DESIGN CONCEPT OF IN-PIPE HYDRO SYSTEM PROTOTYPE FOR RENEWABLE ENERGY GENERATION: VERTICAL AXIS PARALLEL TURBINES

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Electrification and renewable energy generation through In-Pipe Hydro System: prototype development

Field of Study: Electricity and energy

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ABSTRACT

A new design concept for in-pipe hydropower generation is proposed to optimally harness power from the flowing water in a pipe without having to fully block or divert the main water flow, while at the same time makes maintenance work doable without having to stop the whole operating system. The experiment was first conducted to evaluate the performance of the specially designed nozzle and turbine set to get the most optimum performance, using a water pump with a flow rate of 0.48 m3/min. After getting the most optimum condition for the nozzle and turbine set, the actual prototype was fabricated based on a water pipe of 5-inch diameter. The prototype was then tested using a water pump with a maximum flow rate of 4.4 m3/min and maximum water pressure of 1.4 Bars. The maximum value of water pressure is measured by fully closing the pipe while running the water pump at maximum speed. The speed of the water pump is adjustable using a variable speed drive (VSD). Under the best condition, the differential pressure at P1 (The value of water pressure before the prototype) and P2 (The value of water pressure after the prototype) was 0.29 Bars. The percentage of pressure loss or the ratio between the value of pressure (P1 – P2) and the total pressure inside the pipe was 20.7%. The electrical power generated from the in-pipe hydropower system was 1 kW. Based on the study, the in-pipe hydropower system developed here is proven to be workable for inpipe hydropower generation. At the same time, the system can also act as an alternative for a pressure relief valve (PRV).

Keyword: Hydropower, In-pipe hydropower generation, Vertical axis turbine system, pressure relief valve

ABSTRAK

Satu konsep rekabentuk baharu untuk penjanaan tenaga dalam paip diperkenalkan dalam usaha untuk menjana kuasa elektrik daripada aliran air di dalam paip tanpa menyekat atau mengubah laluan air daripada paip utama. Oleh yang demikian, pada masa yang sama kerja-kerja penyelengaraan dapat dilakukan tanpa perlu menutup aliran air. Pertama sekali, kajian dilakukan untuk menilai prestasi muncung dan turbin untuk mendapatkan prestasi yang optima, dengan menggunakan pam air dengan kadar aliran pada 0.48 m3/min. Setelah mendapatkan prestasi yang optima untuk reka bentuk muncung dan turbin, prototaip akan fabrikasi daripada size paip 5 inci. Prototaip kemudiannya diuji dengan menggunakan pam air yang boleh menghasilkan kadar aliran air maksima sebanyak 4.4 m3/min dan tekanan maksima sebanyak 1.4 Bar. Tekanan maksima air di uji dengan menutup paip sepenuhnya sementara pamp air beroperasi dengan kelajuan yang paling laju. Kadar aliran air juga boleh dikawal dengan menggunakan peralatan pengawalan kelajuan motor. Pada keadaan yang terbaik, perbezaan diantara tekanan air pada P1 (Tekanan air sebelum prototaip) dan P2 (Tekanan air selepas prototaip) adalah 0.29 Bar. Peratusan tekanan air yang menurun atau nisbah diatara nilai tekanan air (P1 – P2) dibahagiakan dengan tekanan air maksima ialah 20.7%. Kuasa elektrik yang berjaya dihasilkan oleh protaip pula ialah sebanyak 1 kW. Berdasarkan hasil kajian ini, sistem tenaga dalam paip yang dihasilkan di sini telah terbukti boleh berfungsi dengan baik. Pada masa yang sama, sistem ini juga boleh bertindak sebagai alternatif kepada injap pelepasan tekanan (PRV).

Kata kunci: Tenaga hidro, tenaga dalam paip, sistem turbin paksi selari secara menegak, Injap pelepasan tekanan

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Symbols	Explanation
ω	Angular velocity
t	Torque
η	Efficiency
°	Degree (Angle)
π	Pi

Abbreviations	Explanation
CNC	Computer numerical control
PRV	Pressure reducing valve
PG	Power generation channel
UM	Universiti Malaya
AAIBE	Akaun Amanah Industri Bekalan Elektrik
MESTECC	Ministry of Energy, Science, Technology, Environment and Climate Change

CHAPTER 1: INTRODUCTION

1.1 Background

Due to rapid population growth and increasing demand for water supply source, there has been a vast expansion of water supply distribution (WSD) network system. Time constraints and the surge of desperate demands have led to the poor planning and inefficiency of the operating systems (Coelho & Andrade-Campos, 2014). The water flow is pumped much higher than the actual demand and energy is wasted to power up the oversize pumping system (Energy, 2004; Luna, Ribau, Figueiredo, & Alves, 2019). Reducing the size of the pumping system is not a good idea because it involves considerable cost and larger scale of civil work. Eventually, the growth of the population will catch up with the supply-demand in the future (Dawadi & Ahmad, 2013).

Another challenge is the oversize pumping system creates excess pressure inside the pipeline. Excess pressure is the value of pressure that is over the limit setup by the pipeline network system (Amjadi, Khashehchi, & Soltani, 2020). The excess pressure can cause leak at joint and burst the pipe during the water delivery process (van Zyl, 2014). To solve the problem, the pressure reducing valve (PRV) or variable speed control (VSD) is used. PRV can reduce the pressure inside the pipe by converting the excess pressure into the heat. At several locations, the pressure reducing valve (PRV) is installed to reduce high water pressure. Meanwhile, variable speed drive (VSD) can regulate the pressure inside the pipe by adjusting the frequency of the water pump (Kiselychnyk, Bodson, & Werner, 2009). VSD system is also capable of controlling the water flow rate, Q, water head, H and consequently, reduces the number of water hammer in the distribution system (Feldman, 2009). However, the capital cost to set up the VSD in the whole distribution network is expensive (Saidur, Mekhilef, Ali, Safari, & Mohammed, 2012).

However, instead of wasting the energy into the heat via the PRV mechanism, in-pipe hydropower system can convert the excess pressure inside the pipe into the electricity (Karadirek et al., 2016). The design of an in-pipe hydropower is compact and straightforward where this system is relatively easy to set up and does not require additional infrastructure or substantial upfront capital like VSD (Abdullah, Jauhari, Mohd Sabri, & Nik Ghazali, 2021)

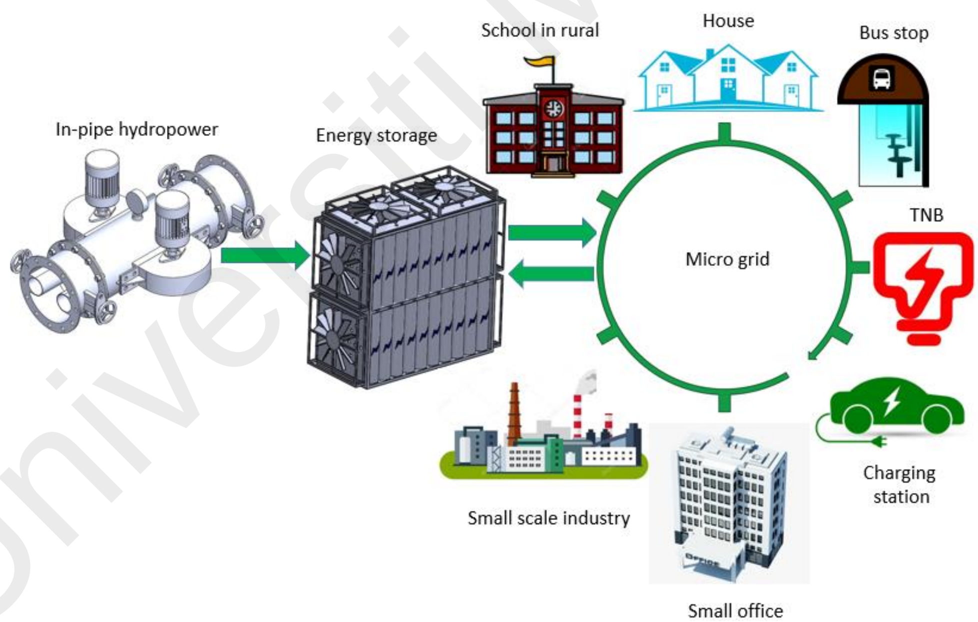


Figure 1.1 Schematic diagram of the in-pipe system connected to the microgrid

Figure 1.1 shows the benefit of installing the in-pipe hydropower system. The electricity generated from the excess pressure inside the pipeline can be supplied to the micro grid. Later, the microgrid supplies electricity to the users such as school, house, bus stop, charging station, small office and small-scale industry. The electricity can also be sold to TNB to generate income for the owner of the system.

1.2 Objective

1. To develop and fabricate a new in-pipe hydropower system using two vertical turbines.
2. To study, evaluate and select the design of the nozzle and turbine for an in-pipe hydropower system.
3. To evaluate the performance of the in-pipe hydropower system based on the water flow, water pressure, electricity generated and pressure loss inside the pipe.

1.3 Research work and scope

1. Preliminary experiment:
   I. To study, evaluate and select the suitable nozzle and turbine design for the in-pipe hydro system.
   II. The data and result analysis here are used to design and fabricate the prototype at the next step.

2. Designing and fabricating the prototype:
   I. To develop and design the concept of the in-pipe hydro system.
   II. To fabricate the prototype of in-pipe hydro system for testing at the next step.

3. Testing and evaluating the prototype's performance:

I. To measure the value of the turbine RPM and torque against the water flow.

II. To measure the pressure loss inside the pipe against the water flow.

III. To measure the value of the power generated (mechanical and electrical).

1.4 Research Outline

The outline of the research is as below:

(1) Introduction

A brief background of research, the research objectives, research work and scope and the layout of thesis are presented in Chapter 1.

(2) Literature review

This chapter reviews the current design of the in-pipe hydropower. Every design of in-pipe hydropower is unique and they have been designed for their specific function and operate at specific condition like water flow rate and water heads. The content also includes the location where the technology is implemented, the type of turbine blade or runner uses in the system, pressure drop inside the pipe and the amount of electricity generated based on the water flow conditions.

(3) Methodology

This chapter explains the flow chart in research and development of the new in-pipe hydropower system. The first section introduces the design concept for new in-pipe hydropower. The research begins by studying, evaluating and selecting the suitable design of the nozzle and turbine. These two components are critically important in defining the performance of the prototype. The last section is testing and evaluating the performance of the prototype using a range of water flow rates and pressure inside the pipe.

(4) Result and discussion

This chapter discusses the performance of the nozzle and turbine design in the preliminary experimental test and the performance of the prototype. The evaluation is based on the criteria below:

The value of the turbine RPM against the water flow rate.

The value of the turbine torque against the water flow rate.

The value of the pressure drop inside the pipe against the water flow rate.

The value of the mechanical power generated against the water flow rate.

(5) Conclusion

The conclusion is based on the in-pipe hydropower system performance. Performance of the system evaluated is based on the water flow rate, water pressure, electricity generated and the pressure loss inside the pipe.

CHAPTER 2: LITERATURE REVIEW

The design of in-pipe hydropower can be differentiated in terms of internal system and external system. The internal system is defined as having the runner inside the pipe section and external system has the runner inside the secondary pipe section that bypasses the main one (Casini, 2015).

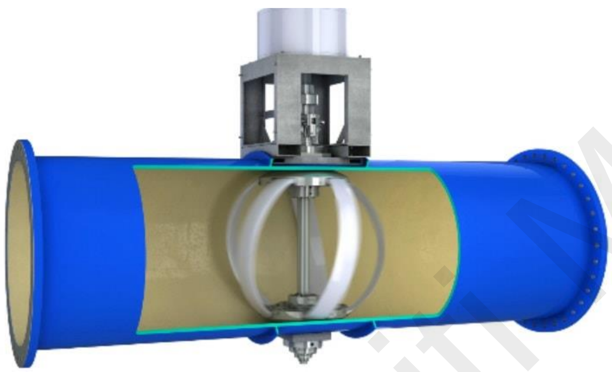
Some examples of internal system are Lucidpipe, Fuji Micro Tubular Water Turbine and SOAR GPRV hydropower. The benefit of the internal system is that it does not require a lot of space for installation, in case of the pipe is located underground and performing the modification works there is difficult. Its design is compact, unlike the external system which is too bulky.

Some examples of external system are Rentricity, Leviathan Benkatina and Hitachi Energy Recovery systems. The benefit of the external system is that it does not insert the turbine directly on the main pipe but in the bypass. The maintenance can be done without having to stop the water flow unlike required by the internal system.

The research gap of this project is the proposed design has to be an internal system but functions as an external system whereby the design of this new in-pipe hydropower is compact and also capable of performing maintenance works without having to stop water flow at the main pipe. This hybrid system between internal and external in-pipe hydropower system is much more competitive than the current design.

2.1 Lucidpipe power system

In January 2015, Lucid Energy became the first company in the US to install a commercial micro-hydro energy system, recovering nearly 1,100 MW of electrical energy annually (Lucid Energy, n.d.). Figure 2.1 shows the Lucidpipe power system design (Right view and front view).



A) Right View

B) Front View

Figure 2.1 LucidPipe power system (Lucid Energy, n.d.)

A hollow spherical turbine is installed inside the pipeline. It rotates transversely against water direction, continued to harvest a small amount of water potential. The turn of mechanical turbines that are connected directly to the power generator by the shaft will generate electricity. The capacity size of hydropower generation is based on the characteristic of water potential such as water flow and head as listed in Table 2.1.

Table 2.1Characteristics of the LucidPipe power system (Casini, 2015)

Pipe size diameter (mm)	Flow rate (L/min)	Rated water head pressure (m)	Power rating (kW)	Productivity kWh/year (60% capacity)	Electricity bill saved/year ($0.12/kWh)
600	60 000	32	14	73584	$8830
1000	162 000	35	50	262800	$31536
1500	336 000	27	100	525600	$63072

The sizes of the lucid pipe are 600 mm, 1000 mm and 1500 mm. The electricity generated are 14 kW, 50 kW and 100 kW when the hydropower system is operated at the rated water flow rate and water head (water pressure). For the three sizes of the lucidpipe, the annual energy saving are $8830, $31536 and $63072. The electricity bill used in Table 2.1 is based on the US, where the cost of 1 kWh is $0.12. The target project payback is 10 years.

The benefit of Lucidpipe is it only extracts a small percentage of water pressure when operating, allowing the water operator to deliver water without any obstacles. According to the Lucid Energy Company, the difference between pressure when closed and operating is only 1and 6 psi (Team, 2016), indicating that the turbine can be placed directly into the pipelines without the need for a bypass piping system.

2.2 Rentricity

Rentricity is intelligent in-pipe hydropower that uses the SCADA integration system. The system is working together with the pressure reducing valve which is placed in a parallel manner to the hydropower. The water flow is diverted from the main pipe into the in-pipe hydropower before returning back into the main pipe (Rentricity, n.d.). The system is using the pump as the turbine (PAT) to generate electricity, which helps to reduce the R&D cost (Motwani, Jain, & Patel, 2013).

These systems generally include a micro-turbine, generator, sensors, processors, electronic controls, and communications equipment that operate seamlessly and autonomously within the water utility infrastructure, as shown in Figure 2.2.

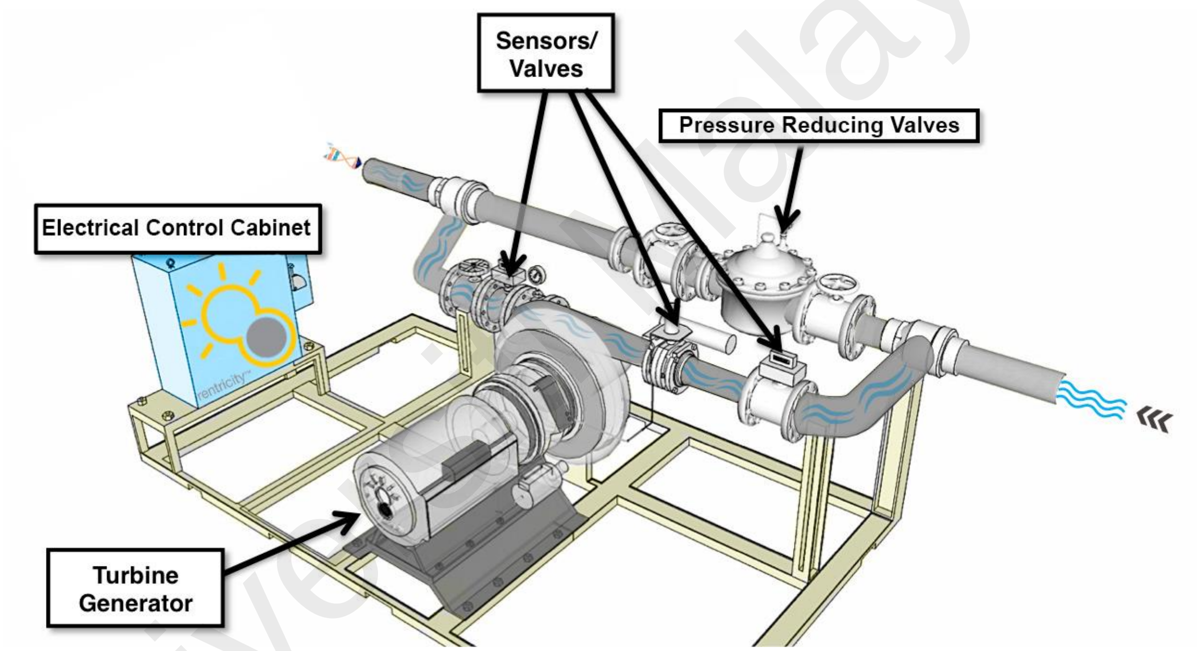


Figure 2.2 Sustainable Energy and Monitoring Systems (SEMS™) (Rentricity, n.d.)

Currently, Rentricty only deploys two in-pipe hydro energy recovery systems, Flow-to-Wire™ for 30kW to 350kW and plug-and-play Sustainable Energy and Monitoring Systems (SEMS™) for applications in the 5kW to the 30kW range. They have been used for broad applications in the US to recover energy.

Table 2.2Characteristic of Rentricity in-pipe hydropower

Reference	Type	Flow rate (L/min)	Power (kW)
(City of Barre, n.d.)	Flow to Wire™	1514	12
(North Wales, n.d.)	SEMS™	5300	12
(Westmorland, n.d.)	SEMS™	17806	30
(Oneida Valley, n.d.)	Flow to Wire™	N/A	30
(Halifax, n.d.)	Flow to Wire™	6246	31
(City of Keene, n.d.)	SEMS™	7836	50

Table 2.2 shows the project done by the Rentricity at various locations in the US. The range of power generated is 12 – 50 kW. The size of hydropower used is the micro hydropower. Most of the projects can supply energy or electrical power into the grid and generate annual income.

2.3 SOAR hydropower

SOAR hydropower introduces Generating Pressure Reducing Valve (GPRV®) turbines (SOAR Hydropower, n.d.). Generating Pressure Reducing Valve (GPRV®) turbines are custom designed systems by SOAR Hydropower placed within water networks at key locations to recover energy over system pressure drops.

The system is using a concept similar to the Francis turbine to tap water flows into electricity. To get the maximum rotation of the turbine, the water flow is compressed into the high-velocity flow before reaching the turbine as shown in Figure 2.3.

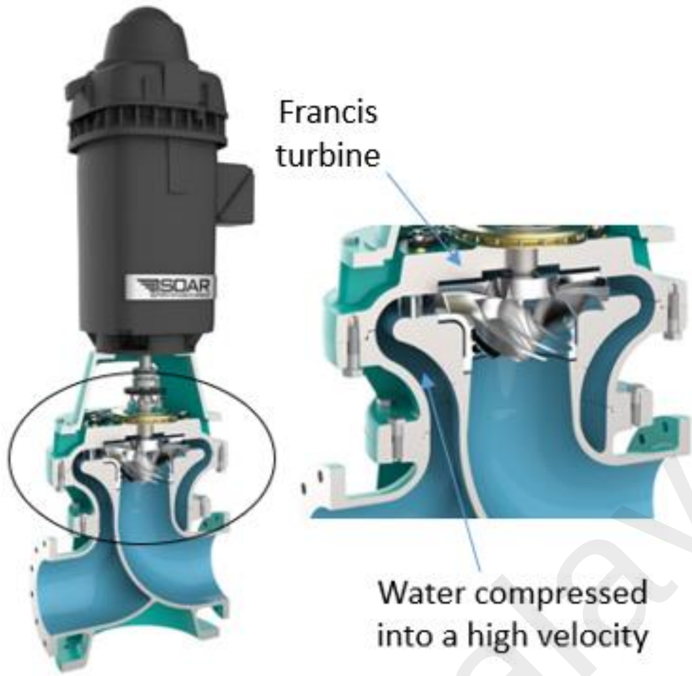


Figure 2.3 SOAR GPRV hydro turbine (SOAR Hydropower, n.d.)

The products have a specific range of site conditions, pipe diameter, head, and flow rate as classified in Table 2.3.For example, TKW operates at the highest water flow rate which is at 76 000 – 314 000 L/min. The In-line and Pelton are only operating at a water flow rate of 379 – 114 000 L/min and 2 – 6 814 L/min. The smallest size is Micro which operates at a water flow rate of 150 – 228 L/min.

Table 2.3 Generating Pressure Reducing Valve (GPRV®) turbines characteristics

Type	Pipe Diameter (mm)	Head (m)	Flow rate (L/min)
In-line	100 - 600	7.7 – 174.0	379 – 114000
TKW	150 -760	9.0 – 304.0	76,000 – 341000
Pelton	150 -760	16.0 – 915.0	2 - 6814
Micro	Min 100	N/A	150 – 228

2.4 Hydro-engine Natel energy

Figure 2.4 shows the HydroEngine by Natel Energy. Hydro-engine consists of the drive train with two parallel shafts and a belt between the shaft and forms a horizontal loop. Cups are mounted by crossbars on the belt to make parallel rows outboard of the belt.

Later, the flat nozzle willinject the water from the center out into the two rows of cups. The parallel cups will move to transfer the rotation to the power generator and generate electricity. The speed increaser is installed to increase the rotation speed for better input.

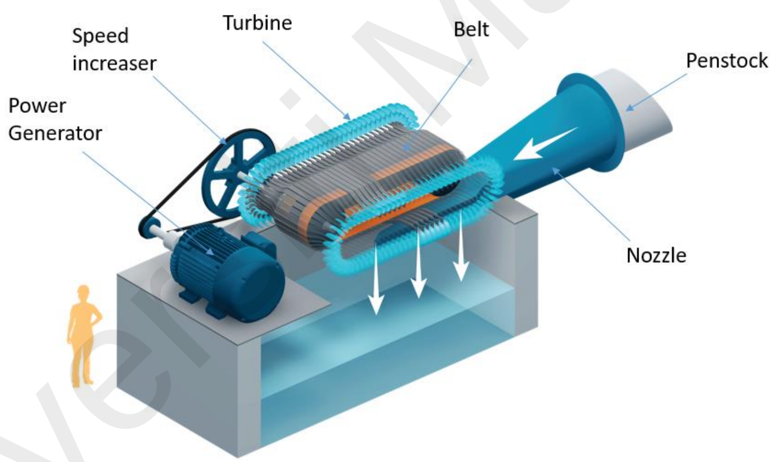


Figure 2.4 HydroEngine (NATEL ENERGY, n.d.)

The advantages of HydroEngine are its low civil cost, the application is available at under 6m head, built with anti-cavitation and fish-friendly if install along the river. In comparison to Kaplan or Archimedes turbine, it is more compact and less expensive but still delivers the same power output as shown in Figure 2.5.

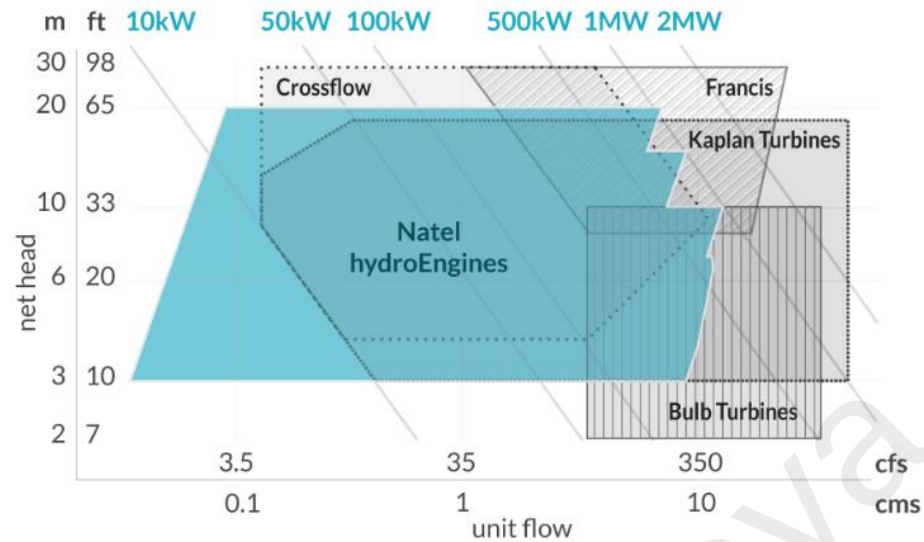


Figure 2.5 Flow condition and power output of HydroEngine (NATEL ENERGY, n.d.)

Figure 2.5 shows the flow condition and power output condition for the hydro engine compare to other reaction turbines. By observation, the hydro engine has the widest range of operation than the rest of the reaction turbines. It supports the lowest flow rate > 0.1 m^3/s and head = 3 meters to higher flow rate = 10 m^3/s and head = 20 meters. The product is suitable to be installed in the agriculture industry, along the river beds and any suitable water channel.

2.5 Leviathan Energy hydroelectric Ltd

Leviathan Energy Benkatina™ is in-pipe hydropower uses the pump as the turbine (PAT) to convert water pressure into electricity. This product consists of a turbine, a generator, optional customized sensors, and electronic sub-elements, as shown in Figure 2.6.

The benefits of Benkatina™ in-pipe hydropower is it is user-friendly and suitable to install at all municipal and transport water systems, water tanks piping systems and reservoirs in the remote area.This hydropower is an excellent opportunity for rural electrifications as the size is small and easy to install.However, this model is not appropriate for piping and other systems where water flow rates vary (water use varies with time of day and season of the year, among other factors) and pressure downstream from the turbine must be regulated so the water system can function. A requirement for dealing with the variable flow rate is that it should produce efficient power over a range of water flow rates. The specification for this hydropower is listed in Table 2.4.

Figure 2.6 Benkatina™ in-pipe hydropower (Leviathan Energy Hydroelectric, n.d.)

Table 2.4 Benkatina™ specifications (Leviathan Energy Hydroelectric, n.d.)

Specification	Value
Size	W 100 x L 110 x H 106 cm
Power Capacity	Up to 100 kW
Flow range	10 to 20 Liter per second
Pressure range	1 bar to 8 bars
Head range	10 to 80 meters

2.6 Mini hydroelectric system

The purpose of this type of in-pipe hydropower is to tap the water flow from the household piping system as shown in Figure 2.7.The mini hydroelectric system will use the water potential that flows from the tank to generate electricity.The arrow is used to show the direction of the water movement.

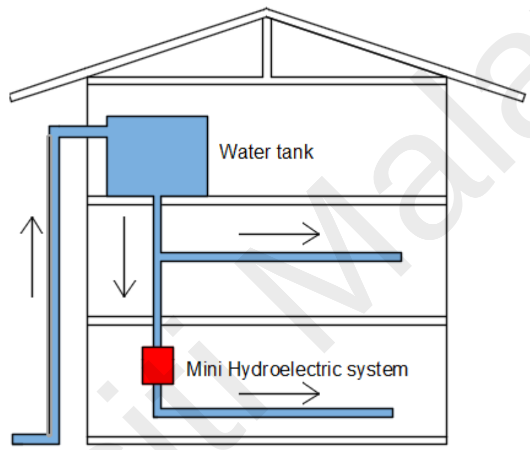


Figure 2.7 Schematic diagram of household

Figure 2.8 shows the design of the mini hydroelectric system. The Mini Hydro was built by incorporating three important components, which are the pipe, the blade and the dc generator.The butterfly blade used to improve the efficiency of the turbine.

The blade was attached to the pipe by sliding a shaft between it and the pipe. This particular shaft is linked to the dc generator. A metal frame has been adapted to increase the stability of the DC motor. The diameter of the pipe is 30 mm.

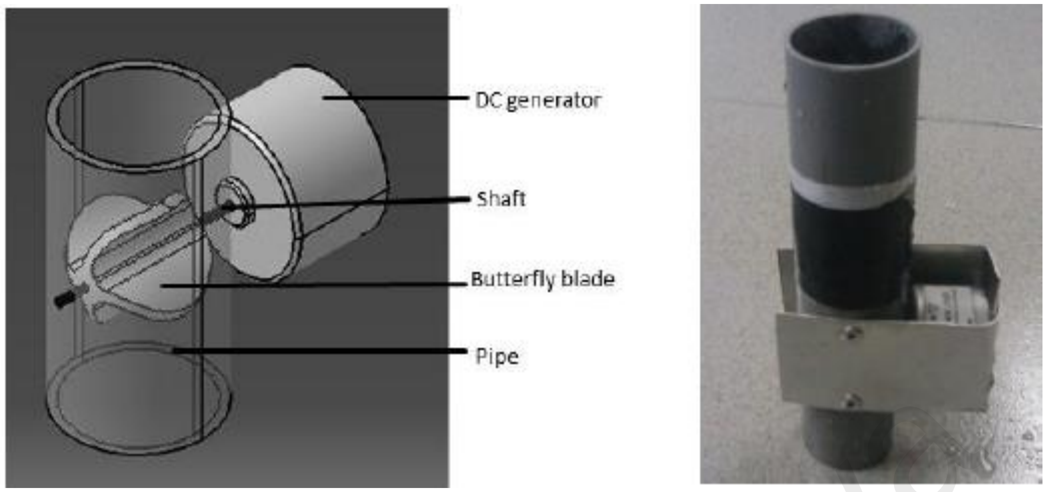


Figure 2.8 Mini hydroelectric system (Jusoh et al., 2014)

When the water from the tank flows through the in-pipe hydropower system, the butterfly blade that is connected to the dc generator will rotate and generate electricity.The flow rate is around (0.258- 0.73) x 10^{-3} m3/s and the energy generated is around 10 - 52 mW.

The electricity generated by this system is too low. The performance of the dc generator is not fully achieved due to minimum flow rate requirements and the butterfly blade inside the system itself might not be efficient to harvest the flow of water.

As a suggestion, the system might be efficient if the pipe diameter is much larger to fulfill the flow rate requirements. The in-pipe hydropower system might not be suitable for the small households but suitable in high rise buildings where the piping diameter is much bigger.

The butterfly blade can be changed into a much efficient turbine like a solid or hollow spherical blade and cross-flow turbine. More water flow can be tapped to increase the output of the electricity generated.

Finally, it is important to select a suitable generator based on the water flow rate and head. The dc generator used in this project is not suitable for low-speed rotation turbines. The high number of generator poles are suggested for this project.

2.7 Inline vertical turbine

The inline vertical turbine was proposed to harvest the potential hydropower inside water pipelines for supplying power to the water monitoring systems. The in-pipe hydropower design is shown in Figure 2.9.

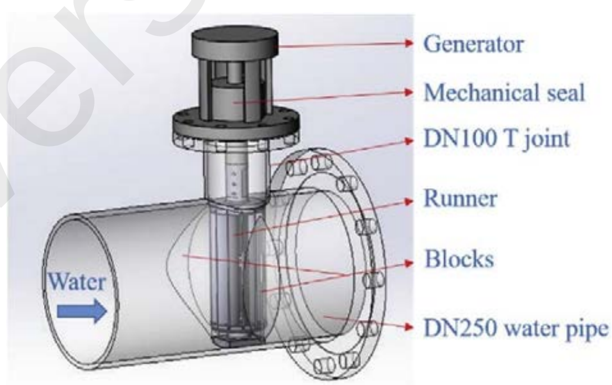


Figure 2.9 Inline vertical turbine (Jiyun, Hongxing, Zhicheng, & Xiaodong, 2018)

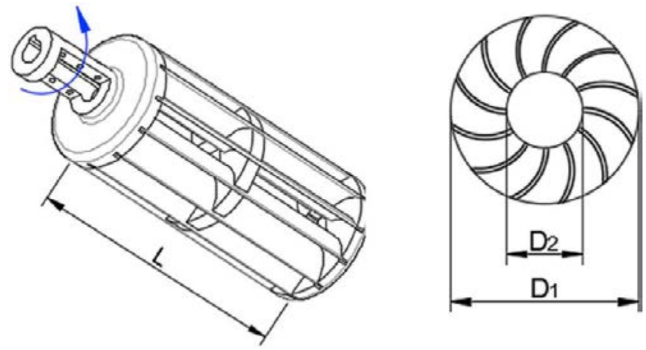


Figure 2.10 Cross-flow turbine (Jiyun et al., 2018)

The design is similar to the lucidpipe power system but this in-pipe hydropower is using a cross-flow turbine instead of a hollow spherical turbine as shown in Figure 2.10. The outer diameter and inner diameter of the cross-flow turbine are 98 mm and 45 mm. The length is 215 mm.

The system works by placing the cross-flow turbine into a vane as shown in Figure 2.11. The vane can direct the concentrated flow of water into the blade. The positive torque (water force in the same direction of turbine rotation) can be increased while at the same time reducing the negative torque (water force in the backward direction of turbine rotation).

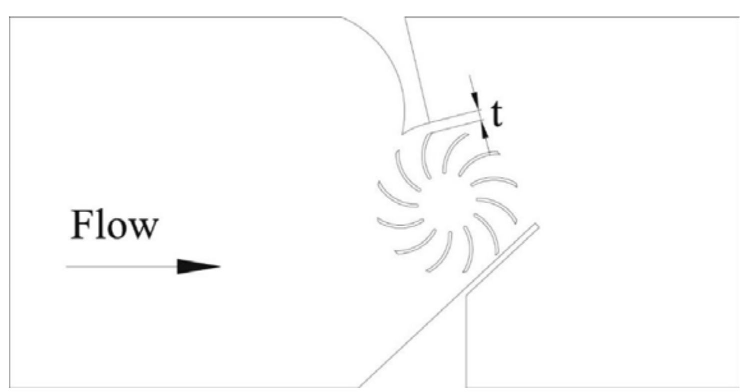


Figure 2.11 Schematic diagram of the vane (Top view) (Jiyun et al., 2018)

The benefit of this design is that it can harvest much more water potential compared to other in-pipe hydropower (Chen, Yang, Liu, Lau, & Lo, 2013; Jiyun et al., 2018). The output power at the design point is 69.1W with 2.62m water head loss. The water flow velocity is at a range varying from 1.2 m/s to 2.2 m/s, the water head loss is below 5 m. In summary, the daily electricity generation is about 600Wh, reliable enough for commercial purposes.

The disadvantage of this design is that it can cause a huge amount of water pressure loss inside the pipelines as shown in Figure 2.12. The initial pressure inside the pipelines is 38.5 kPa (Red color) but after passing through the inline turbine system, the pressure inside the pipeline drops to 1.1 kPa (Green color). As this much pressure is lost, the water operator will expect to face some problems in delivering water to the customers.

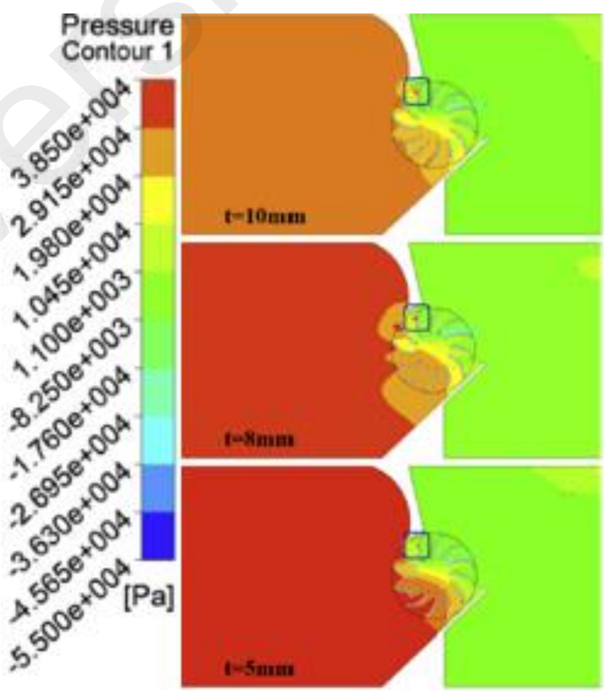


Figure 2.12 Pressure drop in pipelines (Jiyun et al., 2018)

2.8 In-pipe Micro hydropower by Practical Action

Practical Action is a charity organization based in the UK. They are working with the undeveloped country, especially in Latin America, East Africa, Southern Africa and South Asia to fight against poverty and raise the standard of living.

In this research topic, Practical Action has developed in-pipe Micro hydropower to supply energy to the local areas. The construction map of Micro-hydropower is shown in Figure 2.13. The Micro-hydropower system is built by diverting water flow from the river. The water flow is then channeled to the powerhouse that contains a turbine and a generator by using the pipelines (penstock). It is the powerhouse that generates electricity. Meanwhile, the water eventually flows back into the river after passing through the system.

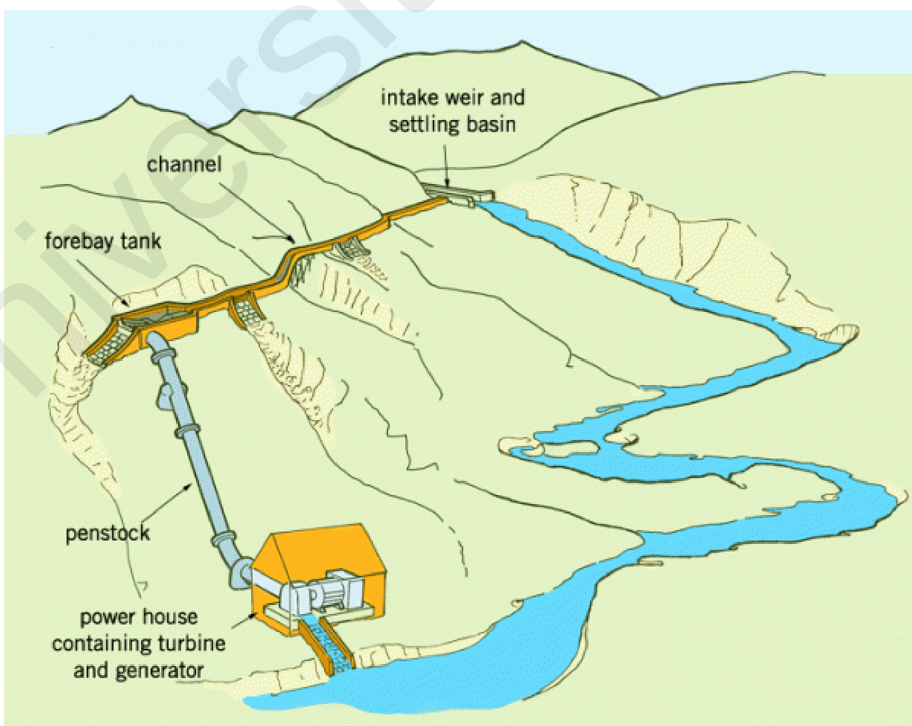


Figure 2.13 Construction map of Micro hydropower (Practical Action, n.d.)

The benefit of this "Run of the river" system is it does not require a dam or storage facility to be constructed. Consequently, the cost to build an expensive dam for water storage can be avoided and the cost of electricity generation is lower and affordable.

This construction also prevents from damaging the environment and social effects that larger hydroelectric schemes can cause, including the risk of flood. However, this system is only suitable for rural areas where the place must have geometric advantage and a large scale of the river water flowing to generate effective energy.

2.9 Pumped-storage hydroelectricity

The pumped-storage hydroelectricity works by generating energy from the shifting of water volume between two reservoirs; a high reservoir and a lower reservoir at different elevations (Duke Energy, n.d.) as shown in Figure 2.14.

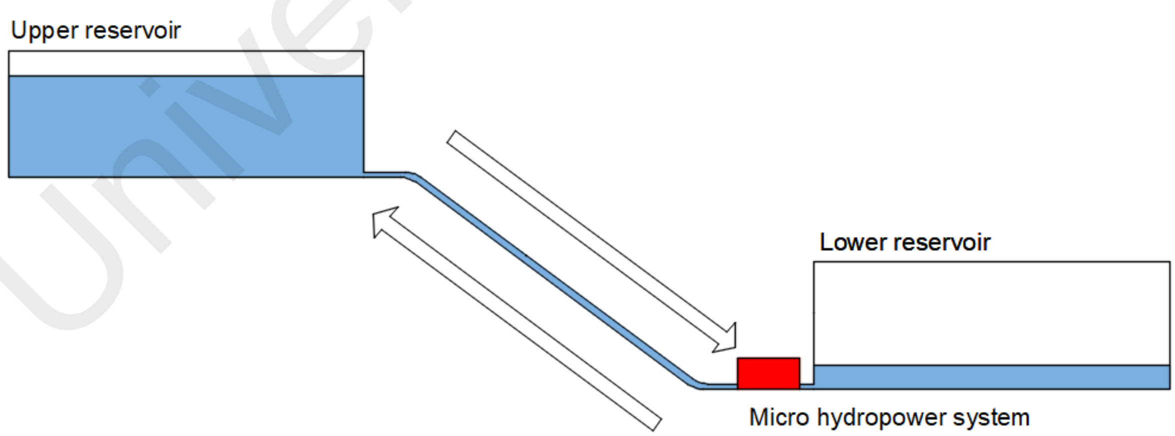


Figure 2.14 Pumped-storage hydroelectricity

The pumped-storage hydroelectric is acting like a big battery capacity. The system stores energy in the form of water rather than electrical charge. During low electricity demand, such as at night (off-peak) or on weekends, the unused electricity is used to pump water volume from the lower reservoir into the upper reservoir. Micro hydropower will act as a pump at this time. The upper reservoir will store a huge amount of water volume.

During high electricity demand, such as working hours (peak hour), the water will be flowing back from the upper reservoir into the lower reservoir.The water will flow through the Micro hydropower system. The Micro hydropower will act as a reverse pump (pump as turbine system) and tapping the water potential to generate electricity. The electricity is transferred to the national grid to fulfill the high electricity demand.

The benefit of this hydropower is it balances the load between times of high electricity demand (Peak hour) and low electricity demand (Off-peak). The round trip cycle efficiency is about 80 % (Energy Storage Association, n.d.). The Pumped-storage facilities can be very economical due to peak hour and off-peak price differentials and their service in the critical ancillary grid.

The pumped-storage hydroelectric might only be suitable for a particularly wealthy country as the capital and installation cost is expensive to build the system, especially the civil cost to construct the upper reservoir and lower reservoir. The installation of two reservoirs also needs a suitable location which has geometric advantage. They must have a big elevation difference between the two reservoirs as the system is taking advantage of gravitational feed to generate electricity.

2.10 Energy recovering in the air conditioning system

Figure 2.15 shows a schematic diagram of energy recovering in the air conditioning system. The in-pipe hydro generator is placed between the valve in the piping system. The high-pressure water from the air conditioning flows through the in-pipe hydro generator before returning to the thermal storage tank.

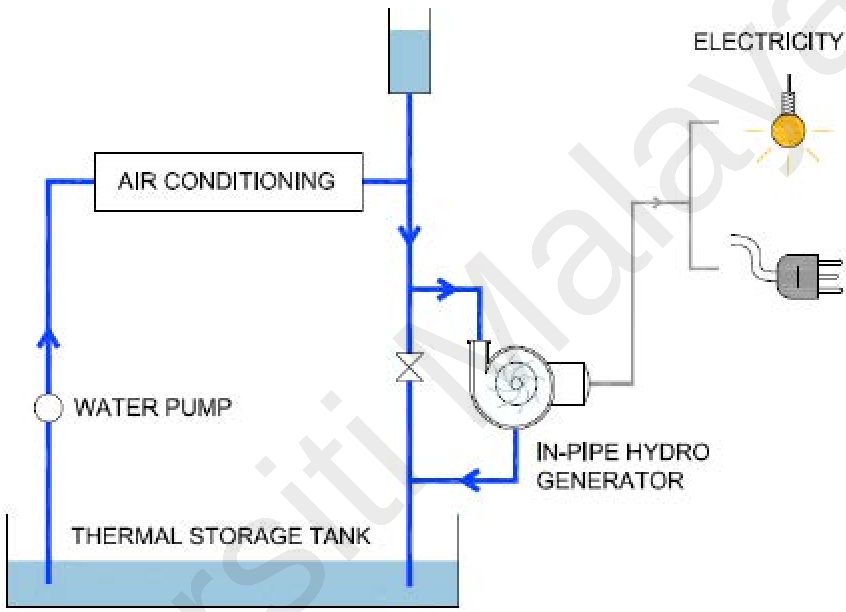


Figure 2.15 In-pipe hydro generator in the air conditioning system (Casini, 2015)

The vertical axis Francis turbine in the cooling and heating circuit can provide energy in the range of 3 kW to 9 kW. Currently, the device has been tested in the Iwatsuki office of Fuji Xerox (2.4 kW with 25 m water head), Koyo paper (9.6 kW with 40 m head) and NGK Spark Plug factories (6.0 kW with 25 m head). Although the power generated is small, it is enough in its objective to power up the power lighting systems in stairwells, elevators and lobby.

2.11 Radial flux energy harvester

Figure 2.16 shows the Radial flux energy harvester. This type of in-pipe hydropower is placed on the water pipelines to power up metering devices. The design of the radial-flux energy harvester is fitting for the house that uses a conventional mechanical water flow meter.

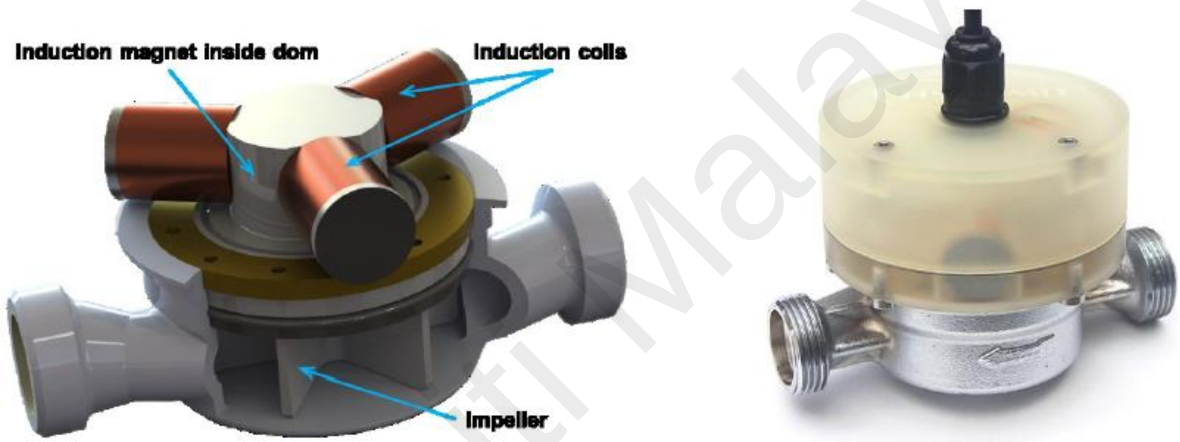


Figure 2.16 Radial flux energy harvester (Hoffmann et al., 2013)

At a minimum flow rate of 3 L/min, the energy harvester can generate electricity approximately to 2mW. When the water tab is fully opened, producing the water flow rate of 20 L/min, the device can generate electricity up to 720 mW. The energy generated is deficient but sufficient enough to power up low power usage devices like a smart meter.

This way, it is possible to install the metering devices at a specific location in existing piping systems without the need for electric and data connections since the devices are self-powered and transmit data via Wi-Fi.

2.12 Summary of current technology In-pipe hydropower

Despite all these in-pipe hydro systems' unique designs and features, it would be very challenging to implement in certain water piping areas, for example in Malaysia where the water piping operators here are very concerned with any objects installed in their pipes that could disrupt water flow in the event of machine failures.

Cost factor certainly is the other critical issue. Thus, a new design should be proposed if the technology is to be viably implemented under such circumstances. In this work, the parallel vertical turbines in-pipe hydro system is proposed to harness the hydropower optimally. The key feature of the design is that it will not have any structures, like a five spherical turbine or cross-flow turbine, placed in the middle of the pipe or anything that will divert the water out of the main passage flow.

The design also allows for maintenance work as any failure incidents of its turbine will not stop the water operation - water will flow as usual. The in-pipe hydropower must never disturb the water flow inside the pipelines. Some of the current design of in-pipe hydropower use too much water pressure inside the pipelines to generate electricity that interrupts the water delivery process. Priority should be given to the water operator to deliver water to the customer.

The outcome of the in-pipe hydropower project not only will generate more awareness on this untapped renewable energy in the country, but also could become a strong case to explore the possibilities of implementing in-pipe hydropower system in the country soon.

3.1 Process in research and development of the prototype

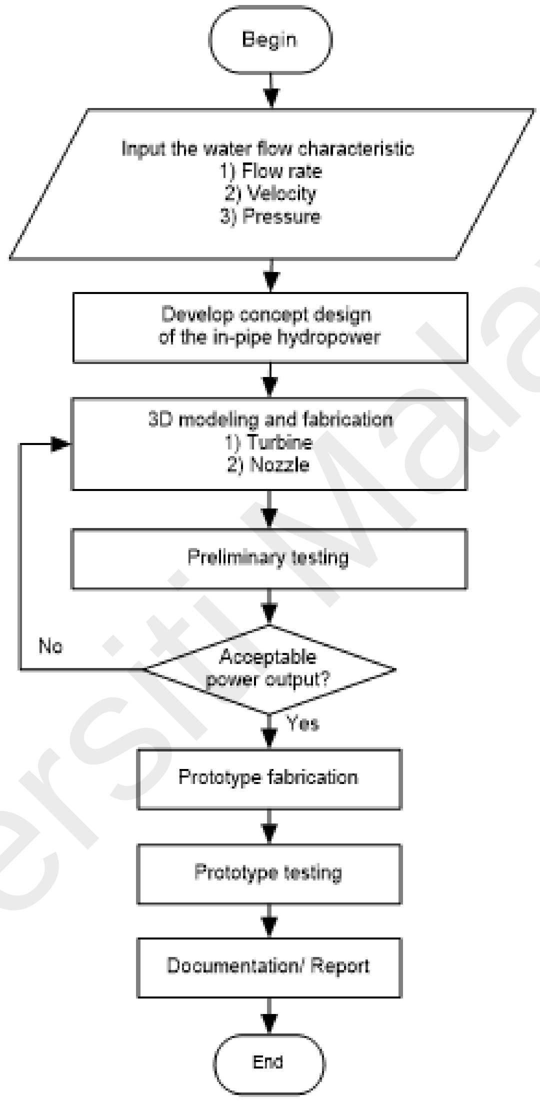


Figure 3.1 Flow chart of the project

The project begins with input of the characteristic of the water flow inside the pipe such as water flow rate, velocity and pressure. This step is important to design a suitable experimental test rig to test the prototype, especially the specification for the water pump and the size of the pipe.

The concept design of the new in-pipe hydropower is designed based on the two vertical turbines. The general idea is to not have something inside the pipe that totally blocks the flow of the water or diverts the water from the main course and causes a significant pressure drop. This design is also equipped with a mechanism that is capable of stopping the water from flowing into the turbine during the maintenance. Therefore, water delivery process is not disturbed.

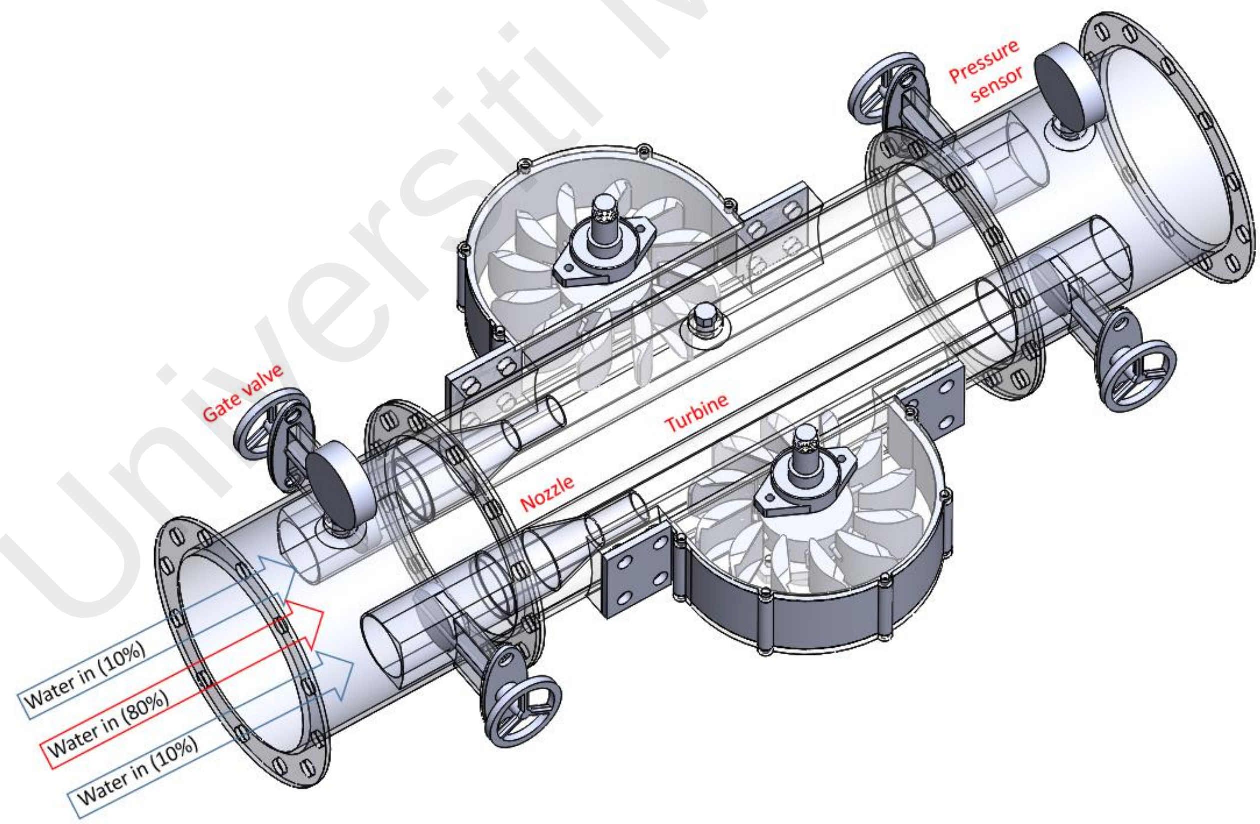
In order to produce an efficient system of the in-pipe hydropower, two critical components play a major role which are nozzle and turbine. A good nozzle produces the strongest water injection force to rotate the turbine and a good turbine should be capable of receiving the maximum water force that is shot from the nozzle to produce the highest mechanical power. Hence, a preliminary test was conducted to the nozzle and turbine to select the most suitable design for the both components.

The test was not directly conducted on the prototype because of lack of flexibility and expensive. In preliminary test, several nozzles and turbine designs can be tested just by doing a little modification on the preliminary experimental test rig. The characteristic of the water flow can also be observed directly as the case of the turbine is made from acrylic which is transparent.

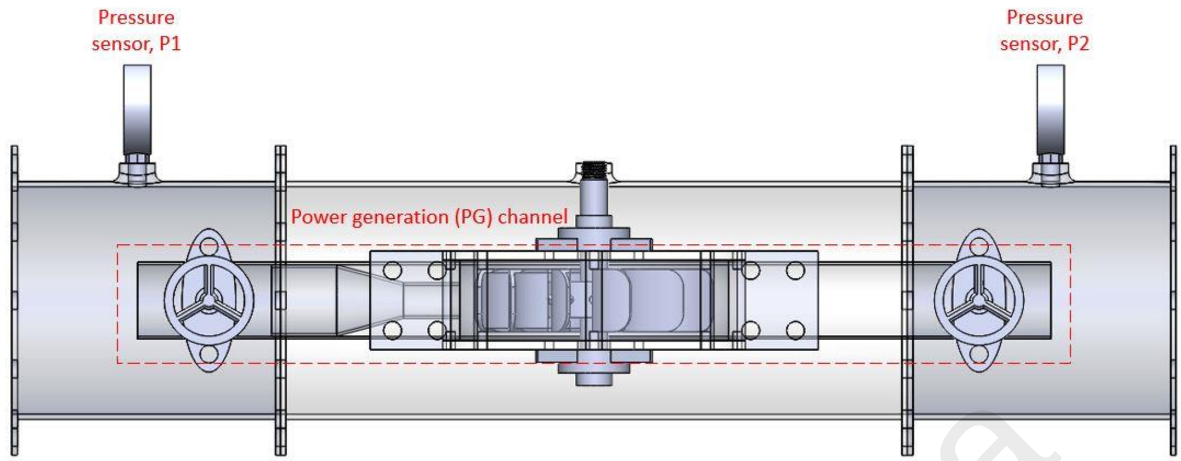
Prototype was fabricated based on the data obtained from the preliminary design conducted. A series of test was conducted on the prototype to measure the value of pressure drop inside the pipe and the amount of electricity generated by the system.

3.2 Design concept of the in-pipe hydro system

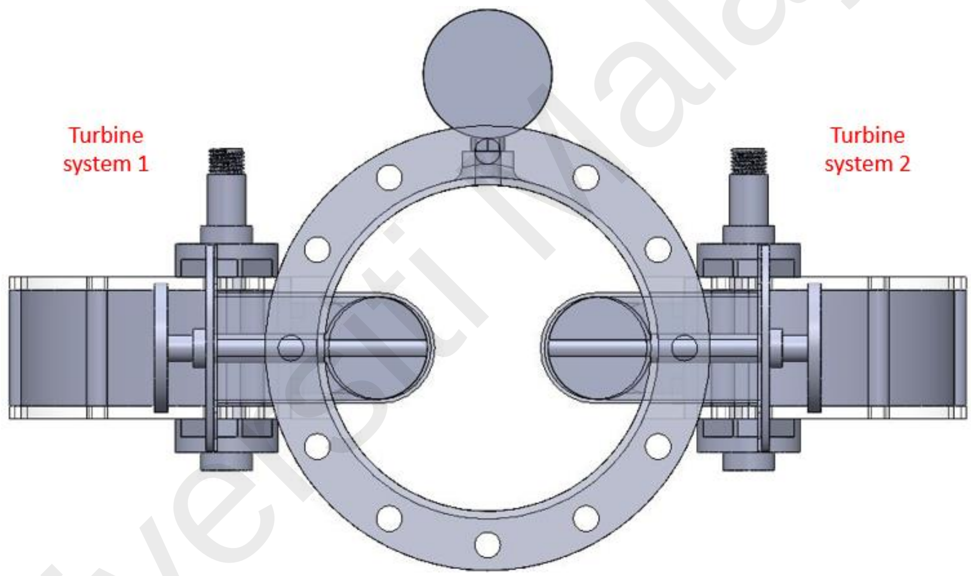
The new in-pipe hydropower system that is proposed in this study is basically a system by which two vertical turbines are incorporated symmetrically side by side in a parallel manner on a pipe that transfers the water, as shown schematically in Figure 3.2. For optimum power generation and at the same time avoiding water diversion from the main pipe watercourse, the system is designed in such a way that part of the turbine is partly inside the pipe and partly outside. The water in the pipe will flow in three different channels – a main channel and two power generation (PG) channels.



3.2a) 3D view



3.2b) Right View



3.2c) Front View

Figure 3.2 Prototype of parallel vertical turbines in-pipe hydro system

Most of the water will flow into the main channel and the rest will be directed into the two PG channels where each is to receive the same amount of water flow. In the PG channels, nozzles are incorporated. These nozzles will increase the velocity of the water before it hits the turbine blades. For electrical power generation, each turbine is connected to the electric power generator by an extension shaft. After hitting the turbine's blades, the water will flow along the PG channels back into the pipeline and mix with the water again from the main water channel.

Unlike other available in-pipe hydro systems, the approach of the design here is not to totally obstruct the pipe with any structures or diverting the water out of its original course to generate power. The idea is to generate power by only partially using the water that is flowing in the pipe while at the same time maintains the watercourse. In another word, within a single pipe, water is separated into regions.

By having this type of design, it allows for the water having excessive pressure to be channeled for electricity power generation purpose. For example, if the water has an excessive water pressure of 20%, by estimation, only around 20% of the water flow will be channeled into the PG channels – 10% for each PG channel – while the balance 80% will flow almost uninterruptedly into the main channel. This way, the nozzles can optimally accelerate the water that flows into the PG channels before hitting the turbines' blades.

Another key feature of the proposed in-pipe hydropower in this work as compared with the existing in-pipe hydropower system in the market is on the design that foreseen the issues of services and maintenance work. The in-pipe hydropower system is equipped with gate valves. The gate valves at the power generation (PG) channels can be opened and closed depending on the situation. During the maintenance or service work, the gate valves will be closed and water will not flow into the PG channels. However, water can still flow continuously into the main channel uninterrupted. This way, maintenance or service work won't be difficult to schedule or carry out. The PG channels basically act as "embedded bypass" that make the system compact, not requiring extra space, thus making it very suitable for urban areas.

Since the in-pipe hydro system is an enclosed one, other than performance, the nozzle and turbine are designed with consideration put on water backflow phenomena, where water flow is restricted and flows in the opposite direction. Backflow phenomena will increase pressure in the pipe. Nozzle ratio and the blade's surface where the injected water will be hitting have to be balanced optimally. This is the reason why the established Pelton turbine that is used in the conventional open hydropower system is not used here. However, it is not to say that the Pelton turbine cannot be totally used in this system. Some modifications might have to be made to the Pelton turbine design if it is to be used here.

In the actual water distribution system, a pressure reducer valve (PRV) is normally used to regulate water flow. The excess pressure available in the pipe might change with water demand. Higher future water demand means the PRV will be further opened making more water flowing thus lowering excess pressure (Dawadi & Ahmad, 2013). This is the reason why the prototype in this work is using two turbines instead of one with a larger size. With two turbines, it makes the system more flexible with demand and more cost-effective.

Another benefit of using a twin-turbine is making sure power is always available if one of them experiences a problem. This is very critical for most energy-intensive activities (Harrison Cahill, 2015). It will also dependency on an expensive backup system like energy storage (Wood III, Li, & Daniel, 2015).

3.3 Lab-scale experimental setup

Figure 3.3 shows the schematic diagram of the test rig - consisting of a water tank, a water pump, a working unit, flexible pipe, turbine, power generator, pulley system, and the hydro valve used in this study.

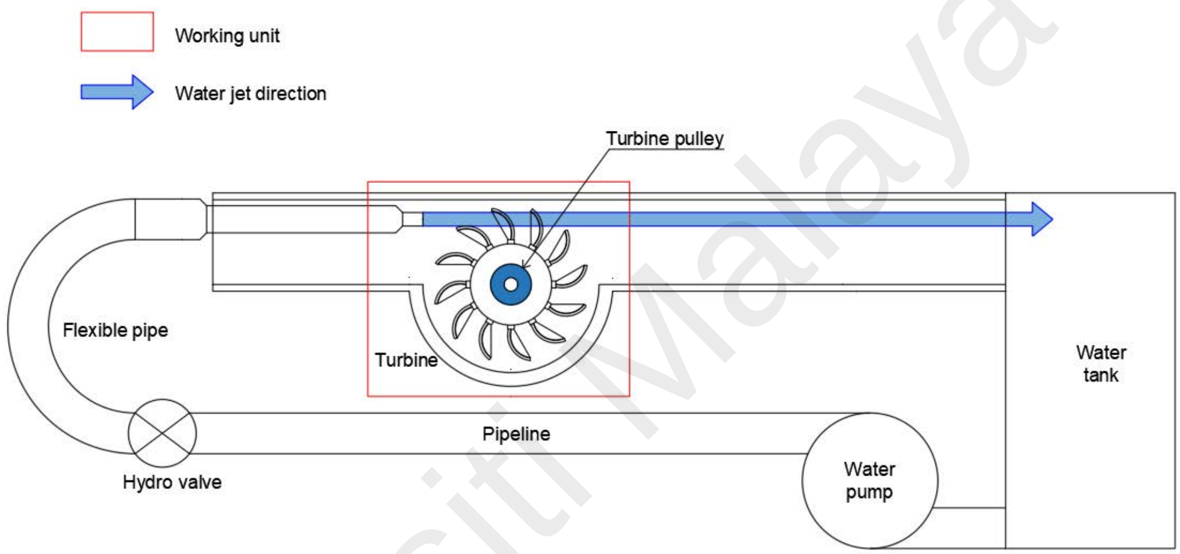


Figure 3.3 Schematic diagram of the experiment set up

Firstly, the water pump with 1648 W (2.2 hp) of power rating is used to pump water flow into the working unit. The pump will suck water from the water tank and flows it into the nozzle through a 60 mm pipe (Outside diameter = 60 mm and inner diameter 55 mm).

The nozzle will then compress and inject the water to turn and rotate a specially designed vertical turbine attached to the working unit. The water then will flow back into the water tank. The cycle will be repeated until the switch is off. The results and data will be recorded for analysis.

3.4 Working unit

In the actual design, the working unit is basically the PG channel where the turbine and nozzle are incorporated. To visually observe the water flow characteristics, here, the working unit is fabricated from acrylic, a transparent plastic material as shown in Figure 3.4.

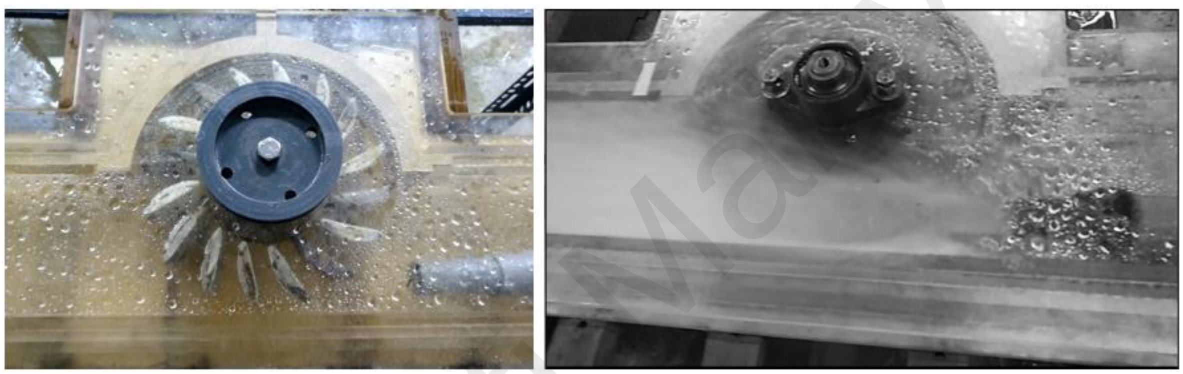


Figure 3.4 Working area made of acrylic

3.5 Nozzle

The nozzle has a specific nozzle ratio – input diameter/ output diameter – is also designed to optimally compress the water to produce the highest possible force when it hits the blades' surface at a designated distance, *h* of 85 mm.

The Nozzle detail is listed in Table 3.1. The input inner diameter is fixed at 40 mm before reduced into the different output inner diameter. The thickness of the nozzle is 2 mm. The angle of the reducer is fixed at 90 degrees.

Table 3.1 Nozzle details

Input Inner diameter (mm)	Output Inner diameter (mm)	Nozzle ratio = $\frac{\text{Input diameter}}{\text{Output diameter}}$
40	40	1.000
40	30	0.750
40	20	0.500
40	17	0.425
40	15	0.375
40	10	0.250

3.5.1 Nozzle design

The nozzle is designed by using AutoCAD and Solidworks. Figure 3.5 shows the nozzle design. The CAD image from the SolidWorks is imported into the simplify 3D software to generate G-code, the slicing information. This information will be transferred to a 3D printer machine for the fabrication process.

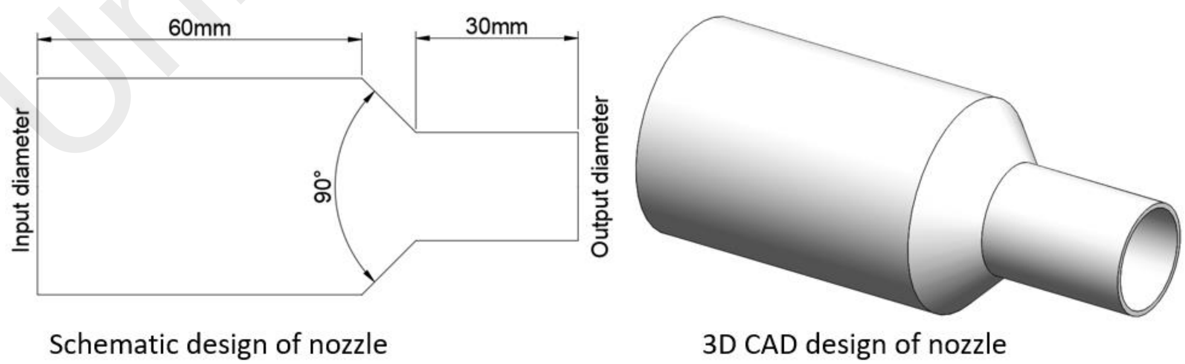


Figure 3.5 Nozzle design

3.5.2 Nozzle fabrication process

The nozzle used in the experiment is fabricated by the 3D printer. A 3D printer machine can print the nozzle at very specific details. For example, the reducer angle of the nozzle is fixed at 90 degrees and nozzle ratio is set between 0.25 to 1.00. The production cost is low and much easier than using conventional methods like sand casting or CNC machine.

As a start, the filament is fed into the machine. The machine will melt the filament at the melting temperature. The melted filament will flow into an extruder and the machine will start printing. The printing product and details are shows in figure 3.6 and listed in table 3.2.

Table 3.2 Printing details

Characteristics	Details
3D Printer model	Anet A8
Material	PLA (White)
Printing density	100 % filling
Filament diameter	1.75 mm
Extruder tip size	0.4 mm
Extruder temperature	190 – 210 ºC
Bed temperature	30 – 60 ºC
Method of slicing	Grid (Zip zap)
Rotor speed travel	100 %
General quality	High
Time	Approximately 1.30 hours

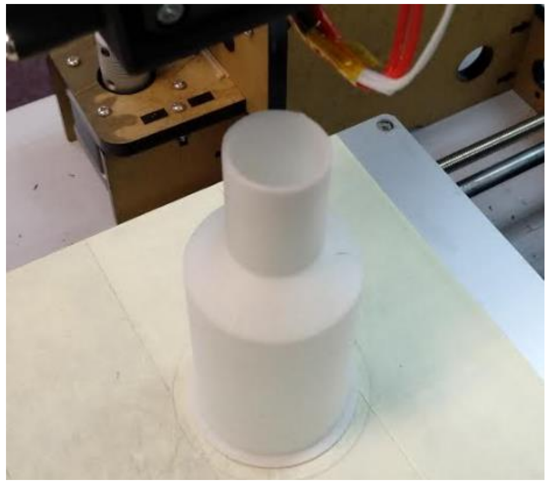


Figure 3.6 Nozzle fabricated by 3D printer

3.5.3 Nozzle testing and evaluation

In this experiment, the different ratio size of the nozzle will be tested in term of water flow rate and water force. The best design of the nozzle will be used in the prototype.

3.5.3.1 Flow rate

The flow rate of the water flow is measured by using a conventional method. The experiment test does not use the flow rate meter. The reason is the existence of blades inside the flow meter that act as a flow sensor, disturb the flow of water. It create the small bubble that reduce the value of water force. Hence, lacking in accuracy.

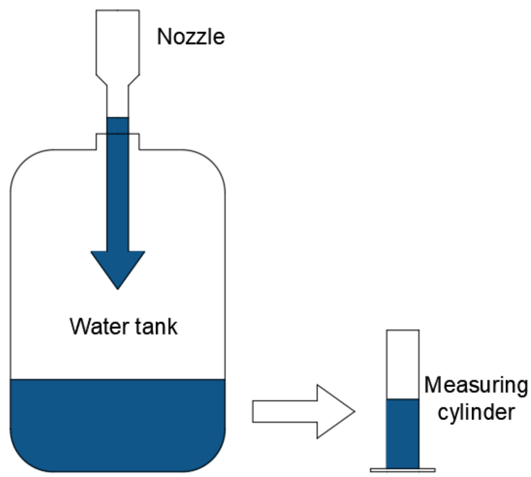


Figure 3.7 Flow rate measurement

Figure 3.7 shows the schematic diagram of the flow rate measurement setup. First, the water is shot inside a water tank for 3 minutes. The total volume of water inside the water tank is measured by using a measuring cylinder. The value of the water flow rate is obtained by dividing the total volume of water inside the tank with 3 minutes, as stated by formula 3.1. The experiment is repeated by using the nozzle at a different ratio, 0.25 to 1.00.

$$\text{Flow rate} = \frac{\text{Total volume of water}}{\text{Time}} = \frac{\text{Total volume of water}}{\text{3 minutes}} \qquad (3.1)$$

3.5.3.2 Water force

The value of the water force is measured by using a digital hanging weighing machine. Figure 3.8 shows the schematic diagram for the force measurement method.

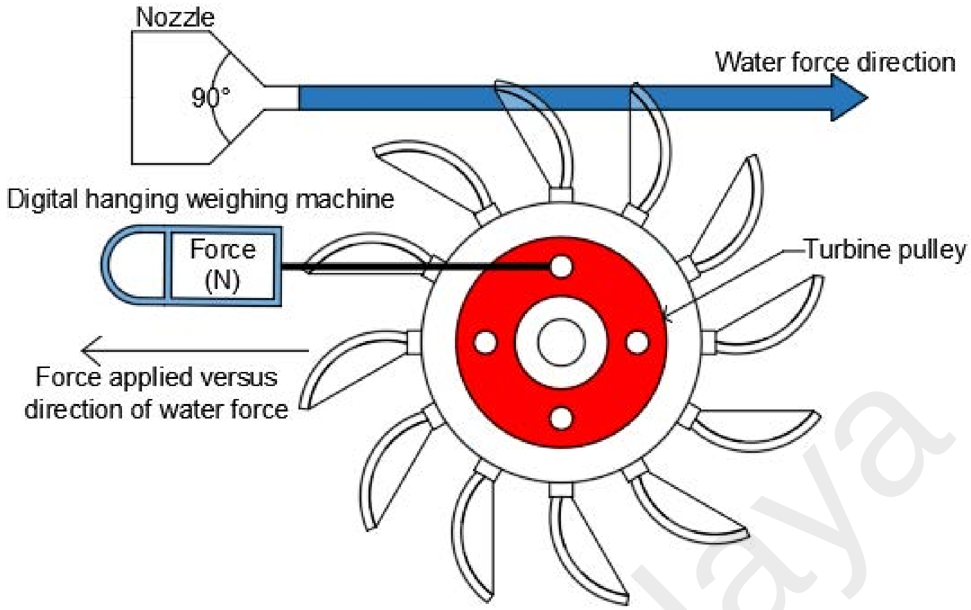


Figure 3.8 Force measurement method

The actual force here is measured using a digital hanging weighing machine that is connected to the pulley when the water force hits the blade as schematically shown in Figure 3.8. The opposite force is applied to the digital hanging weighing machine.

When the turbine stays in a stationary position, the value of the water force is equal to the opposite force. The value water force can be determined by taking the value of the opposite force that displays on the sensor. However, the digital hanging weighing machine will only measure the unit of mass. The value of the opposite force or water force can be calculated by using formula 3.2.

$$F = ma \tag{3.2}$$

Where F is force, m is mass of the water and a is the acceleration of the water.

3.6 Turbine

Turbine is designed base on the pelton turbine and turgo turbine. However, both of these turbine are working at the higher water head and flow rates. Making it difficult to use in this prototype. Hence, some modification is done to make sure this inhouse turbine is suitable for the prototype.

3.6.1 Housing

The turbine housing here is designed to accommodate up to 12 and 16 blades. Each blade is inserted into the housing and tightened using the Allen key screw. The housing is designed by using AutoCAD as shown in Figure 3.9. The workpiece is fabricated by using the CNC machine. The housing is made up of mild steel and weighs about 1900g. The thickness is 20 mm.

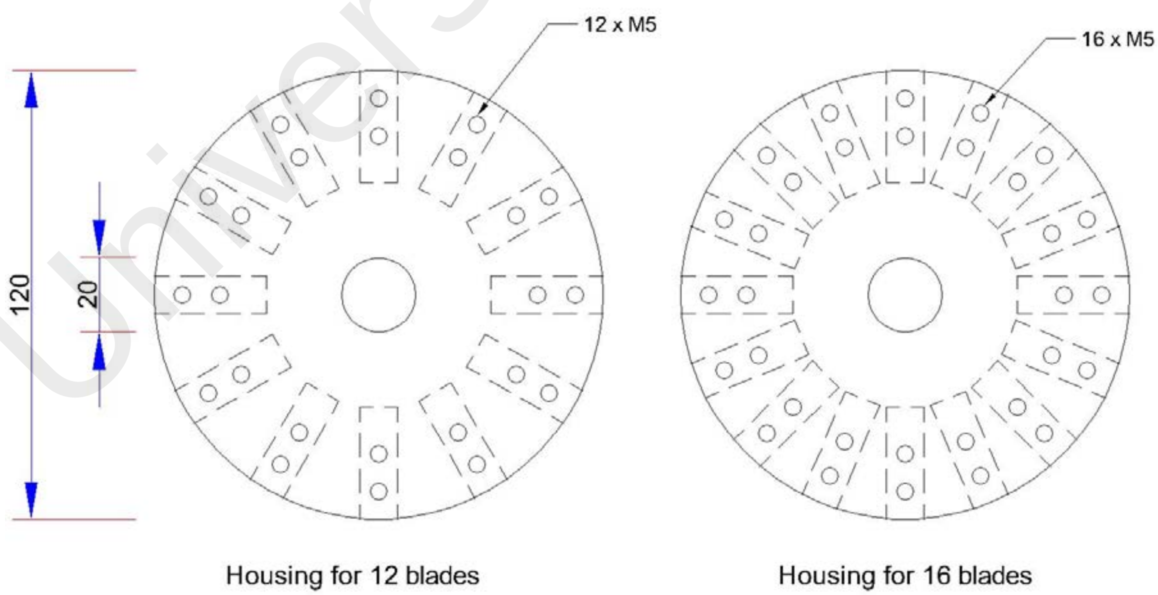


Figure 3.9 Housing

3.6.2 Blade

The blade is designed so that it will be able to receive the water injection force from a nozzle and produce rotational movement optimally. The design is shown in Figure 3.10. The blade is designed with an angle of 60 degrees, facing toward the injection nozzle. The reason is to increase the surface area of the blade. The area of the blade is 46 mm (Width) x 60 mm (Length). The material used is mild steel and each blade weighs about 110g.

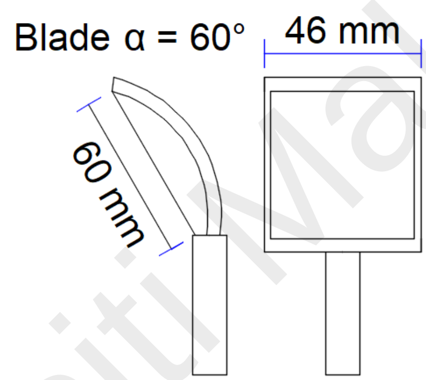


Figure 3.10 Blade

3.6.3 Turbine testing and evaluation

To test and evaluate the blade's point effectiveness, the nozzle is positioned so that it can inject water typically at three different blade parts – high, mid and low. Figure 3.11 shows the working unit components and water injection details. The distance between the injection nozzle and blade is 85 mm and the angle of injection is 0 degrees.

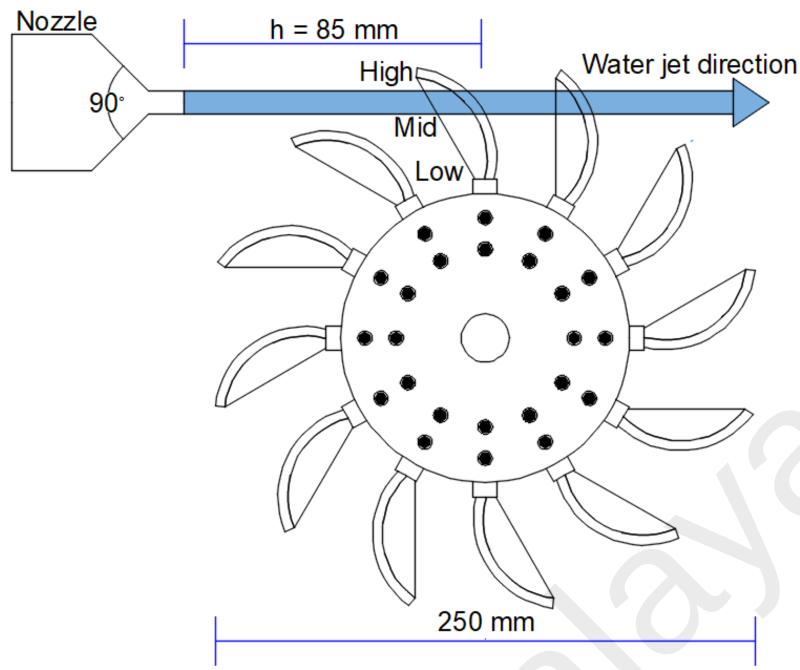


Figure 3.11 Water injection details for turbine housing with 12 blades

Table 3.3 listed the details of the turbine with the respective number of blades used in the testing. A balanced arrangement of blades is very critical for stable and effective power production.

Table 3.3 Turbine wheel details

Number of blades	Weight of turbine wheel (Kg)	Angle per blade $\left(\frac{360^0}{\text{No of blade}}\right)$	Circumference per blade $\left(\frac{2\pi r}{\text{No of blade}}\right)$ (mm)
2	2.12	180.0	188.50
4	2.34	90.0	94.25
6	2.56	60.0	62.83
8	2.78	45.0	47.13
12	3.22	30.0	31.42
16	3.66	22.5	23.57

3.6.4 Turbine efficiency

The performance of the nozzle and the turbine are evaluated based on the force and power that is generated from the system. The actual force here is measured using a digital hanging weighing machine that is connected to the pulley when water force hit the blade.

A tachometer is used to measure the turbine rotation. The power obtained in the experiment is also compared with the power from the as-received water flow. The power obtained in the experiment can be calculated by using formula 3.3.

$$P_{mech} = \frac{2\pi\tau\omega}{60} \tag{3.3}$$

Where P_{mech} is mechanical power (Watt), τ is torque (N m) and ω is turbine rotational speed (RPM).

Torque is derived from the following equation:

$$\tau = rF\sin\theta \tag{3.4}$$

Where r is radius of the turbine pulley (m), F is water injection force (N), θ is the angle of the water injection force (°).

The efficiency, η of the system could be calculated from the following equation:

$$\text{Efficiency, } \eta = \frac{\text{Experiment power}}{\text{As recieved water flow power}} \text{ x } 100 \quad (3.5)$$

The “As received water flow power “ is derived from the following equation:

$$As\ received\ water\ flow\ power = Fv\sin\theta \quad (3.6)$$

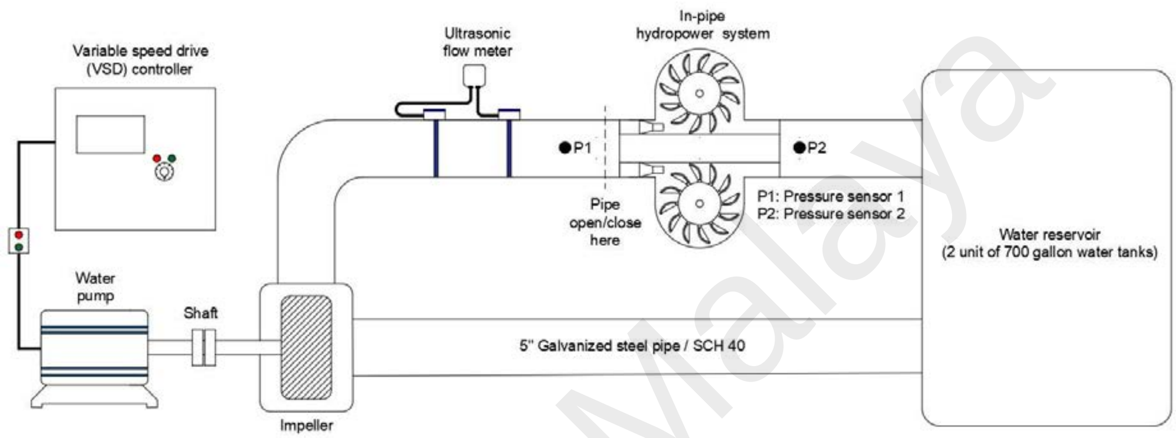
Where *v* is the velocity of the water (m/s).

3.7 Prototype fabrication and testing

Based on the earlier experiment results, at a smaller scale, the prototype of the in-pipe hydropower system is fabricated based on a 5-inch diameter steel pipe. The PG channels of the prototype is estimated to receive 20% (10% each) of the water flow. It is fabricated from a combination of steel (turbine system) and aluminum (body) as shown in figure 3.12.

Figure 3.12 Actual image of the prototype

To test the workability of the prototype, a new set of test rig – consisting of 2 units of 700 gallons water tanks, a 7.5 kW water pump, an ultrasonic flow meter, pressure sensors, a variable speed drive (VSD) motor controller and electric power generator – is designed. Figure 3.13 shows the schematic diagram of the experimental rig and the actual image.



3.13a) Schematic diagram of the experimental test rig

3.13b) Actual image of the experimental test rig

Figure 3.13 Prototype testing rig

There are two situations here, where the experiment runs at a fully opened pipe and at fully closed pipe. Running at a fully closed pipe is only to measure the total pressure inside the pipe generated by the water pump against the water flow. Other than this situation, the experiment runs at a fully open pipe at all times.

Lastly, A fully opened pipe without the prototype fixed into the experimental test rig was also conducted to observed the pressure at P1 and P2. The percentage of pressure loss from the prototype is shown below:

$$\frac{\text{Pressure at P1 - Pressure at P2 (pipe fully opened)}}{\text{Pressure at P1 }\left(\text{pipe fully closed}\right)} \text{ x } 100 = \text{Percentage of pressure loss} \tag{3.7}$$

Equation 3.7 is used to calculate the percentage of pressure loss by the prototype. The value of the pressure at P1 minus the value of the pressure at P2 stands for the pressure loss caused by the prototype. The value of pressure is taken at P1 and P2 when the pipe is fully opened and the prototype is fixed to the experimental test rig.

The value of the pressure when the pipe is fully closed stands for the total pressure inside the pipe.The value of pressure is taken at P1 when the pipe is fully closed. By dividing the two values and multiply it by 100, the percentage of pressure loss is obtained.

To estimate the electric power generation, the turbines are connected to the power generator (Missouri Wind and Solar, n.d). The electric power generator rotational (RPM) and power range relationship is provided by the manufacturer and shown in Table 3.4.

Table 3.4: Generator properties

Generator rotational speed (RPM)	Electrical power range (Watt)
0 – 300	0 – 300
300 -1400	300 - 800
1400 - 2500	800 - 1500
2500 - 3700	1500 – 2500

CHAPTER 4: RESULT AND DISCUSSION

4.1 Preliminary testing result

Figure 4.1 shows the results of the water flow rate at different nozzle ratio conditions. The water flow rate and nozzle ratio seem to show a linear relation. The flow rate at nozzle ratio 1 where the water flow was not throttled at all was the highest at 480 L/min. This is the as received water flow value. At the lowest 0.25 nozzle ratio, the flow rate was around 80 L/min.

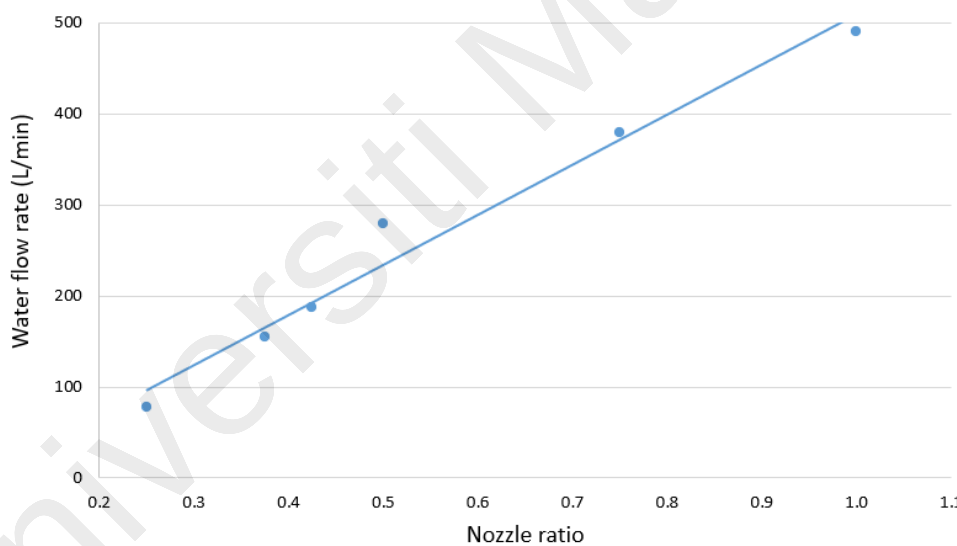


Figure 4.1Water flow rate versus nozzle ratio

Figure 4.2 shows the actual force generated by the water flow at the blade's surface under different nozzle ratio conditions. The generated force depends on the mass (flow rate), the velocity of the water and the surface area of the injected water and the receiving side – the blade.

The water force increased with the nozzle ratio until it reached a maximum value of about 67 N at a 0.5 nozzle ratio. When the nozzle ratio is bigger than 0.5, the injected water surface area becomes bigger and the water doesn't fully hit the blade's surface, thus the water force decreases. This can be proved by comparing the blade design in figure 3.9 and the nozzle properties in table 3.1.

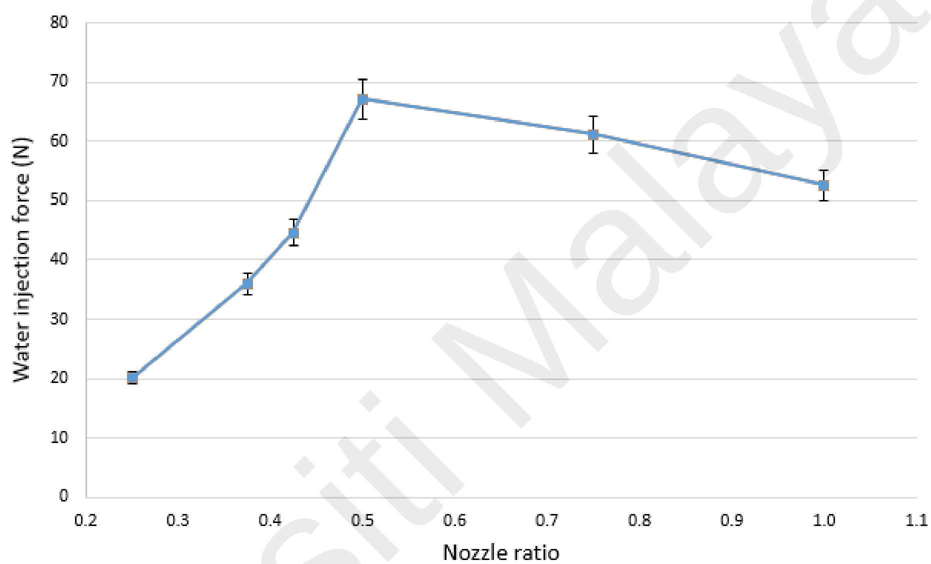


Figure 4.2Water injection force versus nozzle ratio

To get the optimum rotational speed (round per minute – RPM) of the turbine, the test was conducted at various numbers of blades. It was tested using 0.5 nozzle ratio condition (water force of 67 N), Figure 4.3 shows the RPM produced and also the resultant mechanical power. The rotational speed and mechanical power increased with the number of the blade and reached a maximum value of 1125 RPM and 950 W respectively with 12 blades. With 16 blades, both the rotational speed and mechanical power decreased.

Having more blades will make the water force hit the blades more frequently and thus increases the rotational speed. However with 16 blades, as schematically shown in Figure 4.4, the injected water force from the nozzle will most likely hit 2 blades (circled area) at a time thus reducing the amount of force per blade and as a result, the rotational speed is compromised.

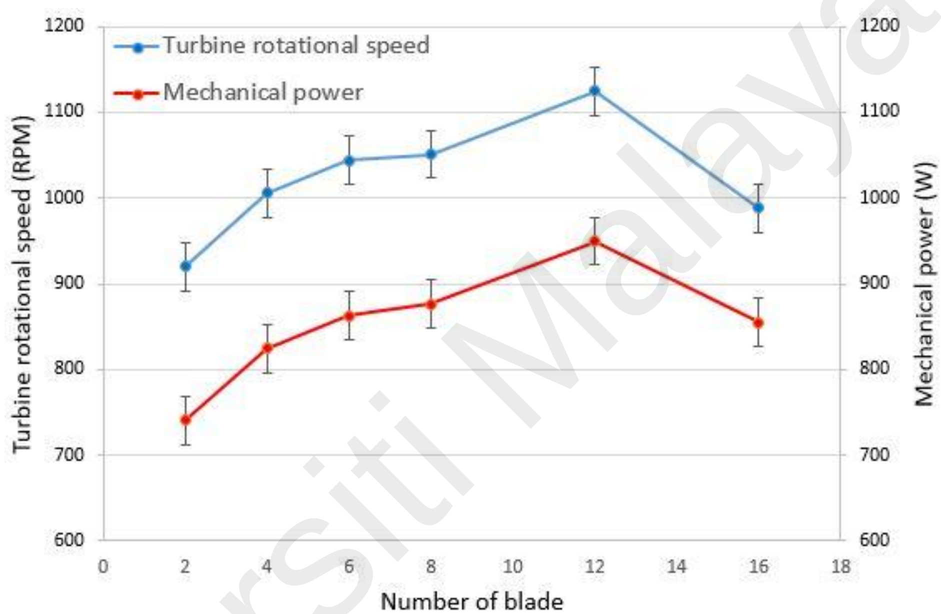


Figure 4.3Turbine rotational speed and (RPM) Mechanical power (W) versus the number of blades

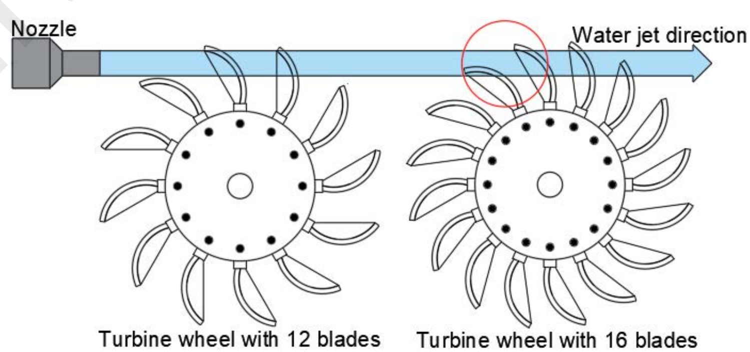


Figure 4.4 Comparison of the injected water hitting point between 12 blades and 16 blades

Figure 4.5 shows the mechanical power obtained when the injected water from the nozzle hit at the high, mid and low regions of the blade. Directing the injected water at the right point is very critical in obtaining effective power. As shown in figure 3.10 and figure 4.4, when the nozzle is moving at position mid and low, the water injection force will hit 2 blades, similar situation when the number of the blade is 16.

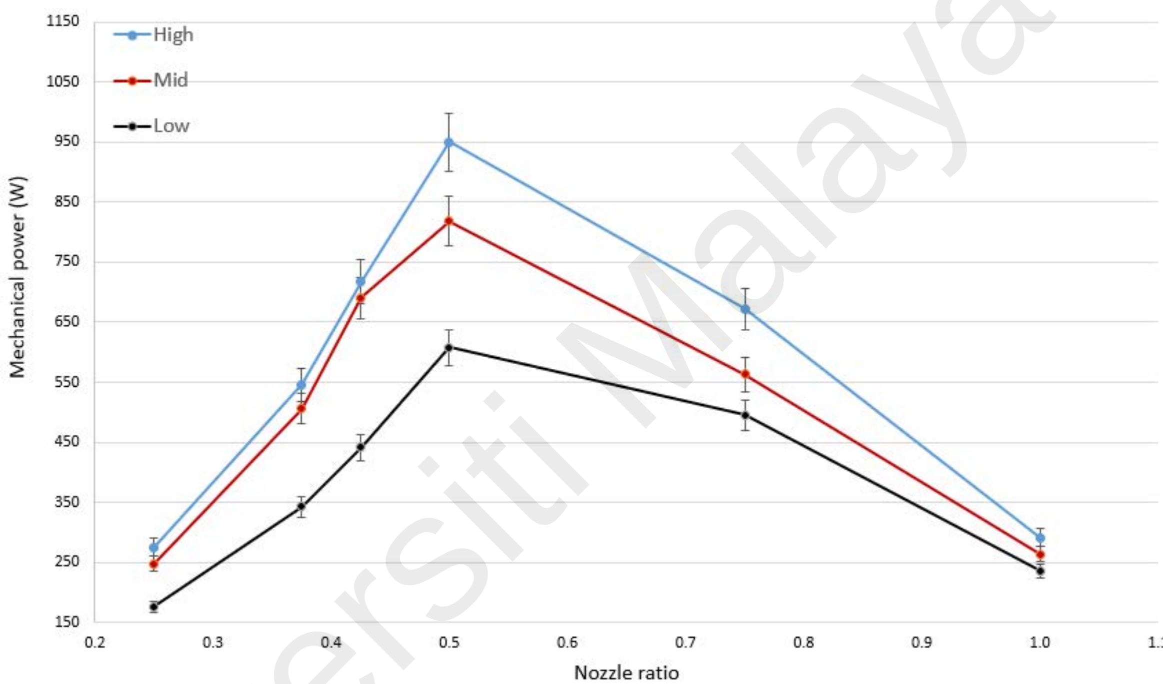


Figure 4.5 Mechanical power when water aimed at 3 different positions (high, mid and low)

The optimum 950 W experimental mechanical power achieved here was about 93% of the theoretical value derived from equation (3.5). In comparison to the Turgo and Pelton, the efficiency of those turbines is at 80 - 91 % (Cobb & Sharp, 2013; Williamson, Stark, & Booker, 2013) and 75 – 85 % (Thake, 2000) under the best condition. While the efficiency of the pump as the turbine (PAT) is only 60 % (Motwani et al., 2013). This turbine efficiency can be considered good enough to be used in the prototype.

4.2 Prototype testing results

Figure 4.6 shows the relation of the pressure and flow rate when the pipe is fully closed, fully opened but without the prototype fixed to the test rig, and also when the pipe is fully opened with the prototype fixed to the test rig.

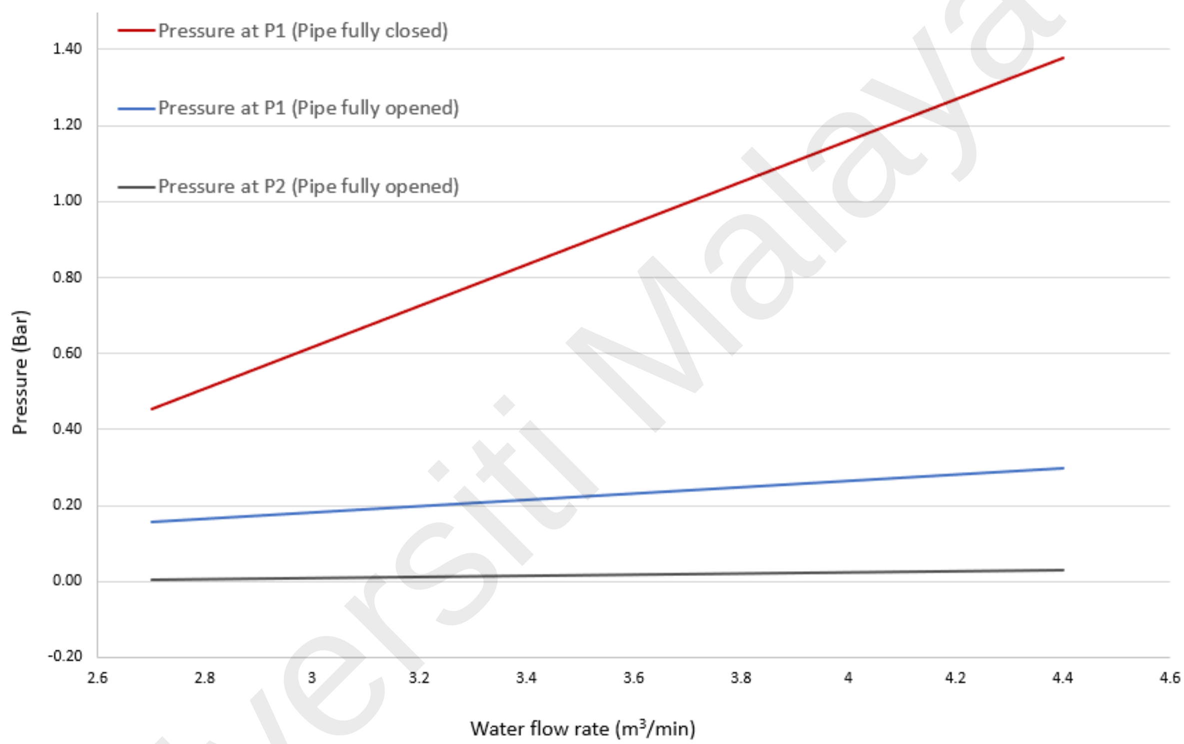


Figure 4.6 Pressure versus water flow rate

As shown in the figure, when the pipe was fully closed, the pressure increased quite markedly from around 0.5 Bar at a flow rate of about 2.7 m^3/min to 1.4 Bar at 4.4 m^3/min. However, when the pipe was fully opened but without the prototype fixed to the test rig, the pressure dropped to almost 0 and almost constant with the flow rate. When the pipe was fully opened but with the prototype fixed to the test rig, the pressure was around 0.18 Bar at

2.7m^3/min flow rate but just slightly increased to 0.30 Bar at 4.4 m^3/min flow rate. No sign of water backflow was noticed throughout the testing.

The pressure loss because of the prototype can be obtained from relation (3.5). The pressure loss at the lowest and highest flow rate – 2.7 and 4.4 m^3/min –was about 36% and 21% respectively. This shows that the pressure loss will reduce as the flow rate is higher.

The pressure sensor was placed at two locations which were at before (P1) and after (P2) the prototype. The pressure only spiked at P1 because the prototype was partially blocking the water flow. The pressure sensor at P1 was reading the pressure accumulating there.

Meanwhile, the pressure P2 remained zero of all time because there was no resistance placed inside the pipe after the prototype. There was no pressure accumulated there. This shows that once the water converges after the system, the pressure will be back to its original condition of free-flowing without restriction.

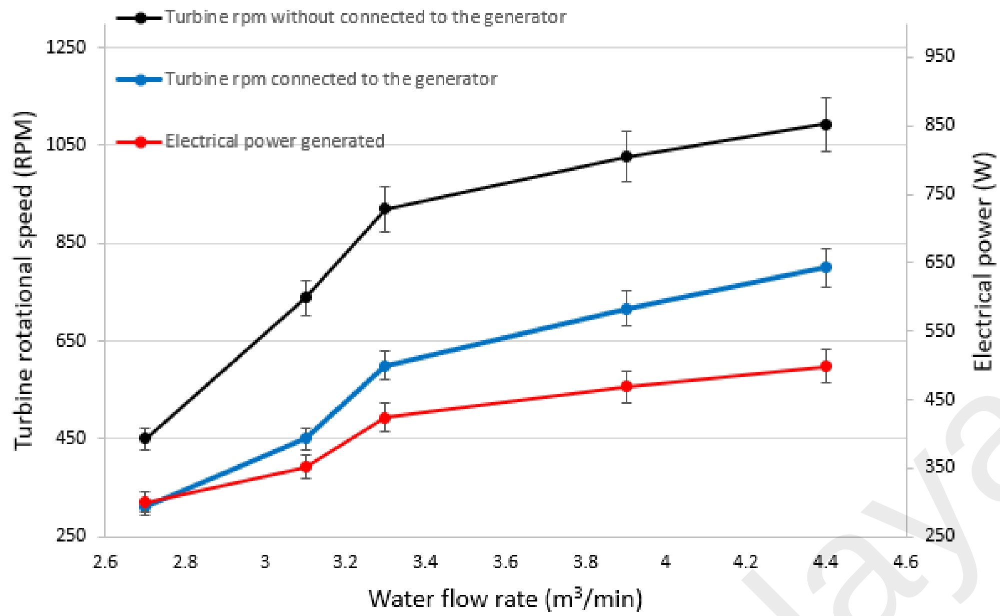


Figure 4.7 RPM and estimated electrical power versus water flow rate

The RPM of each turbine when it is not connected and connected to the electric power generator is shown in Figure 4.7. The RPM increased from about 600 to 1100 when the electric generator was not connected. A decrease in the RPM when the generator is connected is expected due to magnetic field resistance in the power generator.

The RPM value for each turbine was however very consistent suggesting that the water flowed uniformly in both PG channels. The estimated electrical power generated from each generator is also shown in the figure. At the highest flow rate condition, in total, about 1 kW of electric power was generated from the prototype.

From the preliminary testing results, the newly designed and developed in-pipe hydropower prototype has shown that not only it offers an alternative way of harvesting hydropower, it is also a workable system. As mentioned earlier, depending on the amount of allowable pressure available, the system can be designed to harness the power optimally. With some improvement and modification to the design, it can also act as a pressure relief valve (PRV).

CHAPTER 5: CONCLUSION

This study is about the development of a new in-pipe hydropower prototype system using two vertical turbines, designed to harness energy from the water that is flowing in a pipe.

A series of testing has been conducted to evaluate the performance of the specially designed nozzle and turbine system first, before fabricating the actual in-pipe hydro prototype based on a 5-inch steel pipe. Preliminary testing on the prototype was conducted to evaluate its workability and performance.

The results show that the prototype was working appropriately without any sign of water backflow throughout the testing. Testing was conducted at a range of water flow up to the maximum of 4.4 m^3/ min, with maximum pressure of 1.4 Bar. At the maximum water flow condition, the system can generate about 1 kW of electric power, with around 21% of pressure loss.

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