also have been discussed in this chapter. Emphasis on design and features is crucial.

However, the study of hydropower in pipes is still relatively new in our country. If this system is implemented hydropower in the pipe will not only benefit water suppliers, it will also create more awareness of untapped renewable energy as a new source of clean energy.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This research was carried out to develop and observe the performance of an IPHS with PG40. It acknowledges the IPHS's readiness with PG40 towards TRLs 6 in the appropriate environment. In this chapter, the performance of hydropower generation was observed and recorded using a laboratory test. Both hydrodynamic (pressure and flow rate) and mechanical (rotational speed and torque) conditions were varied during the tests (Postacchini *et al.*, 2020). It will provide valuable hints for possible real-world applications.

3.2 Study Flowchart

A flow chart has been created to aid in the execution of this research. Figure 3.1 depicts the research flowchart. This research can be divided into three sections that will cover all of the research objectives. This chapter will cover the first and second research objectives, while the third research objective will be covered in the following chapter based on the outcome of the experiment.

The design is reconstructed from a previous study conducted by Abdullah *et al.* While his research focused on the conceptual design and preliminary experiments of a novel in-pipe hydropower vertical axis parallel turbine using PG 20, this research focuses on the performance evaluation of an in-pipe hydropower system with vertical axis parallel turbine using PG40. After completing the design and the prototype, several tests will be performed. The performance test of the prototype is observed as a second part of the objective during the experiment. All necessary data will be collected, including water flow, pressure at selected points, turbine rotational speed, and torque.

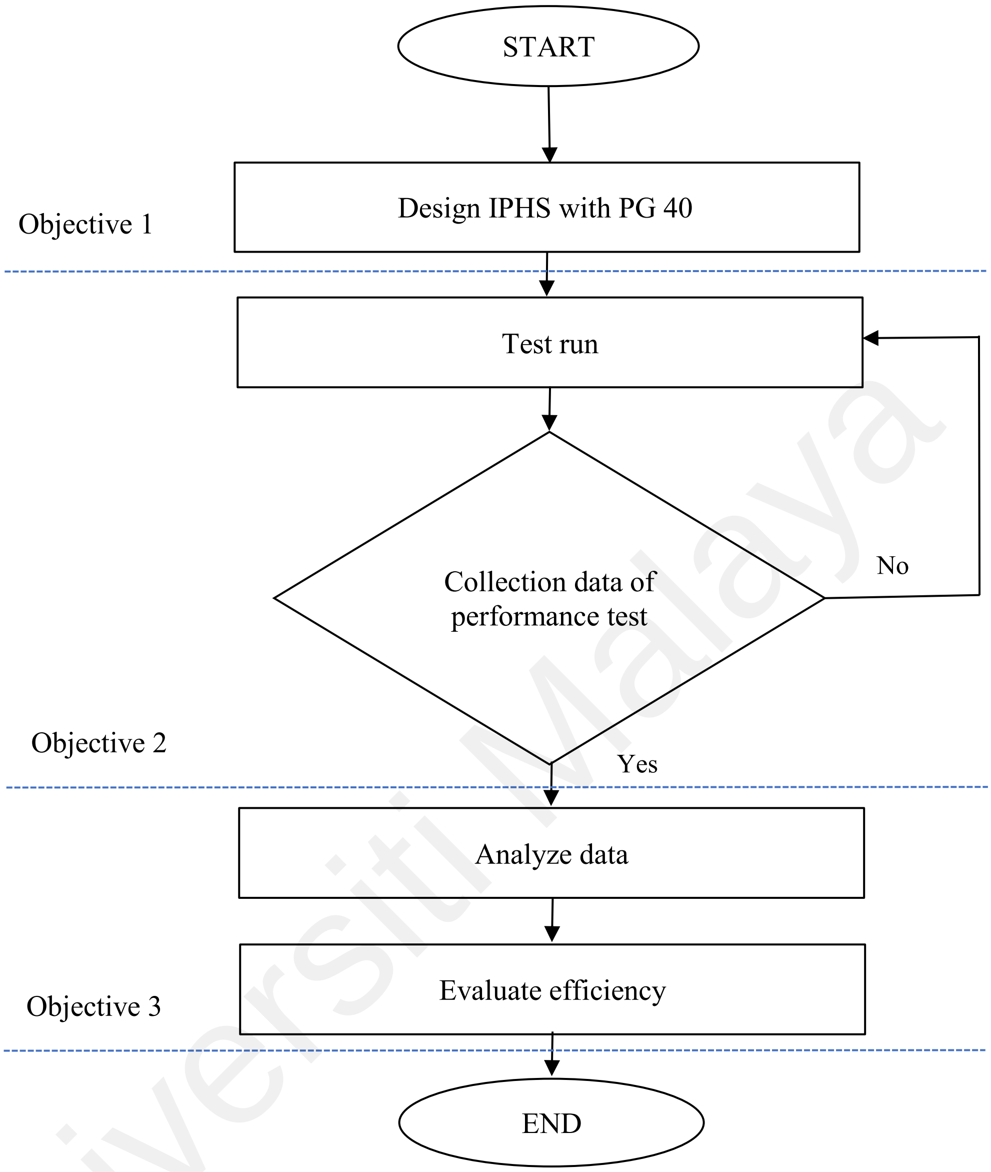


Figure 3.1: Study flowchart.

Data analysis and efficiency evaluation in terms of mechanical power and pressure loss inside the pipe are performed with this system. Its purpose is to ensure that the prototype is ready for use in the appropriate environment according to TRLs 6.

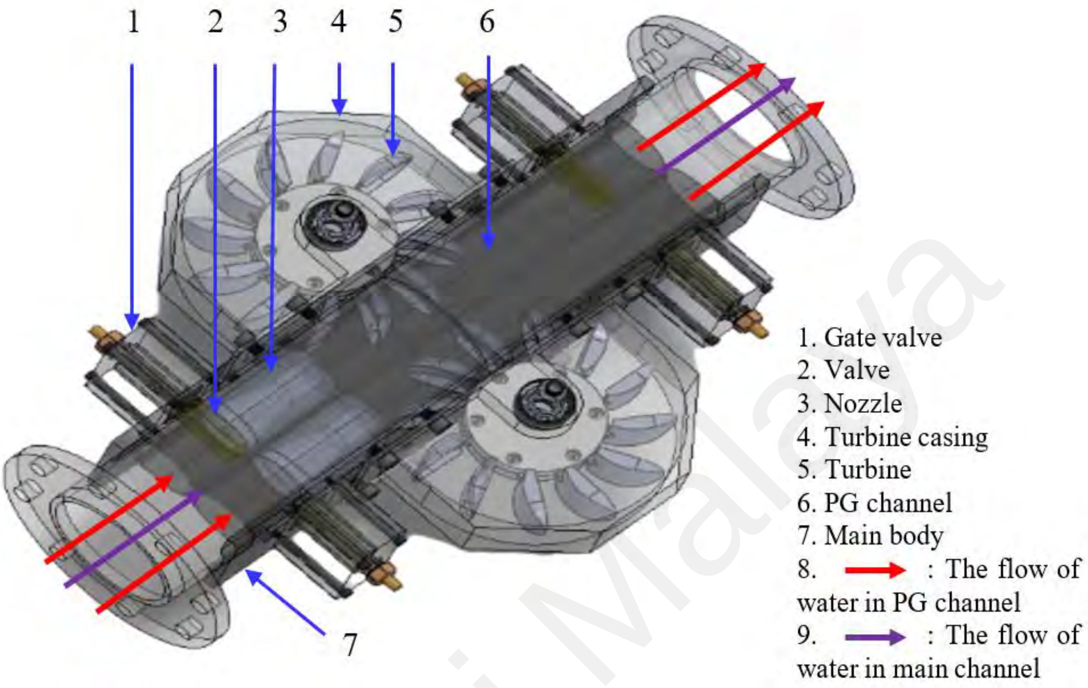
3.3 Prototype Design

The lab experiment used an in-pipe hydropower vertical axis parallel turbines prototype system with PG40. It is a system that consists of two vertical turbines that are symmetrically positioned parallel to each other. As previously stated, this study was built on the work of Abdullah *et al.* (2021). Therefore, the prototype's design was nearly identical to the previous study. Table 3.1 compares this study to Abdullah *et al.* (2021). The PG channel size was the most significant modification in the study. The size was changed to maximise the amount of power harvested. The maximum diameter that can fit into the main pipe was used to calculate the PG channel size. Other prototype parts were designed to fit the PG size.

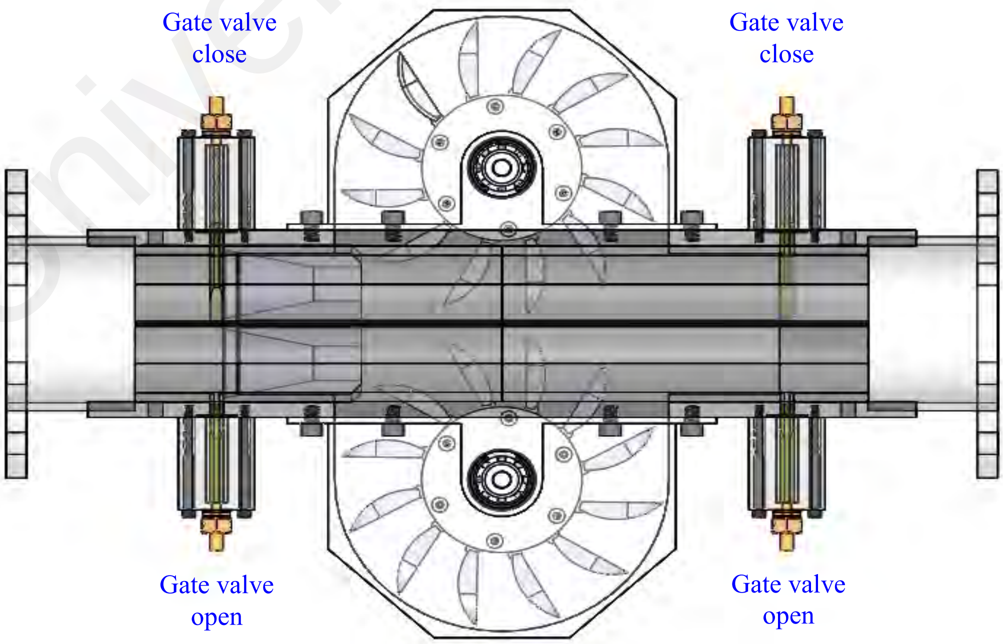
Table 3.1: Design comparison between the current study and a previous study conducted by Abdullah *et al.*, (2021)

Prototype part	Prototype	
	P20	P40
Main body	aluminium	mild steel
PG channel	10% each (total 20%)	20% each (total 40%)
Turbine size	Suit according to PG size	
Nozzle	Suit according to PG size	
Valve	no physical gate valves in the prototype	4 installed (2 at each PG channel at inlet and outlet)

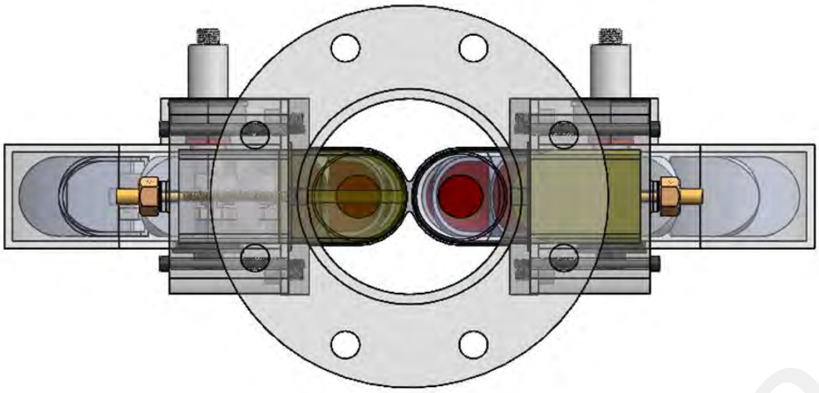
The schematic design of the system is shown in Figure 3.2. Water flowing through the pipe is divided into the main channel and two PG channels that valves can control. Each of the PG channels will consume 20% of the flowing water, for a total of 40%, with the remaining 60% flowing continuously in the main channel. Because the PG channel size differs from the previous study, the turbine, nozzle, and valve size will be designed to fit the PG channel size.



(a) 3D view



(b) top view



(c) front view

Figure 3.2: Schematic diagram of P40. (a) 3D view, (b) top view, and (c) front view.

As with most in-pipe hydro systems, the turbine design and location are almost identical to the pipe. This is done to harvest as much energy as possible. However, if the system requires service or maintenance, they must turn off the water to complete the work (Abdullah *et al.*, 2021). Hence, a bypass pipe must be added to counteract an uninterrupted water supply. It also requires additional space for the installation of the bypass. This will increase the cost of installation in some way.

Therefore, this design intends to circumvent the issue where the system is built-in together and installed without a bypass system at the main pipeline. It is the essential element of this design. This makes the system applicable, particularly in urban areas. When service or maintenance is required, gate valves will be closed to prevent water from entering the PG channel. At the same time, water can continue to flow uninterruptedly in the main channel. Since the system is integrated with two flow channels, only a portion of the water that flows through the PG channel is used to generate energy. The PG's excessive pressure is utilised for this purpose. For instance, if the water pressure is excessive by 40%, only 40% of the water flow will be channeled into the PG channels, resulting in a 20% reduction per PG channel. The remaining 60% of the water flow continues uninterrupted in the main channel.

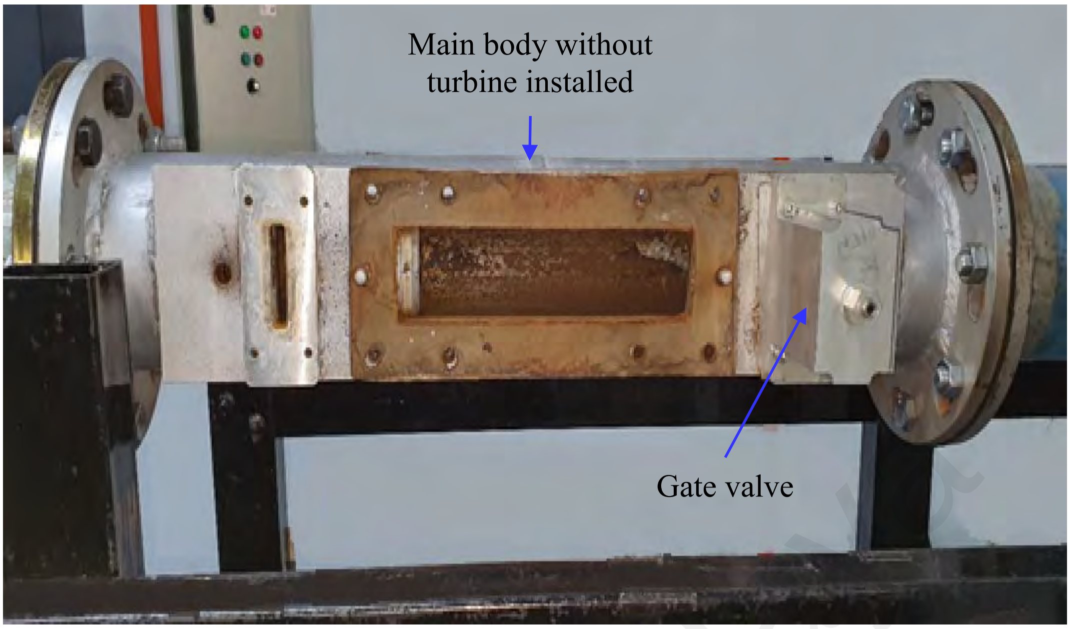
Typically, water flow in the existing water distribution network is regulated by a PRV. The PRV will be widely opened when water demand increases, allowing more water to flow while reducing excess pressure (Dawadi & Ahmad, 2013). Depending on water usage, the amount of additional pressure in the pipe may vary. The system can adapt quickly to fluctuating demand using two parallel turbines. This is why the prototype in this study utilises two smaller turbines instead of a giant turbine. Another benefit of a dual-turbine system is that electricity is always available, even if one turbine fails. This is essential for energy-intensive processes. In addition, it will require an expensive backup solution, such as energy storage (Wood *et al.*, 2015).

3.4 Prototype Parts

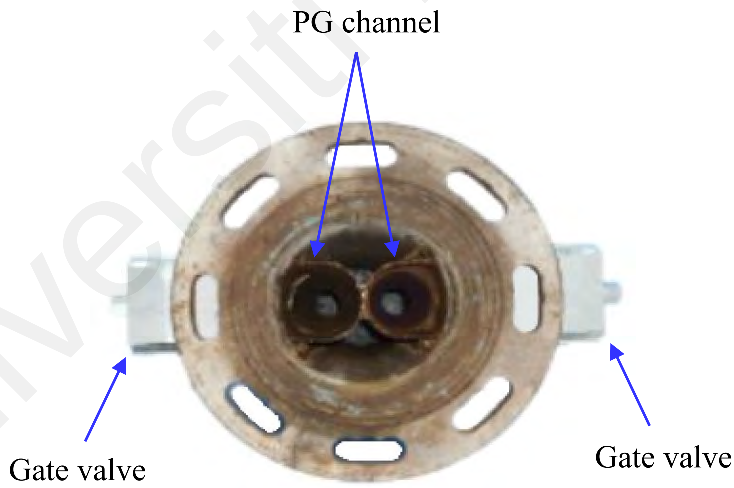
This section will explain several prototype parts. The prototype consists of several components: the main body, turbine, nozzle, and valve. The schematic diagram of the components can be referred to Figure 3.2 (a).

3.4.1 Main body

The diameter of the main body is 5 inches (127 millimeters). Body and PG channels are both made of mild steel compared to aluminium from the previous study. Alumunium considers a soft metal with relatively low density. Mild steel is selected due to its low carbon content, chosen for its long lifespan, maximum yield strength, and moderate cost. Mild steel is widely used for general applications. Figure 3.3 illustrates the actual appearance of the main body. Figure 3.3 (a) is a side view of the prototype illustrating the turbine attachment to the main body, while Figure 3.3 (b) depicts the top view of the main body where two PG channels are welded together.



(a) Side view



(b) Top view

Figure 3.3: Main body actual image.

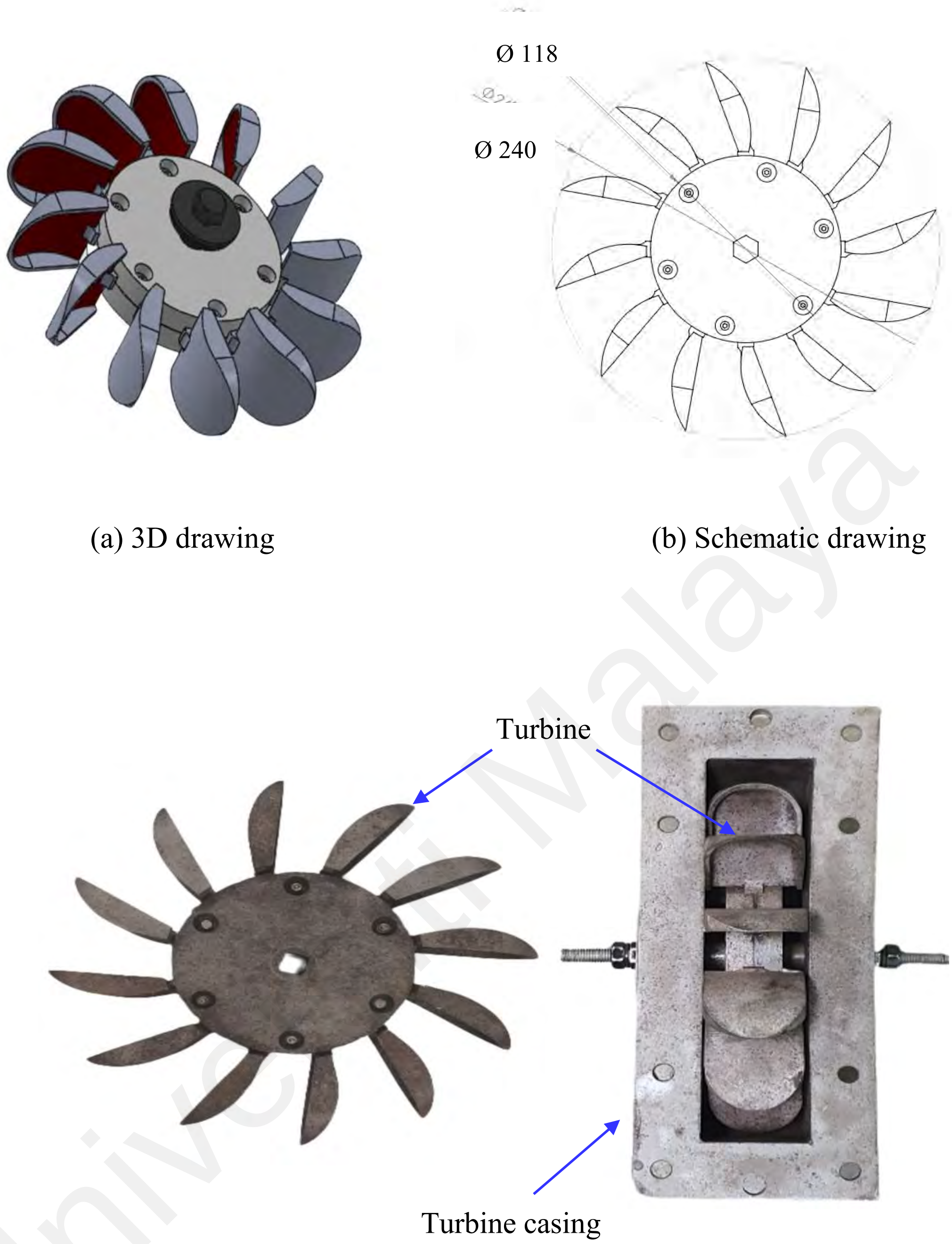
3.4.2 Turbine

This experiment employs a turbine with 12 blades at 60 degrees towards the injection nozzle. The selection of turbine blades and the degrees towards the injection nozzle is made based on the conceptual design from the previous study by Abdullah *et al.* A shaft holds the blades, then is inserted into the housing and tightened together. Output shaft power can be calculated from the following equation,

$$W\,\text{shaft} = \rho r\omega V(vj - r\omega)(1 - \cos\beta) \quad (3.1)$$

where ρ is the fluid density (kg/m^3), rω is the velocity of the blade at radius r (m/s), V is the volumetric flow rate (m^3/s), vj is the tangential velocity (m/s), and $\cos\beta$ is the blade angle (radian).

The turbine's blades and casing are composed of mild steel. Since the size of the PG channel has been increased, the size of the turbine, including the blades, has increased as well. This is because turbine size is one of the factors that affect the efficiency of the system (Sritram & Suntivarakorn, 2021). Higher power output can be generated when a higher resistance force (torque) is applied to the turbine as the turbine size increases. Since this study is an extended study with a modification of the diameter of the PG channel, it is estimated that more power will be generated (Power *et al.*, 2015). This assumption is related to Equation (2.7). The 3D schematic drawing and the actual image of the turbine are displayed in Figure 3.4.



(a) 3D drawing

(b) Schematic drawing

(c) Actual image

Figure 3.4: Schematic drawing and actual image of the turbine.

3.4.3 Nozzle

The nozzles are constructed with PG channels to increase the water's velocity. It also helps to effectively project water onto the turbine blades, allowing them to rotate more efficiently. The nozzle used in this experiment is constructed from Polylactic Acid (PLA). PLA is utilised because it offers greater strength and stiffness than acrylonitrile butadiene styrene. It is manufactured using a 3D printer. This research modifies the design of the nozzle based on a previous study. Figure 3.5 depicts a schematic illustration of the nozzle.

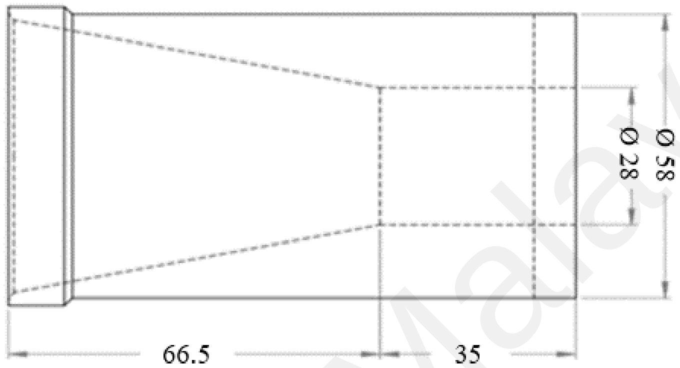


Figure 3.5: Schematic drawing of the nozzle.

3.4.4 Valve

Knife-shaped valves were installed before and after the PGs and the system. The prototype valve was constructed from two different materials. The knife was brass, while the casing was crafted from aluminium. Due to its superior machinability and corrosion resistance, brass is commonly used in valve applications. As a result of its low cost and lightweight, aluminium was chosen to construct the valve casing. The valve was installed to prevent water from entering the PG channel if it required service or maintenance. This will ensure uninterrupted water flow in the primary water channel as this function requires no bypass pipe, unlike other turbine installations. Figure 3.6 depicts the actual valve within the casing.

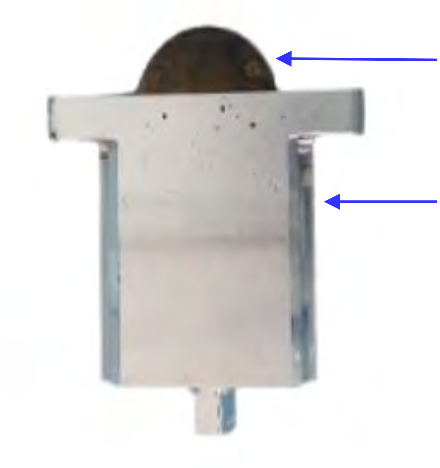
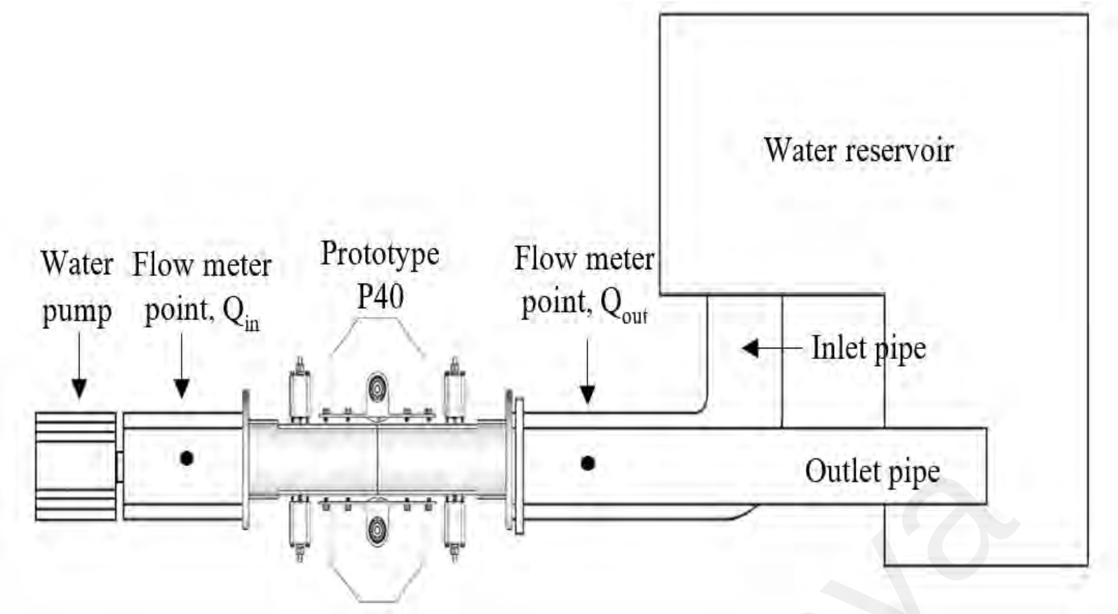


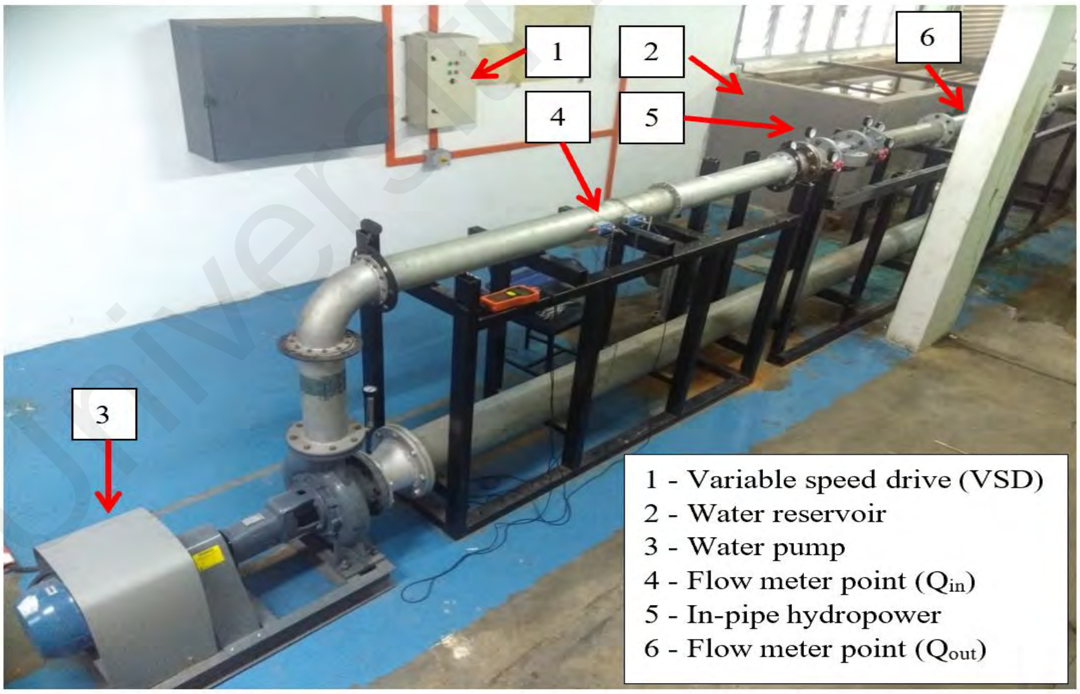
Figure 3.6: Actual image of the valve.

3.5 Experimental Testing Rig

A test rig is constructed to simulate the actual flow characteristics of a real-world application. The rig is connected to an 8-m^3-capacity concrete water reservoir pumped by a 7.4-kilowatt motor from a pump inlet with an eight-inch-diameter pipe to a five-inch-diameter pipe (pump outlet). The water will return to the reservoir after passing the P40 system. Figure 3.7 depicts a schematic diagram and actual image of the continuous process, while Figure 3.8 illustrates the actual appearance of the prototype.



(a) Schematic diagram of the experimental test rig



(b) Actual diagram of the experimental test rig

Figure 3.7: Schematic and actual experimental test rig.

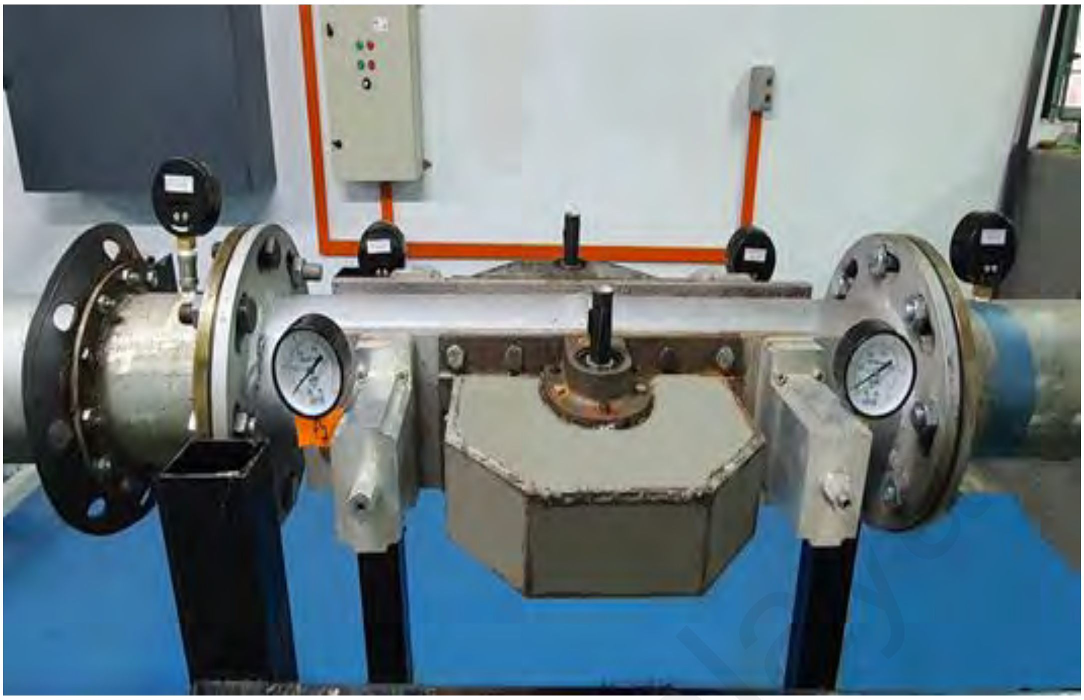


Figure 3.8: Actual prototype image.

3.6 Experiment Implementation

It is necessary to observe the performance of an in-pipe hydropower prototype with PG40 to achieve objective number two. Experimentation was conducted under two conditions: controlled experiment (without prototype) and actual performance with prototype installed. As depicted in Figure 3.9, pressure sensor points were installed to measure pressure at critical locations.

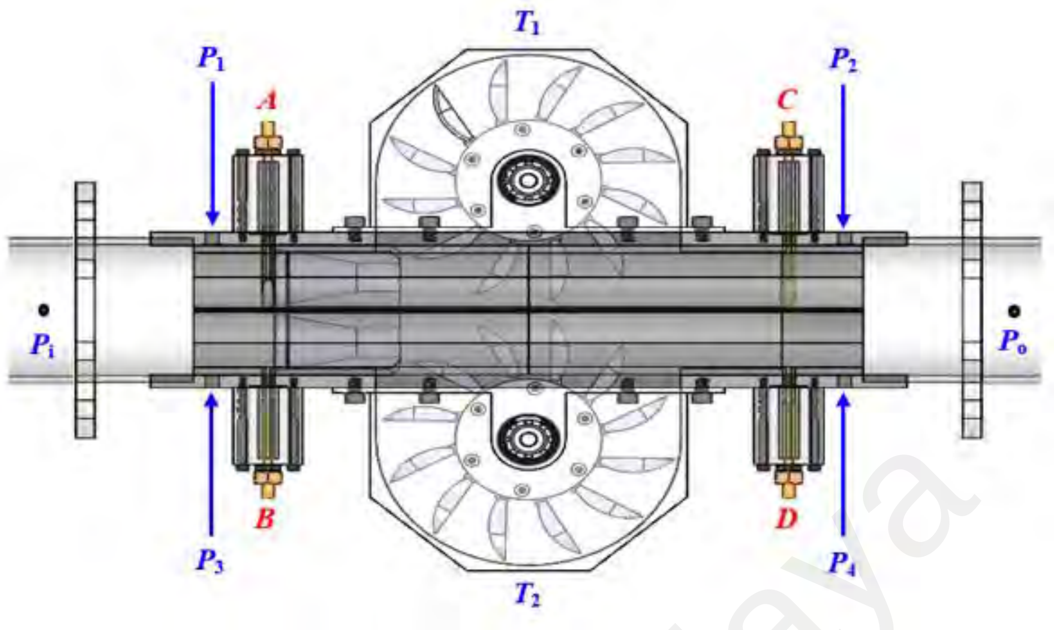


Figure 3.9: Position of pressure sensor point.

The experiment was carried out under two conditions:

(i) Controlled condition

Flow rates, $Q_{in,}$ and Q_{out} were measured when the 5-inch | 127 mm pipe was fully opened during the controlled experiment. Pressure readings at P_i were also taken when the pipe was fully closed. This was done to compare the pump's actual real performance and the water flow without the system to the specifications given in the pump manual. The actual or effective water pressure at a given flow rate can be calculated using the following equation, which considers the pressure created by friction between the water and the pipe wall:

$$\text{Effective Pressure } (P_{eff}) = P_{st} - P_{op} \tag{3.2}$$

(ii) Performance test

During the performance test, pressures at different points (P_i, P_1-P_4, and P_o), turbine rotational speeds, and turbine torques readings were taken at different flow rates, Q_{in}, and Q_{out} when valves at PGs were open. Pressure at different points concerning various flow rates was considered when valves at PGs were closed to test the valve at PGs channel functionality. Therefore, the effective pressure of the P40 prototype (P_{40eff}) at the specified flow rate is determined from the following relation;

$$P_{40eff} = P_{40} - P_{op} \tag{3.3}$$

Subsequently, the following equation can be used to calculate the effective pressure loss caused by the installation of the P40 prototype;

$$P_{40-losseff} = \frac{P_{40eff}}{P_{eff}} \times 100\% \tag{3.4}$$

where $P_{40\text{-}losseff}$ is the effective pressure loss.

Therefore, the mechanical power generated by the turbines and the pressure loss caused by the installation of P40 can be calculated using the data collected.

3.7 Summary

In this chapter, the research methodology was described. The flowchart, which serves as a guide to ensure the process is followed correctly, was also described. This chapter discusses the development of the prototype design and its parts. The experiment was done with two conditions, controlled condition and performance condition.

Data measurement of water flow rate, power pressure, turbine rotational speed and torque was recorded. The experiment results will be summarised and discussed in the following chapter. Overall, the experiment went well indicating that the design was acceptable.

CHAPTER 4: RESULTS & DISCUSSION

4.1 Introduction

In this chapter, the experimental results will be presented. As mentioned earlier, this chapter will do data analysis and evaluate the efficiency in terms of electricity generated and pressure loss inside the pipe with this system. Discussions related to the results of this research are also described in this chapter. By this, the second and third objectives of the research will be covered.

4.2 P40 Flowing Testing

4.2.1 Controlled Environment

Effective pressure (P_{eff}) can be calculated using Equation (3.2) based on data from the experiment. The relationship between the pressure at P_i (P_{op} – when the pipe is fully opened) and the flow rate (Q_{in}) is illustrated in Figure 4.1. In general, as the flow rate increases, the pressure also increases. However, the increases in the pressure are almost not detected at the flow rate below 0.03 m^3/s. A clear increase in pressure is only detected after a flow rate of more than 0.04 m^3/s, and it reaches a maximum value of 0.16 ± 0.01 bar at a maximum flow rate of 0.076 ± 0.000 m^3/s. The P_{op} refers to the pressure that is created from the friction between water and the pipe wall. Figure 4.1 also shows the relationship between the pressure at P_i and the flow rate (Q_{in}) when the pipe is fully closed (stagnation pressure, P_{st}). The pressure increases substantially with the flow rate and reaches a maximum pressure of 1.25 ± 0.03 bar at the highest flow rate. P_{eff} was also shown here and was expectedly lower than the stagnation pressure.

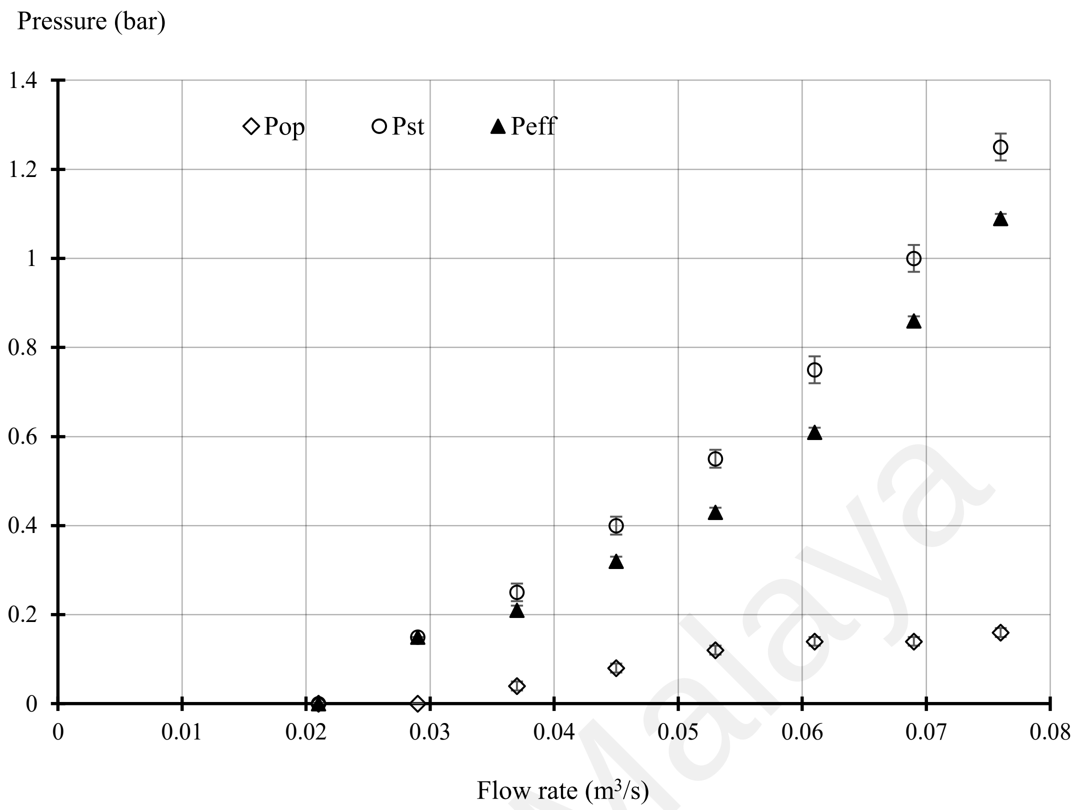


Figure 4.1: The relationship between the pressure and the flow rate.

Based on the pressure value, hydraulic power can be calculated using Equation (2.6). The relationship between the hydraulic power and the flow rate based on P_{st} and P_{eff} is shown in Figure 4.2. At the highest flow rate, the maximum stagnation power (W_{st}) was 9.32 kW while the effective power (W_{eff}) was 8.13 kW.

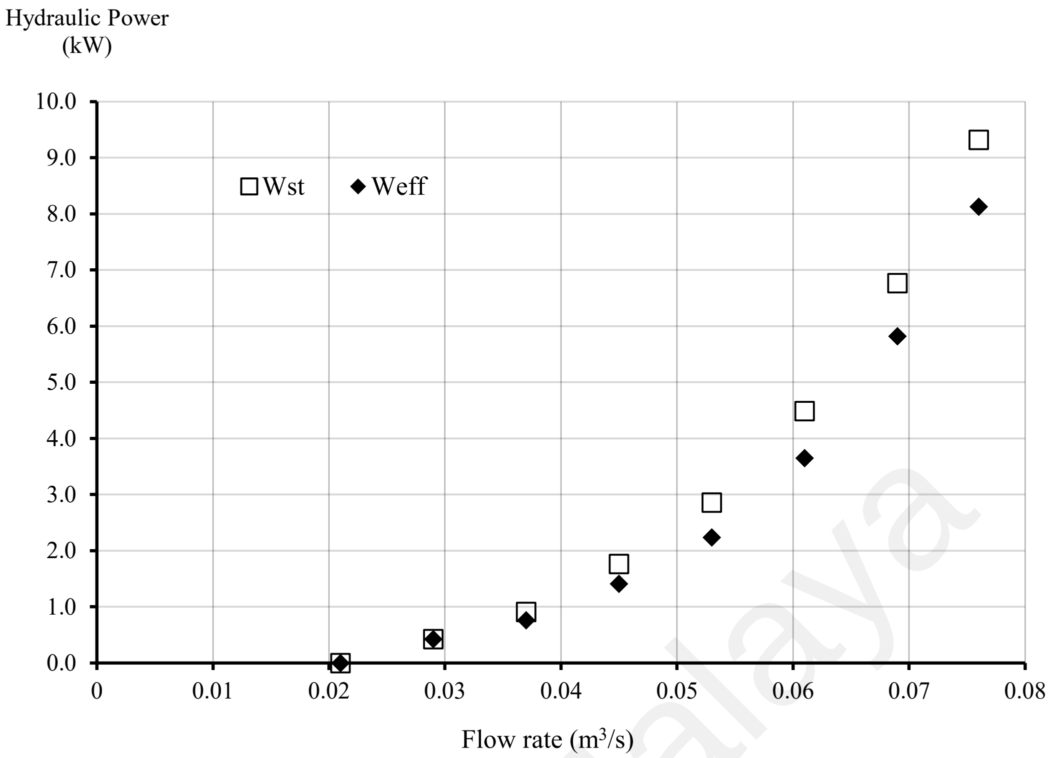


Figure 4.2: The relationship between the hydraulic power and the flow rate.

4.2.2 P40 Flow and Pressure Characteristics, Performance and Reliability Test

4.2.2.1 P40 Flow and Pressure Characteristics

The performance of the PG 40 prototype is discussed in this section. The effective pressure (P_{40eff}) of the P40 at the specified flow can be determined using Equation (3.3). Figure 4.3 illustrates the relationship between the pressure (P_{40} and P_{40eff}) and the flow rate. From the figure, a clear increase in pressure is recorded even at a flow rate of slightly below 0.03 m^3/s. At the maximum flow rate condition, the P_{40} reaches a pressure of 0.43 ± 0.01 bar. Also, at the maximum flow rate, the P_{40eff} gives a value of 0.27 ± 0.00 bar.

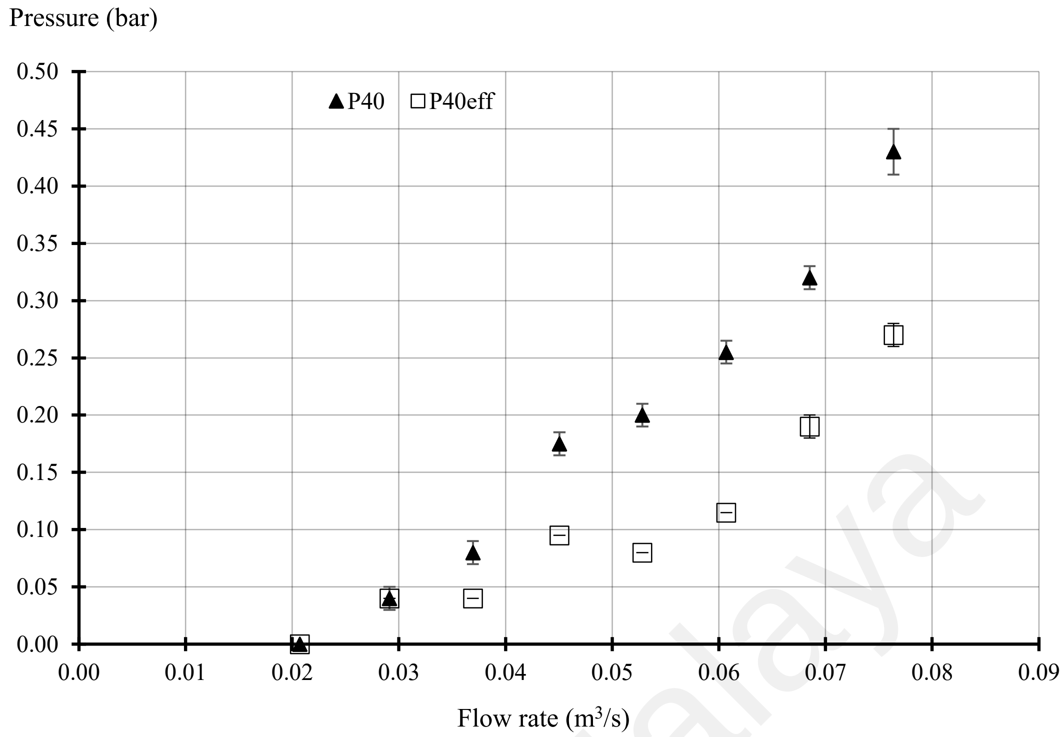


Figure 4.3: The relationship between the pressure (P_{40} and P_{40eff}) and the flow rate.

Comparisons between the P_{40eff} and P_{eff} recorded previously are shown in Figure 4.4. The results indicate that the placement of the P40 prototype in the pipe causes a certain amount of flow resistance and loss of pressure.

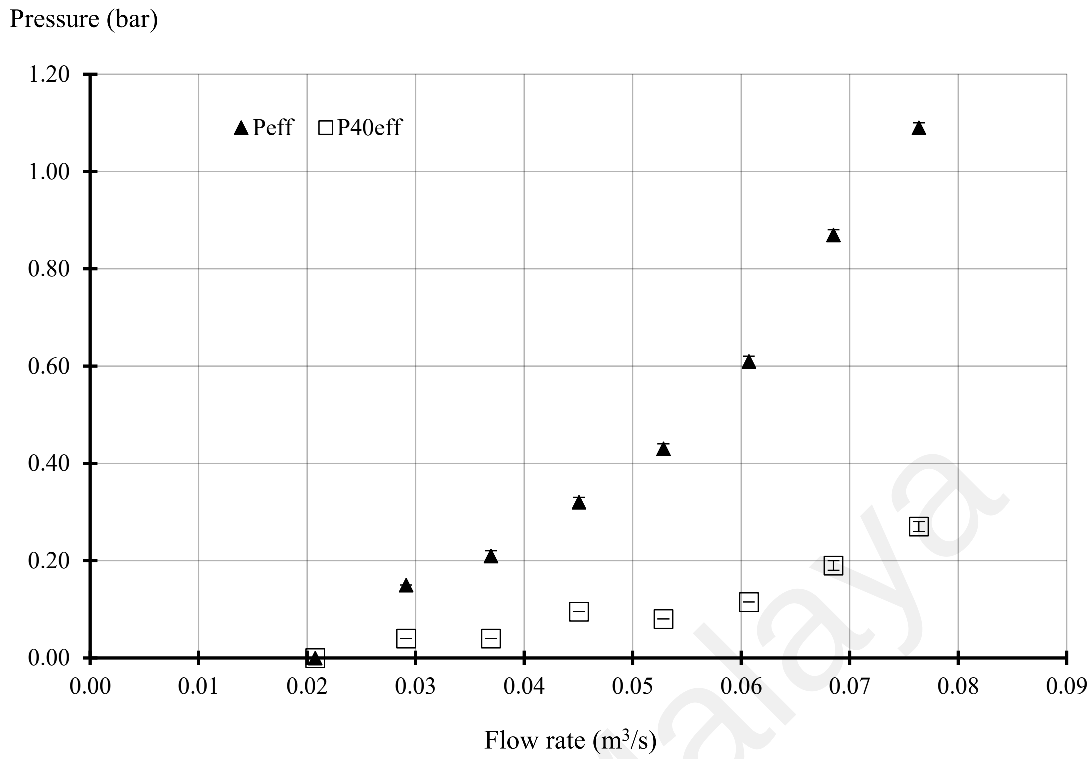


Figure 4.4: The relationship between the pressure loss (P_{eff} and P_{40eff}) and the flow rate.

The effective pressure loss ($P_{40\text{-}losseff}$) due to the installation of P40 can be calculated using Equation (3.4). The relationship between $P_{40\text{-}losseff}$ and flow rate is shown in Figure 4.5. The pressure loss as a percentage reduces drastically as the flow rate increases from 0.02 to 0.03 m^3/s. It stabilises after that, and at the maximum flow rate, the value is around 24.8%. That is to say, the P40 absorbs roughly 24.8% of the water pressure at its maximum flow rate.

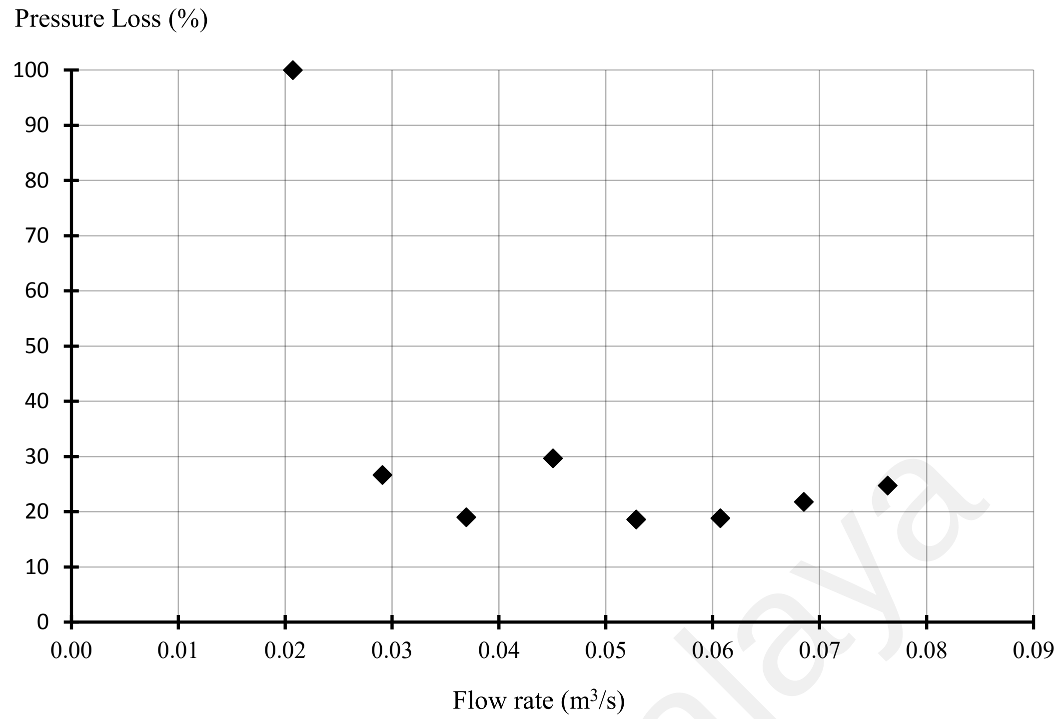


Figure 4.5: The relationship between the effective pressure ($P_{40\text{-losseff}}$) and the flow rate.

Figure 4.6 shows the relationship between effective pressure ($P_{40\text{-losseff}}$) and flow rate. The pressures at both points increase with the flow rate and show almost the same values and trends. At the maximum flow rate, pressures at P_1 and P_3 are 0.60 ± 0.02 bar and 0.58 ± 0.02 bar, respectively. The results suggest that the conditions in both PG channels are practically the same. At all flow rates, the pressures at P_3, P_4, and P_o are close to zero.

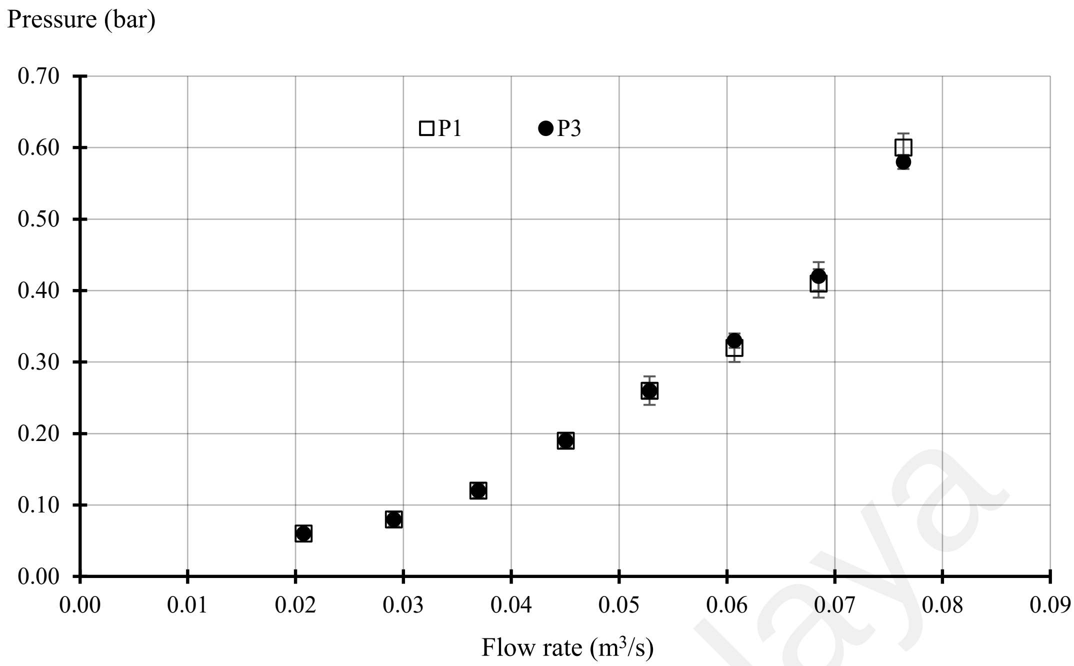


Figure 4.6: The relationship between the pressure and the flow rate with valves opened.

4.2.2.2 P40 Performance Test

The relationship between the RPM and the flow rate is shown in Figure 4.7. The RPM values of both turbines increased with the flow, operating at nearly identical speeds. The RPM values ranged from 87 to 480, with almost similar pressures in both PG channels (Figure 4.6). The RPM data indicated that both turbines were approximately identical in terms of their size, shape, and setup.

The relationship between turbine RPM with torque is shown in Figure 4.8. The minimum torque of 0.45 Nm is exerted by the turbines starting at around 87 RPM. The torque then gradually increases with the RPM, reaching a maximum torque of 6.03 Nm at around 480 RPM. Even though the P40 turbine size in this study was bigger compared to the of Abdullah *et al.*, the RPM value in both cases was almost similar. However, P40 torque shows a higher value compared to P20. This is because a higher resistance force was needed to stop the larger blade surface area compared to the smaller blades. The amount of torque required to turn on the generator is proportional to the power as in

Equation (2.7). This causes the mechanical power to increase. This proves that P40 can generate more energy compared to P20.

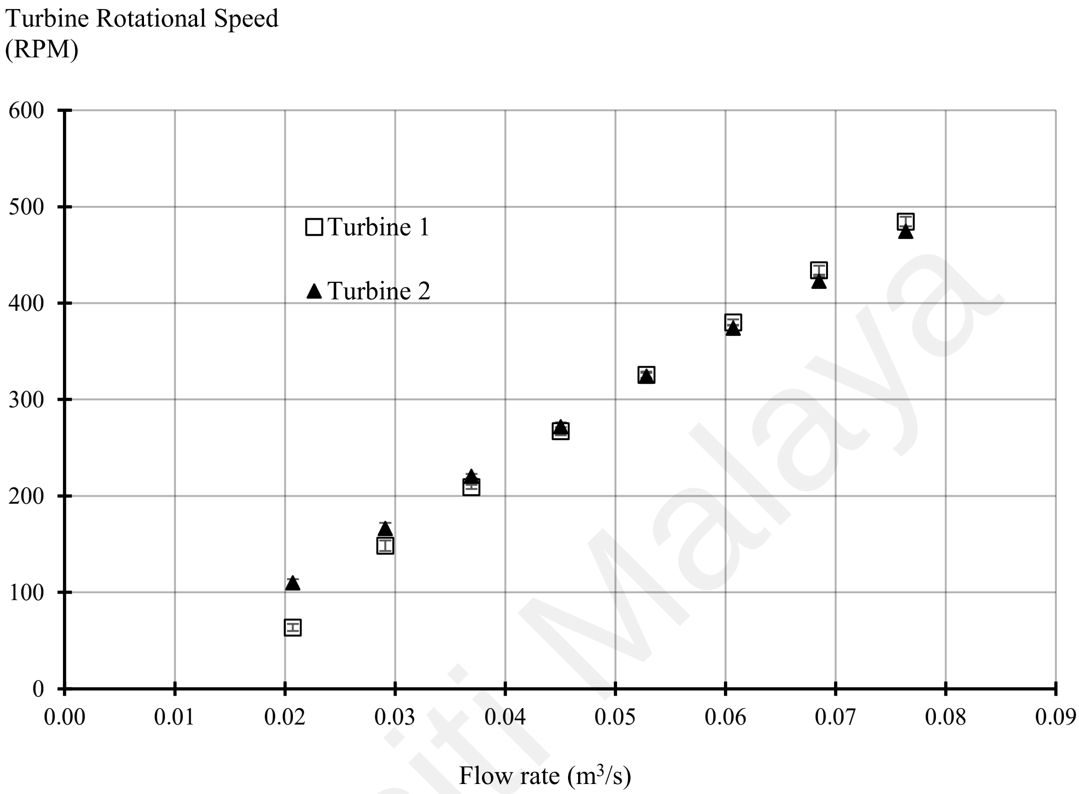


Figure 4.7: The relationship between the turbine rotational speed and the flow rate.

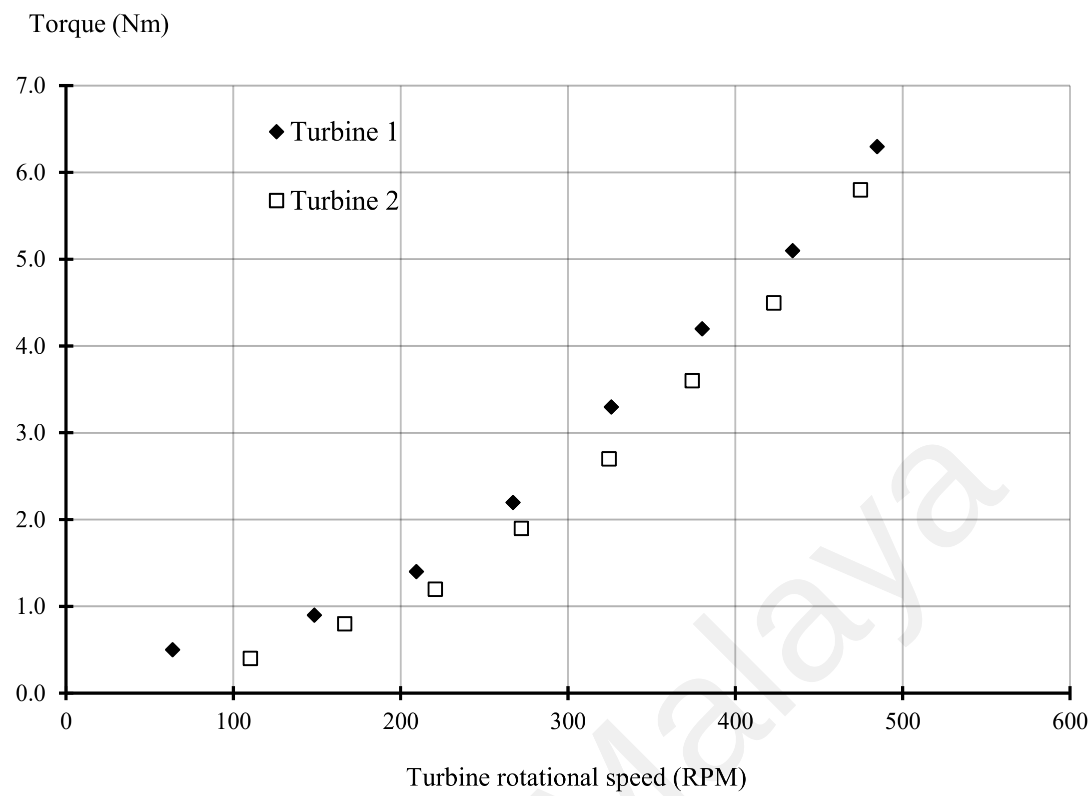


Figure 4.8: The relationship between the torque and the turbine rotational speed.

4.2.2.3 Mechanical Power Conversion

The result of the mechanical power at different flow rates is shown in Table 4.7. Mechanical power can be calculated using Equation (2.7). The relationship between the mechanical power and the flow rate is shown in Figure 4.9. The mechanical power increases with the flow rate and yields a maximum value of 304 W the highest flow. Therefore, a total of 608 W of mechanical power was produced from the P40 at the maximum flow.

Compare to previous studies, mechanical power for P20 provides a greater value compared to P40. However, this comparison cannot be taken into account. This is because in previous works the measurement was not carried out correctly, due to the possibility of error in the measurement prospect.

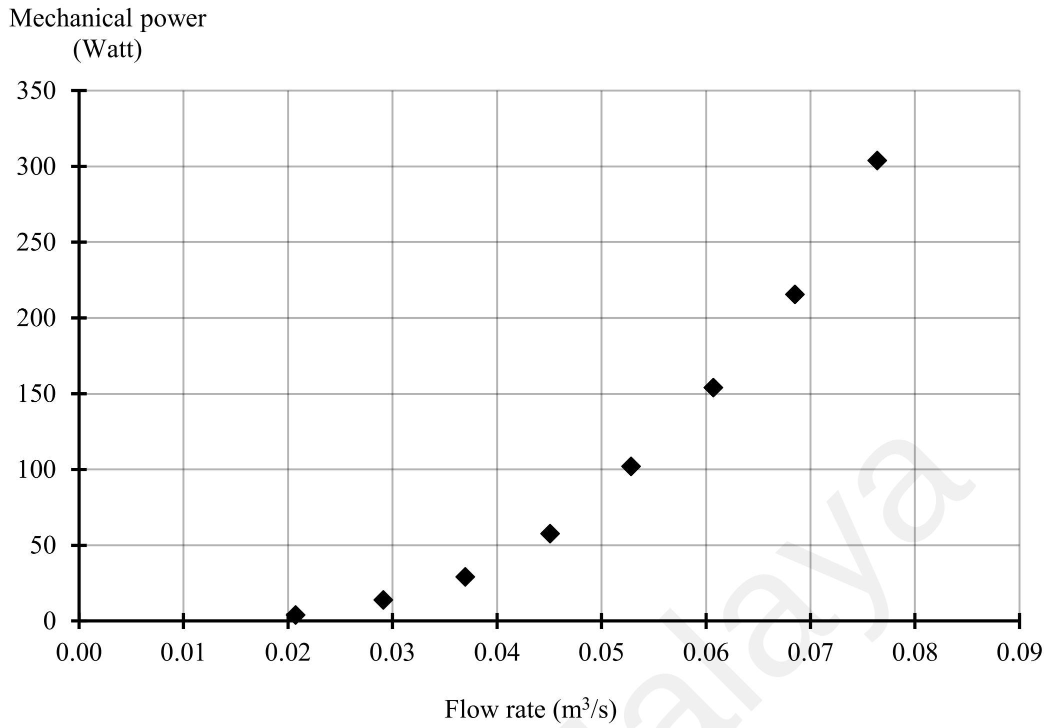


Figure 4.9: The relationship between the mechanical power and the flow rate.

4.2.2.4 Turbine Efficiency

The discussion of turbine efficiency in this section is focused on the maximum flow rate condition as it provides the biggest input value and is closer to the actual environmental flow condition.

The mechanical power obtained at the maximum flow rate here – 0.608 kW – appears to be much less than the effective hydraulic power (W_{eff}) – 8.13 kW – under the same flow rate condition. This is only about 7.5% of the input power (W_{eff}). Nevertheless, as illustrated in Figure 4.3 and Figure 4.4, at the highest flow rate condition, the P40 prototype absorbed only about 0.27 bar or about 24.8 % of the effective pressure (P_{eff}). Using Equation (2.6) and the maximum flow rate, the hydraulic power at this 0.27 bar is 2.0 kW. The efficiency of each turbine can be calculated then by dividing Equation (2.7) by Equation (2.6), which is 2 kW, as follows:

$$\text{Turbine Efficiency} = \frac{2 \times 0.304}{2}\ (\text{kW}) \times 100\ \% = 30.4\ \% \qquad (4.1)$$

However, as shown in Figure 3.3(b), while a flow rate of 0.076 m^3/s is expected to pass through the P40 prototype here, the water flow rate going into the PG channels is expected to be relatively smaller than the figure. The turbine efficiency of 30.4% obtained earlier is not based on the actual flow rate received by the turbine. Hence, the value is not accurate.

As mentioned earlier, the P40's concept design only uses 20% of flowing water into each PG channel while the remaining will flow into the main water channel. However, there are nozzles installed in the PG channel before the water reaches the turbine. This means the actual water flowing into the PG channel is likely less than 20% theoretically. Thus, the flow rate in the PG channel must be calculated to determine a more accurate turbine efficiency value.

In the previous discussion, the pressure at the PG channels P_1 and P_3 gives almost the same value of 0.60 bar at the maximum flow rate condition as shown in Figure 4.6. As shown in Figure 3.5, the PG channel has a diameter of 58 mm, and the nozzle has a diameter of 28 mm. Therefore, the surface area of the PG channel and nozzle are 2642 mm^2 and 616 mm^2 for the PG channel and nozzle, respectively. Since the pressure after the nozzle is predicted to be extremely low (close to zero at the maximum velocity), the theoretical flow rate in the PG channel can be determined using the Continuity Equation (2.3) and Bernoulli's Equation (2.5). Since the value of H_1 and H_2 is the same, therefore, it can be eliminated. The theoretical flow is calculated as follows:

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \qquad (4.2)$$

$$60{,}000 \text{ Pa} + \left(\frac{1}{2} \text{ x } 1{,}000 \times \left(\frac{\mathrm{Q}}{\mathrm{A}_1}\right)^2\right) = 0 + \left(\frac{1}{2} \text{ x } 1{,}000 \times \left(\frac{\mathrm{Q}}{\mathrm{A}_2}\right)^2\right)$$

$$60{,}000 \text{ Pa} + \left(\frac{1}{2} \text{ x } 1{,}000 \times \left(\frac{\mathrm{Q}}{0.002642 \text{ m}^2}\right)^2\right) = \left(\frac{1}{2} \text{ x } 1{,}000 \times \left(\frac{\mathrm{Q}}{0.000616 \text{ m}^2}\right)^2\right)$$

$$\mathrm{Q} = 0.007 \text{ m}^3/\text{s}$$

As a result, the flow rate Q in each PG channel is estimated to be approximately 0.007 m^3/s, which is around 9% of the maximum flow rate.

Figure 4.10 illustrates water flow in the PG channel. Before entering the nozzle, the flow rate gives a value of 0.076 m^3/s at the maximum flow rate. When the water flows through the nozzle, the flow rate changes as the nozzle size has been reduced. Therefore the actual flow rate that flows after the turbine as calculated gives a value of approximately 0.007 m^3/s.

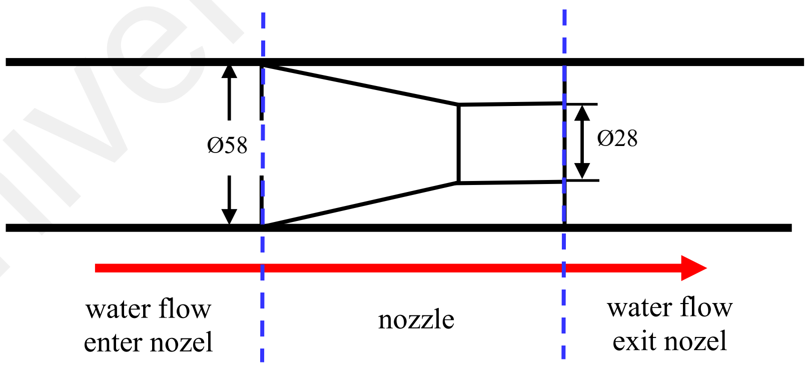


Figure 4.10: Water flows in PG channel.

In this experiment, there is a point to be highlighted regarding the water flow rate in the PG channel. Each PG channel is allowing about 9% of the flow rate to pass through it, for a total of 18% for both PG channels, whereas the total theoretical hydraulic power in both PG channels is 0.824 kW, which is around 41.2% of the effective hydraulic power (2 kW). Therefore, it is to be mentioned that each PG channel on both sides of the prototype is estimated to generate around 20% of the power, for a total of 40% of the whole power capable of being generated.

Using the pressure of 0.60 bar, the hydraulic power in the PG channel can then be calculated using Equation (2.6), which results in a power value of 412 W. The hydraulic power estimated here is in theory, as it does not take into account the friction between the PG channel wall and the water. Using the same method as in Equation (4.1), the following could be done to figure out the precise turbine efficiency:

$$\text{Turbine Efficiency} = \frac{0.304}{0.412}(\text{kW}) \times 100\ \% = 73.8\% \tag{4.3}$$

Therefore, the efficiency of the turbine here is 73.8%. The efficiency is a bit lower as compared to the 80 to 95% range obtained elsewhere (S.U.Patel & Prashant.N.Pakale, 2015). The efficiency of turbines may vary depending on the flow and pressure (Corcoran *et al.*, 2012). In addition, one of the factors that affect turbine efficiency less than common turbine efficiency is the “retained water” in the turbine casing that opposes turbine rotation.

It is well understood that both turbine RPM and torque are strongly dependent on the pressure or force acting on the turbine’s blade. Higher pressure or force will lead to a higher turbine RPM and torque. However, there is a maximum value that the torque can reach at a certain turbine RPM value before it drops again. Based on the results shown in Figure 4.9, the torque seems to have not reached its maximum point. Higher efficiency in mechanical power generation could also be achieved by providing a higher flow rate to work with.

4.2.3 Reliability Testing

In this section, a reliability test is done on the PG40 prototype to check the functionality of the valves. The test is conducted similarly to the previous performance test but with all of the valves closed. The relationship between the pressure and flow rate when all valves at the PG channels are closed is shown in Figure 4.11. From the figure, the pressure increases when the flow rate increases. It also shows that P_1 and P_3 have almost the same value. The pressure here gives a higher value than it was when the valves were open earlier. Since the valves are closed, the turbine is not rotating as there is no water flow in the PG channel. The pressure at P_2, P_4, and P_o gives a zero value.

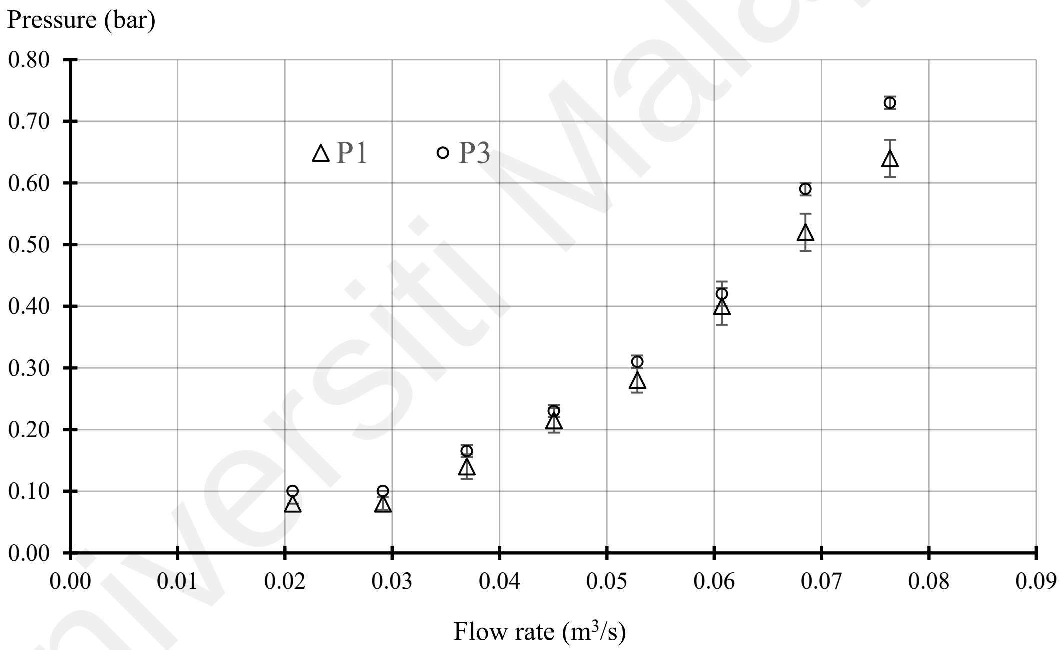


Figure 4.11: The relationship between the pressure and the flow rates.

4.3 Summary

This chapter evaluates the efficiency in terms of mechanical power generated and pressure loss inside the pipe of an in-pipe hydropower prototype with PG40. At the maximum flow rate of 0.076 m^3/s, the prototype absorbed around 24.8% of the water pressure, and the PG channels at both sides of the prototype allowed around 18% of the water to flow through them. The rotating turbines produce a total of 0.608 kW of mechanical power, which is about 73.8% of turbine efficiency.

According to the findings, it is demonstrated that the prototype has operated in accordance with the design as a system that allows the majority of water to flow uninterruptedly while also allowing the remaining water to be used for power generation.

CHAPTER 5: SUMMARY

This chapter provides conclusions from the conducted research. In this study, a new design of an in-pipe hydropower prototype called P40 was developed. A series of tests have been conducted to evaluate the flow characteristics, performance, and reliability. The P40 absorbed 24.8% of the water pressure at the maximum flow rate, and the PG channels at each side of the P40 allowed 18% of the water to flow through them. The rotating turbines generated a total mechanical power of 0.608 kW, translating into a 73.8% turbine efficiency. However, the turbine efficiency can be increased by providing a higher flow rate as the torque in the study seems to have not reached its maximum point.

The implementation of this study was done in the laboratory. Based on the findings, it can be concluded that the P40 prototype has performed as intended as a system that allows the majority of water to flow without interruption while simultaneously enabling a certain amount of water pressure for power generation. Overall, P40 performed effectively as a device that allowed most water to flow uninterruptedly while generating power simultaneously.

Further studies need to be done to improve the design to overcome the water splash effect in the turbine casing so the efficiency of the turbine can be improved. Then, it can be proposed to be implemented in a real environment to determine the actual energy that can be generated on the water distribution network. Thus, the implementation of this study can be utilized as one of the methods to generate renewable energy sources for our country.

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