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An Experimental study on cross flow turbine performance for an In-pipe water system

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ABSTRACT

This paper presents the comparison performance of the cross flow turbines for 110mm in-pipe water distribution system. In this study, a 6-blade, 12-blade and 20-blade cross flow turbines have been designed and developed for the purpose of determination of the optimum blade number for the proposed in-pipe water system. To obtain this, the orientation entry angle was fixed at 54.78°C. Investigation also paid on the comparison performance of alternating current (AC) and direct current (DC) generators; a STD MTR QK1-4637 24V model for DC permanent magnet synchronous generator (PMSG) and a SKU348657 24V AC PMSG. From the experimental study, it has been found that 12-blade presents the best performance in terms of electrical quantity compared to 6-blade and 20-blade, for both generators. This is due to the maximally of the force exerted on the blades' surface. Besides the factors of blade geometry and design, it has been observed that the type of generator also play important role in terms of electrical generation efficiency. For water piping distribution system with diameter of 110mm, DC PMSG is recommended as it has better ability to provide better torque, and hence offering almost two times higher of the electrical power generation compared to the chosen AC PMSG.

Key words: Cross flow, in-pipe system, orientation entry angle, water energy.

1. INTRODUCTION

As Malaysia is a tropical rainforest country, rainfall is present throughout the year and hence supplying consistent water supply for Malaysian. The production of clean water has increased by 377 million litres per day (MLD) in 2016, makes the total production of 16,536 MLD compared to year 2015 and it means that 95.7% Malaysian were piped with clean water supply [1]. Figure 1 shows the amount of rainfall, and the production of clean water supplied for whole Malaysia in 2017 [1]. Based on the figure, it can be seen that 97.2% of urban and 93.5% of rural area were already supplied with piped clean water. This stable and reliable clean water supply are supported with huge amount of rainfall and moderate temperature of Malaysia where the highest average amount of rainfall was 5,423.0 mm at Kuching while the lowest was 1,397.8 mm at Temerloh. Malaysia is a tropical rainforest country, and so far the highest temperature recorded is 34.2 degree Celsius while the lowest temperature is 16.2 degree Celsius. With this range of temperature, lower water level does not become such a big issue since Malaysia has multiple clean water sources to support the demand from the residents.

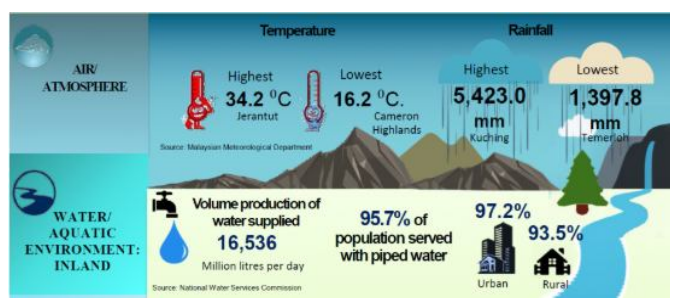

Figure 1: The amount of rainfall and volume production of water supply for rural and urban area [1]

So far, Malaysia still depending on the thermal power plants as its main electricity generation source, which powered by coal and fuel. While for hydro, if compared to thermal power plant, the total electricity generated by hydro is very low. The comparison between electricity generated for hydro and thermal is shown in Table 1. Based on the table, it can be observed that even though there is increment in electricity generation for hydro power plant, a major growth also can be observed for thermal stations. In year 1978, electricity generation is only 77 ktoe for hydro power plant while for thermal stations, electricity generation is 633 ktoe. This is however increased every year and in 2016, electricity generation for hydro power station is 1722 ktoe and 11222 ktoe for thermal stations. This is to support increment in load demands as Malaysia keeps on growing to achieve the status of developed country. Hence, to reduce dependency on thermal energy, renewable energy sources for instance, this hydro power needs to be fully utilized and expanded.

Table 1: The amount of electricity generation in kilotonne of oil equivalent (ktoe) from year 1978 to 2016 for hydro and thermal stations [2]

Year	Electricity Generation (ktoe)		Year	Electricity Generation (ktoe)	
	Hydro	Thermal Stations		Hydro	Thermal Stations
1978	77	633	1998	417	4576
1979	94	695	1999	647	4762
1980	120	744	2000	599	5132
1981	133	795	2001	607	5333
1982	128	885	2002	456	5771
1983	149	948	2003	435	6134
1984	294	888	2004	501	6215
1985	321	964	2005	446	6259
1986	351	1036	2006	554	6687
1987	423	1075	2007	558	7366
1988	488	1176	2008	642	7321
1989	451	1399	2009	574	7957
1990	343	1636	2010	540	8864
1991	379	1904	2011	656	9648
1992	375	2146	2012	779	10253
1993	419	2568	2013	1003	10627
1994	561	2801	2014	1152	11075
1995	535	3374	2015	1346	11047
1996	446	3975	2016	1722	11222
1997	333	4644			

Piping system can be defined as a series of pipe network that connect with one another from a junction to a desired area of supplied. Water piping in Malaysia can be considered as stable, as no major crisis experienced so far. From research conducted by J. Chen et al. [3], energy can be generated from the water piping system by making the flowing water inside the pipe. Flowing water produces force to rotate the water turbine and generate electricity as a concept of hydro.

Based on the report that has been published in 2008 [4], it has been estimated that the average daily domestic water usage (5,481 MLD) [4] in Malaysia was mainly used for the toilet purpose (30%) and followed by bath or shower (28%). 20% went to clothing and washing, cleaning for 15%, cooking or drinking for 4% and leakage was about 2%. However, in 2016, the 16, 536 MLD clean water has been supplied for the whole Malaysia. Hence, this data presents an impressive sign that Malaysia has a good and reliable water supply. Fast load grow rate for electricity became a heavy challenges for utility companies. Due to environmental policies, electricity provider needs to harvest electricity from existing system by utilizing all the possible sources. So, for piping system, running water in it is so far wasted. Therefore, installing a turbine and generate power from the flowing water inside can be a good initiative. Generated power can be used to power up the surrounding facilities such as low powered street lighting without burdening the main grid.

As Malaysian use the piped water every day and frequent, this running water inside the piping system can rotate the impulse type turbine installed on it. Hence, this is not just provide clean water to people, but at the same time can generate renewable energy from it. Even though Malaysia has alternative sources from other renewable energies such as solar and wind, water is still our main concern because it is used almost every time and more stable. Installing a new major hydro power station can be so high in costing and harmful to the environment as it needs a huge dam. At the same time, need to compete for land and water sources during this recent years. Therefore, by focusing on the hydro power in micro scale but considering water flow in huge quantity, we can generate electricity without spending significant amount of money.

Cross flow water turbine has a good performance when used for low head condition and minimal water flow. The construction of cross flow turbine also quite simple and it can be fitted inside the pipeline flexibly. However, the water flow in the water pipeline is difficult to determine due to the time of tap and untapped. This is depend on the user’s need and requirement to the water usage. Hence, estimation of water turbine efficiency related to water flow in pipeline is difficult to be estimated due to the inconsistency of water flow. On the other hand, in terms of cross flow turbine design, so far, there has been a research that testing the performance of 20-blade cross flow turbine for 250mm diameter pipeline application. Research on the optimum blade number of the water turbine for different pipeline size is still lack in the literature. Hence, it is important to do some study on the optimum blade design for variable pipeline size. It is therefore, in this study, the optimum blade number based on cross flow turbine designed is investigated in order to find the best performance when applied in the in-piped water distribution system.

2. LITERATURE REVIEWS

2.1 Types of Water Turbines

Water turbines were introduced by farmers since the ancient Greeks where they used water wheels to grind wheat into flour and its principle has been kept for over centuries [5]. Turbine at that time is typically placed in a river and a water wheel will pick up the flowing water in the buckets located around the wheel. The developed kinetic energy of the flowing river will turn the water wheel and hence the kinetic energy will be converted into mechanical energy that runs the mill. Water turbine has different types and can be classified into two; impulse and reaction class turbine. Impulse and reaction class turbine also known as conventional water turbine. Latest research has come out with new class of turbine which called vertical axis water turbine (VAWT). This new vertical turbine was designed by Lucid Energy and applicable in pico and micro-hydro powers installation [4].

Hydro power became a major source for electricity generation started in the late of 19th century. In 1878, the world's first hydroelectric project was used in the Cragside country house in Northumberl and England to power a single lamp [5]. Several years later, the world once again manage to harvest power from Niagara Falls hydroelectric power plant and was used to power the street light around that area in 1881. In 1882, the world's first hydroelectric power plant began operating in Appleton, Wisconsin, United States to serve a system for private and commercial customers [5].

Impulse class turbine was first invented in 1870 by Lester Allan Pelton, an American inventor [5]. The turbine invented was then named from his name which now called as Pelton turbine. Impulse turbine works with a constant static pressure. This is due to the high speed water jet after the nozzle of the injector. So, during the energy transformation, the static pressure remains the same where energy will lost after the water impacts on the fixed blade [6].

Impulse class turbine has three types, which is Pelton, Turgo and Cross Flow and applied to different kind of situation or applications for example based on the head height. Bryan. R et al [7] in their research on turbine performance characteristic in pico hydro scale stated that both Pelton and Turgo turbine offered high efficiency level. However, Turgo turbine can handle significantly higher water flow rates, thus allowing efficient operation in lower head ranges and potentially expanding the geographic viability [7]. Research are highlighted on improving the design of Turgo turbine since typical Pelton turbines in pico hydro tend to operate in 75-85% peak turbine efficiency range, compared to Turgo turbine [7]. As result, Bryan. R et al found that under the best conditions, the Turgo turbine efficiency was observed to be over 80%, which is quite good for pico-hydro-scale turbines at a speed ratio of approximately 0.46 [7]. Both Turgo and Pelton turbine are suitable to work for typical hydro design, and hence suitable to be used for dam or slight diversion of water flow.

Reaction class turbine was first invented in 1827 by French engineer Benoit Fourneyron [5]. The turbine has a capability to produce up to 6 horsepower and become the earliest version of the Fourneyron reaction turbine [5]. British–American engineer, James Francis in 1849 developed the first modern Francis turbine. This type of turbine remains as the most widely-used water turbine in the world today. Into the 20th century, an Austrian professor Viktor Kaplan developed another turbine, called Kaplan turbine in 1913. This turbine is a propeller-type with an adjustable blades.
Reaction class turbine static pressure decreases between the inlet and the outlet of the runner. Since the turbine is partially or totally immersed into the water, the pressure of the water affects the runner's blades cause decreasing its pressure value. Reaction class turbine usually applied for low and medium head height applications. This turbine offered a good efficiency and cost effective as it does not need a high water head. There are three types of reaction class turbine which is Frances, Propeller and Kaplan, and Pump as turbine. Francis and Kaplan turbine are usually have vertical axis shaft because it will makes the best use of the available water head and makes the installation of its generator more economical.

In 2013, Hasan Akin et al (2013) conducted a research on hydraulic turbine design applied on Francis turbine. The design result to turbine efficiencies rise up to 95% and with a minimum amount of pollution [8]. Francis turbines are applicable to a wide range of head (from 64 m to 700 m) and specific speed (from 51 rpm to 250 rpm). The proposed design was then applied for the design of Yuvacik H.E.P.P turbines in Turkey with the plant capacity of around 2.3 MW and an overall turbine efficiency of 92.3% was reached [8].

Compared to Francis turbine, Kaplan turbine works well in lower head. This type of turbine has high advantage for a small scale electricity generation, like a mini hydro dam. To improve further its performance, lot of research has been conducted, such that improve the turbine controller. With sophisticated controllers, drastic improvement in the dynamic turbine behaviour can be achieved, without the need to change hardware components [9]. Micheal Gratza et al in his research on the effects of large-scale extended-duration blackouts represents a potential national catastrophe and threaten many of the essential services around by introducing this double regulated Kaplan turbine [9].

Pump as turbine (PAT) is however a different case. Pump acts as turbine when it operates in a reverse mode. PAT efficiency is however reduced as the viscosity increases due to the hydraulic friction loss in the impeller [10]. PAT system can be installed instead of pressure relief valves in all sorts of pipelines as a solution in energy recovery systems.

For VAWT, there is no additional head height needed to rotate the turbine. The pressure drop also less compared to conventional water turbine as the VAWT can be directly installed to existing water piping system [3]. While for conventional type water turbine, cross flow are better for in pipe hydro system for impulse class. Meanwhile for reaction class water turbine, propeller and Kaplan type is more suitable as it has good efficiency and simple to design. One of these designs which make into the marketplace is Gorlov Helical turbine (GHT). The GHT is based on the Darrieus turbine which is used in VAWT as well as for hydropower applications and can be used in research on lift type as it is used on Lucid turbine [11]. Just recently, Du Jiyun et al have proving that this inline type of turbine can be used as backup for the generated energy. In their works, they proposed the installation of upstream and downstream blocks to act as nozzle to maximize the performance of cross flow turbine used and the energy generated used for water leakage monitoring system [12].

2.3 Energy Generation through Pipeline

Electricity generation form renewable sources so far depending on major hydro power plant, wind, tidal and geothermal. However, throughout the year, new technologies been developed to harvest electricity through water pipeline. The micro in-pipe hydro power generation system becomes a novel method as it integrate renewable energy sources with the water supply system as rural as well as urban area because of its immense potential to harness clean renewable electrical energy from the flow pressure of water in domestic tanks and pipelines [13]. According to Porkumaran K et al, flowing water through the penstock from the tank and underground water pipeline can be used to run multiple turbines by coupling them to a generator and installed inline [14].

Lucid Energy company has developed a turbine which to be fitted inside the pipeline. The design of the turbine is almost similar as Gorlov Helical turbine. In [3], J. Chen has stated that it is very significant to perform research on the power monitoring system through sensor networks. This is due to the essential requirement for the modern water mains management technologies and methods, especially for the sensors which have no access to grid power and able to monitor the system continuously [3]. In another research that was conducted by J. Chen also, their focus was paid on the development of vertical axis water turbine for 100 mm pipeline to convert as much as possible energy when the average water velocity is 1.5 m/s with water head drop is less than 5 m. In this research, consideration was paid on the turbine design either solid or hollow, number of blades, diameter of turbine, and block type [3].

A research also has been conducted by H. Zainuddin et al in [20], where experimental testing has been made by installing their proposed cross flow turbine in the water distribution pipe to houses. The data obtained was on water energy level within 24 hours period. From the result, it was found that high water energy is available during low peak period of water usage from 1.00 am to 4.00 am. The excess water pressure manage to generate voltage of between 70V to 72V where the manual open circuit voltage from the manufacturer is 100V [15]. On the other hand, the lowest water energy was recorded at noon where 49.8V of open circuit voltage was produced. The generator output voltage can be maintained at 13.8V by controlling the water flow rate using the “Power Valve” in which several values of resistors are alternately connected to the output side of the generator [15].

A research on in-pipe electricity generation has been done by Du Jiyun et al in [12] for water leakage monitoring system, focusing on urban water supply. In this research, an inline cross-flow turbine was proposed to harvest hydropower from the water pipes. A numerical investigation was conducted to study the effects of blocks on the turbine performance and simulation results indicated that the proposed upstream and downstream blocks can act as nozzle and diffuser in traditional cross flow turbine [12]. According to Du Jiyun et al, propeller turbine also can be used in the pipeline system because both (turbine and propeller) can work under low water head. However, some modifications are needed to the flow path of water pipes since the inlet and outlet of the traditional propeller turbine is orthogonal [16]. Bulb type propeller turbine is another alternative but with all electrical components submerged in water, any waterproof insulation failure will result to water pollution [16]. To generate energy through this system, Cross-flow turbines need to be connected to the generator via shaft, inserted in the pipe through the T-join. For their research, a DN100 T-joint was connected to the DN250 pipe.

Beside the issues of turbine and propeller, the tip speed ratio (TSR) of a turbine also influence the performance of entire VAWT system [17]. TSR is the ratio of the circumferential velocity of the turbine to the mean turbine runner inlet velocity [16]. Another factor that could influence the turbine potential is the flow of the angle attack at the runner inlet. In research that was conducted in [18], it was found that their proposed system can improve the flow attack angle at the runner inlet and thus the flow velocity through the runner increased significantly. Therefore, there is still a wide open area to carry on through research works, prototype fabrication, optimization, experimental test, and conversion efficiency enhancement so that an appropriate in-pipe pico and micro scale hydro turbine.

2.4 Summary Discussion Based on the Executed Literature

Different water turbine has its own efficient working condition. Suitability of the turbine can be determined by the net head and flow rate of the water [6]. Figure 2.10 shows the optimum operating head and water flow for different types of turbine. For low head application domain, propeller turbines are normally used, as can be seen in the typical turbine application range diagram in Figure 2.10. From the diagram, it can be observed that Kaplan turbine has the widest working range with a very minimum flow rate at 3m water head. For the turbine selection in pipeline system, the water turbine cannot consume a lot of water head to ensure that the drinking water can overcome pipe friction loss and can be delivered safely to the user. The design of the piping system also need to be considered, where most of the time, space for system installation is very limited in the underground condition and urban cities. Therefore, pathway of the water flow cannot be altered as well as priorities to the water qualities need to be considered. Based on capital cost of hydro turbines and electricity generation profit, work have been done to check the economic feasibility of installing hydro system in remote region and provide electricity to local residents [18].

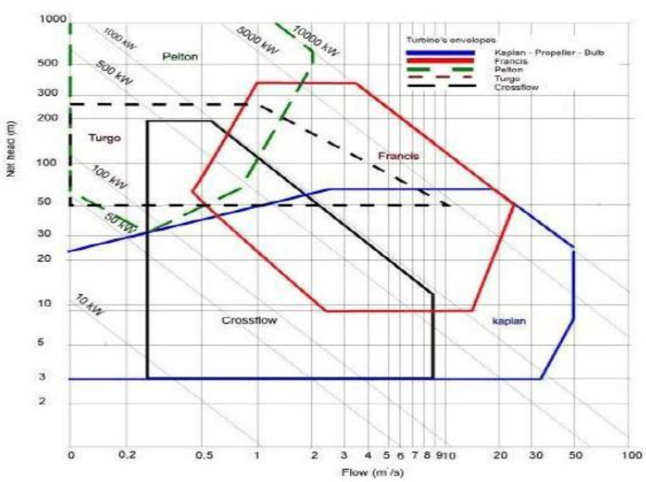

Figure 2: Turbine selection chart based on head and flow rate [6]

For hydro power generation, there are several types of turbine that normally use. However, it depends on the design classification. Typically, there are two-class of turbine, which is impulse and reaction turbine. This two-class of turbine is used in certain application depends on the types of hydro plant and the efficiency of the system. Table 2 shows the types of turbine for impulse and reaction class turbine. The example of application for each design is also given in the table. For major hydro power plant, Pelton, Turgo and Frances turbine are more suitable as it has higher head and need high water flow rate as well as high maximum power produced.

Table 2: The types of impulse and reaction turbine classes [3]

Impulse Turbine		Reaction Turbine	
Type	Example of Application (Head Classification)	Type	Example of Application (Head Classification)
Pelton	High (>50m)	Francis	Medium (10-50m) for Spiral case Low (<10m) for Open Fume
Turgo	High (>50m) Medium (10-50m)	Propeller and Kaplan	Low (<10m)
Cross Flow	Medium (10-50m) Low (<10m)	Pump as Turbine	No head height needed for installation.

From Table 2, its look like Kaplan turbine is a promising turbine for electricity generation for in pipeline system because it can work at low flow rate and low water head condition, however the design will alter the pathway of water flow and cannot be well integrated with pipeline . Some other research paper apply the energy recovery system by using Pump As Turbine system on the high rise building to make sure that the water are enough for the top floor level. In other hand, Pump As Turbine act as energy recovery system. Pelton and Turgo turbine are normally installed o open environment with it runner not completely submerged in water [26]. Therefore, cross flow type turbine are chosen to be used in this project because its design can be fitted inside the pipeline flexibly. Furthermore, this cross flow turbine can be shaped according to the structure of the piping system and it can be operated under low head condition and minimal water flow.

Based on previous reviews and work summaries including its technical specification, the best turbine for inline electricity generation from water flow in pipeline is Cross Flow turbine. Therefore, design method and project implementation considering this turbine type will be discussed further in Section 3.

3. RESEARCH METHODOLOGY

3.1 Cross Flow Rotor Design

In designing a cross flow rotor turbine, there are three main factors must be considered; the orientation entry angle of the conversion block, radius of the runner and the number of blades. In this study, after those parameters have been well determined, proposed cross flow turbine has been drafted or visualized using SolidWorks. Once the design has been optimized, the turbine components such as blade, and conversion block will be printed using 3D printer.

To determine the conversion block orientation entry angle, Equation (1) is used. Once this angle has been determined, other geometrical parameters that suit with the selected water piping system can be identified [7].

$$\gamma = \csc\left(\frac{r\cos\theta_0}{R_0}\right) - \theta_0 \qquad (1)$$

To find the optimum design of orientation entry angle, the orientation angle (θ) of the guide block on different outer radius and radius of upper conversion block to the central of the turbine, RO needs to be fixed. The radius of the upper conversion block (D_1) can be determined from 2D system model as depicted in Figure 3. Due to the mechanical and the design constraints as stated in [11], the blade radius r of 3.5 cm was chosen. The conversion block and guide block orientation entry angle of the system are set at the specified value as in Table 3. By using a water pipe with 1m in diameter length, the block design and turbine dimension are specified and complete system are constructed.

For cross flow turbine design, the identification of blade radius R_b is essential for the determination of degree of attack, to maximize power conversion efficiency [16]. To determine the blade radius, R_b, equation (2) can be used. The blade arc angle δ then can be estimated from the blade outer angle β_1 using equation 3). The relationship between the R_b, δ, β_1, β_2, D_1, and D_2 can be seen in Figure 4. Figure 5 shows the design of turbine using SolidWorks where magnitude and blade central angle are considered. The blades are designed with thickness of 1mm and with 102.2 degrees blade central angle. Magnitude of the blades are standardize for all 3 design and the blades are equally distributed over the blades holder.

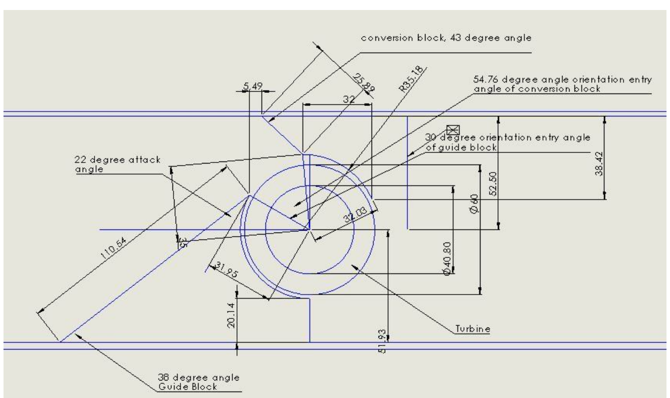

Figure 3: 2-Dimension design of system layout.

Table 3: The parameter needed for turbine design.

Parameters	Symbols	Values
Orientation entry angle of conversion block	γ	54.76 degree
Blade outer angle	$\beta 1$	38.9 degree
Blade inner angle	$\beta 2$	90.0 degree
Outer runner diameter	D1	60.0 mm
Inner runner diameter	D2	40.8 mm
Ratio on outer and inner runner radius	*D2/D1*	0.68
Blade radius	*Rb*	10.36 mm
Number of blades	N	Varied (6, 12 and 20 blades)
Runner length	L	78.0 mm
Blade Thickness	d	1.00 mm
Blade Central Angle	δ	102.2 degree

$$R_b = \frac{D_1^2 - D_2^2}{4D_1\cos\beta_1} \qquad (2)$$

$$\tan\left(\frac{\delta}{2}\right) = \frac{\cos\beta_1}{\sin\beta_1} \qquad (3)$$

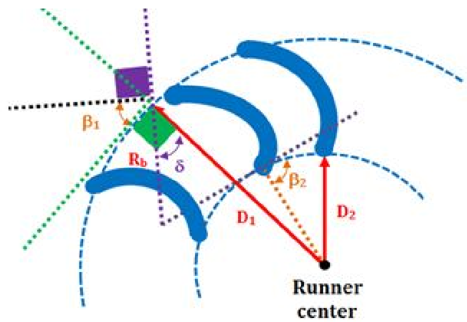

Figure 4: The geometrical parameter of the cross flow runner [17]

Voltage and current measurement for DC PMSG will be measured directly from the multimeter. However, for the AC PMSG, voltage and current measured is the line values. Hence for AC delta connection generator, the phase voltage and line voltage are the same. Meanwhile the phase current is the division of line current with $\sqrt{3}$. Measured values of line voltage are in rms values and the DC values are assumed to be around the peak value.

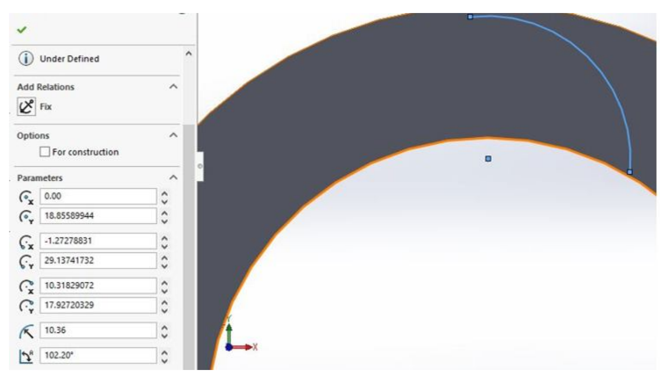

Figure 5: The magnitude and blade central angle of the blade arc

3.2 Generator Selection

Generator that used for this study is targeted to present some kind of low starting torque. This is because at some point, for water distribution system installed around toilet or kitchen, it is quite hard to obtain constant water flow all the times. In this study, two permanent magnet synchronous generator (PMSGs) are used to test the proposed cross flow turbine design, which are 24V DC output 8446rpm R385-ST PMSG (as shown in Figure 6), and SKU348657 24V AC output PMSG (as shown in Figure 7). Permanent magnet excitation eliminates the excitation loss of field excited synchronous generator (FESG). Plus, PMSG has higher efficiency and extra electricity generated as it is cheap and reliable. High speed and low torque are suitable to be used because in this project, as sometimes, low water flow occurs. SKU348657 AC generator gives a 3 phase Delta output with maximum speed 6000rpm. The design specification for the R385-ST DC generator is also given in Figure 6.

R385-ST

Model	Voltage V	No Load		Max Efficiency (%)			Max Output (W)			Stall	
		Current A	Speed rpm	Current A	Speed rpm	Torque g.cm	Current A	Speed rpm	Torque g.cm	Current A	Torque g.cm
RS385-ST-17125	23.5	0.081	8446	0.497	7260	105.6	1.561	4223	375.8	3.04	751.7

Figure 6: Design specification of R385-ST DC generator [30]

Figure 7: SKU348657 AC generator

3.3 Hardware Implementation

In Figure 8, the hardware system of the proposed in-pipe water distribution system at UTM is depicted. The water sourced for the test system is obtained by connecting the input of LKP UPVC 110mm SWV with the water hose holder. The custom made holder is built to enable 5-pipe hoses can be connected to a 5 water-cape heads. The system is tested by assuming that the water flow in this hose is equivalent to the water piping system installed closed to toilet or kitchen, when the 5 water capes are opened at the same time. The more water capes are used, higher the water flow rate in the pipe that hitting on the cross flow blades. Figure 8(a) depicts the outlet of the proposed pipe, while Figure 3.9(b) depicts the inlet of the water system of the testing hardware. Figure 3.9(c) shows the system setup before testing and Figure 3.9(d) is the picture during current measurement when DC generator is employed. The turbine design considered in the study is shown in Figure 3.9(e), where the 6, 12 and 20 blades turbine is tested one by one under the same conditions. Layout of the turbine that attached in the in-pipe system is shown in Figure 3.9(f). The conversion block setup is fixed and the only top cover of the T-joint is removable to enable changing of the turbine.

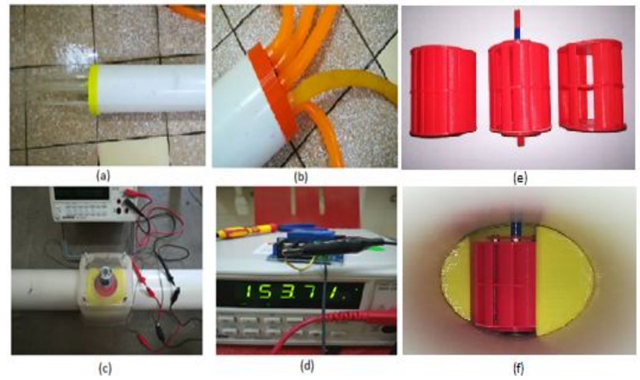

Figure 8: Hardware implementation.

Assembling procedure of in-pipe turbine system:

1) 1 meter 100mm water piping are cut into half and fitted into the designed T-joint.
2) The guide block and conversion block are attached inside the pipe as shown in Figure 8(f), followed by installing the mechanical bearing, and rotor.
3) To enable proposed system to work properly, another bearing is attached on the top of transparent cover so that it can be attached to the generator. The perspex cover is glued to prevent water leaking and pressure loss.
4) Generator is the placed on top of the pipe, and ready to be tested.

3.4 Testing Procedure

In this project, 3 types of cross flow turbine have been designed, built and tested. Testing has been performed using 2 different PMSG generators. Focus are given to the voltage current and power generated for all conditions. For DC generator, voltage are measured by taping the wire to the digital multimeter while for current measurement, charger controller are used as the temporary load. For AC generator, voltage are measured by taping one of the phase voltage while for current measurement inductive load are connected with. This procedure applied to all 3 rotor designs, where all data are recorded with interval of 10 seconds between every measurement. 5 data recorded for every set of measurements.

4. RESULTS AND DISCUSSION

4.1 Water Turbine Selection

Based on the literature studies that have been executed, it was found that Kaplan turbine offers the best solution in terms of output power, as summarized in Table 2. This was supported by the Kaplan efficiency level that has been presented in Figure 2. However, due to Kaplan's limitation in which it requires the alteration of the pathway of water flow, hence it is seems difficult and potentially impossible to be attached or integrated in the existing water distribution pipeline at UTM.

Therefore, cross flow type turbine is the best solution for water piping system whereby it can be integrated or fitted inside the pipeline more flexibly. Besides, cross flow turbine is also applicable for low head application in which it is still suitable for head <10 meters, and minimal water flow. To select the appropriate pipe diameter, the typical water piping for sanitary system in the market which is 110mm piping size has been selected and used in this study. Figure 9 shows the specification for the proposed cross flow turbine system for the 110mm water piping system considered in this study.

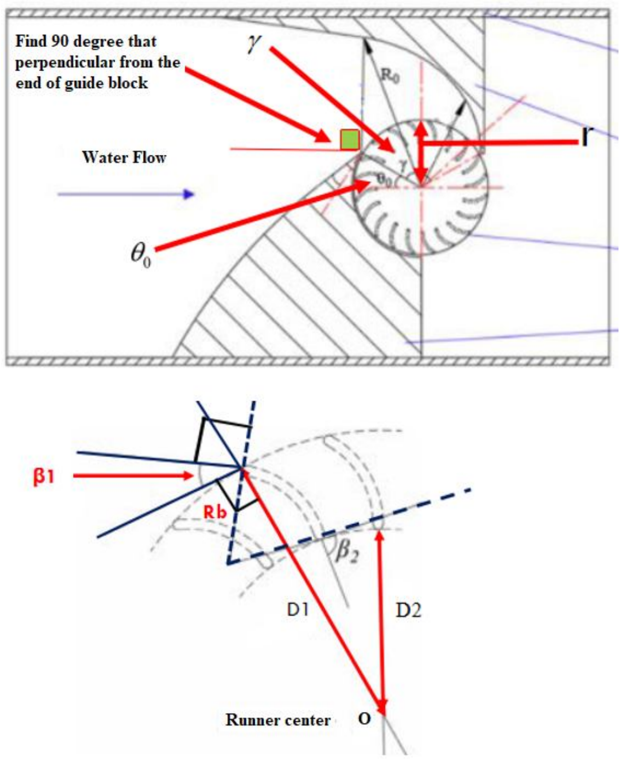

Figure 9: Design specification for the proposed Cross Flow Turbine system

4.2 Orientation Entry Angle

Orientation entry angle is very important to determine the maximum output power that could be generated by the generator. This angle will allow the water to be directed flow towards the turbine blades and hence maximizing its power conversion. At the same time, if more surface areas are being hit by the water, the turbine can rotate faster. Table 4 shows the result for the orientation entry angle, γ when the orientation angle, θo is set at 0.5236. To find the optimum design of orientation entry angle, some comparison study has been performed by fixing the θo of the guide block on several values of different outer radius, r and different radius of RO. From the same table, it can be observed that the γ of the turbine system is nonlinearly affected by the outer radius of the runner, radius of the conversion block to the center of the turbine and the orientation angle of the turbine guide block. The radius of the upper conversion block is determined from the 2D system model as shown in Figure 3 and due to the mechanical and design constraints as stated in [18][19].

Table 4: Results for Orientation Entry Angle Calculation

Orientation Entry Angle Calculation				
Outer Radius Of The Runner, r	Radius of the upper conversion block to the center of the turbine, R0	Orientation angle of the guide block, θ0 (radian)	Orientation Entry Angle, γ (radian)	Orientation Entry Angle, γ (degree)
3	3.5	0.523598776	0.955712779	54.75830868
4	9	0.523598776	2.139753819	122.598863
5	6	0.523598776	0.990055925	56.72602597
6	9	0.523598776	1.308555334	74.9746979
7	10	0.523598776	1.231516076	70.56067356

As estimated using equation (1), when the outer radius of the runner is set at 3cm, and the radius of the upper conversion block to the runner must is set to be 3.5cm, the entry angle gives 54.758°. Meanwhile when the outer radius of the runner is increased, the RO also need to be increased in order to enable θo can be maintained at 0.5236. From the five designs as shown in Table 4, it can be observed that the first design is the best option for this study since this blade can be fixed in the water pipe distribution system at UTM. It is a need to consider the complexity of the design, in which the size of the water pipe distribution must be considered as well so that the proposed turbine can be fixed and rotated well in it.

4.3 Blade Radius Design Parameter

Now, it is time to identify the best size of the blade radius of the cross flow turbine depends on the water pipe size. The blade radius can be estimated using equation (2). Table 5 shows the result of blade radius when 8 pipe sizes were considered. From the table, it has been found that the blade radius varies with changing of the outer and inner diameter of the turbine. All of the parameters are depends on the size of the piping used. Based on the presented data in Table 5, finally, for LKP UPVC 110mm SWV water pipe with thickness of 2.2mm, turbine with 6.0cm outer diameter and 4.02cm inner diameter using a ratio of 0.68 are chosen in this design study. Considering that 0.68 is the optimum ratio as claimed in [28], and when the D1 is varied, the D2 can be determined. When the D1 was set as 6cm, the D2 will be 4.08cm. And by fixing the β1 at 38.9 degrees, the blade radius of 1.03618cm is obtained, in which this is the most appropriate Rb for the blade if installed in the water pipe system. After determine this Rb, the arc angle can be estimated.

Table 5: The Blade Radius Calculation according to Water Piping Sizes

Blade radius calculation						
Outer Diameter D1(CM)	Inner Diameter D2(CM)	Blade outer angle β 1(rad)	Blade outer angle β 1 (degree)	Blade Radius Rb (CM)	angle δ (rad)	angle δ (deg)
3	2	0.678933079	38.9	0.535393941	1.783726496	102.2
4	2	0.678933079	38.9	0.963709095	1.783726496	102.2
5	2	0.678933079	38.9	1.349192732	1.783726496	102.2
6	2	0.678933079	38.9	1.713260613	1.783726496	102.2
4	2.4	0.678933079	38.9	0.822365094	1.783726496	102.2
4	2.72	0.678933079	38.9	0.690786679	1.783726496	102.2
4	2.72	0.678933079	38.9	0.690786679	1.783726496	102.2
6	4.08	0.678933079	38.9	1.036180018	1.783726496	102.2

4.4 Measurement of Generated Power using DC Generator

Flowing water through the blades will give forces on them to rotate the turbine that attached to a generator. From the five iterations/times of the executed experimentation as shown in Table 6, when a STD MTR QK1-4637 24V DC PMSG has been used to measure the performance of the proposed cross flow turbine, it has been found that, proposed cross flow turbine with 12-blade presents the best performance in terms of electrical generation. Average power of about 509.74µW can be generated by the 12 blades compared to 6 blades (285.57µW) and 20 blades (437.99µW). It shown that 12 blades can produce almost double power compared to 6 blades, and also performing 14.08% better compared to 20 blades. The highest voltage and current that can be generated by 12 blades are around 552.6 mV and 0.93mA as can be depicted during time interval of 40 and 50.

Table 6: DC PMSG output generated for 6, 12 and 20 blades turbine

Design	6-Blade			12-Blade			20-Blade		
Time interval (s)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)
10	383.30	0.752	288.24	547.90	0.913	500.23	499.20	0.869	433.80
20	389.50	0.760	296.02	550.30	0.927	510.13	507.00	0.895	453.77
30	371.60	0.718	266.81	552.60	0.928	512.81	487.10	0.890	433.52
40	370.00	0.765	283.05	548.30	0.937	513.76	478.10	0.892	426.47
50	400.20	0.734	293.75	550.90	0.929	511.79	496.50	0.891	442.38

4.5 Measurement of Generated Power using AC Generator

When cross flow turbine is then tested using another generator which is SKU348657 24V AC PMSG, it has been demonstrated that again 12 blades presents the best performance compared to the 6 and 20 blades, aligned with the results presented when DC PMSG was used as can be depicted in Table 7. Since the generator is a delta connected 3 phase AC generator, voltage and current are measured from one of the phase only due to the fact that the magnitude of voltage and current are the same, but different in phase by 120 degrees. By using AC PMSG, the average power of 432.81µW can be generated almost double higher than 6 blades (267.14 µW) and 21.82% better than 20 blades (338.35µW). The highest voltage and current that can be generated by 12 blades for AC PMSG are around 955.4 mV and 0.46mA as can be depicted during time interval of 20.

Table 7: AC PMSG output generated for 6, 12 and 20 blades turbine

Design	6-Blade			12-Blade			20-Blade		
Time interval (s)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)	Voltage (mV) Full load	Current (mA) Full load	Power (µW)
10	656.80	0.395	259.11	935.60	0.457	427.10	767.80	0.437	335.52
20	655.50	0.410	268.43	955.40	0.458	437.29	768.00	0.431	330.78
30	673.60	0.386	259.94	953.70	0.452	431.17	777.40	0.431	334.76
40	687.90	0.396	272.27	956.90	0.456	435.96	800.40	0.433	346.90
50	672.90	0.410	275.96	948.70	0.456	432.51	788.90	0.436	343.81

4.6 Results and Discussion

As recorded in the finding tables, it has been found that 12 bladed turbine presents best performance in terms of energy conversion efficiency compared to 6 bladed and 20 bladed turbine for both AC and DC generator. When the water passes through the blades, it does give forces to the turbine to drive the central rotating shaft and hence rotating the installed pico generator to produce electricity. In the turbine design, it is crucial as well to consider the mechanical constraint of the system, such as diameter of the water piping system. Optimum blades must be determined first depends on case, before deciding to install a turbine in the water piping system as lowest or highest number of blades attached toward a turbine did not promising linear relations. In certain case, higher blade number can present better performance compared to lower one. But, in certain cases, higher number of blades on small rotor size will contribute to the compactness of the design. Hence, lesser force will be exerted on the blades and restricting the turbine to rotate faster, as it is harder for the water to pass through the blades. However, if the blade number is lesser than 12, lesser force will be exerted on the blades, where the water easily pass through the blades, slipping through the spaces between the rotor blades.

For the DC and AC PMSG comparison, as depicted in Table 6 and Table 7, it can be seen that the selected DC PMSG performs better power conversion efficiency than AC PMSG. As listed in the datasheet, STD MTR QK1-4637 24V DC PMSG has rated speed at 8446rpm while for SKU348657 24V AC PMSG, the rated speed is 6000rpm. Since torque is power divided by the speed, hence high rated speed enables lower torque to generate a constant power. Thus this means that, lower torque offered by DC PMSG enabling higher generated current by the generator. Flowing water through turbine gives enough force to rotate the generator without giving so much restriction to the water flow. In terms of pressure drop across the turbine, 12-bladed turbine provides the minimum level, compared to 20-bladed rotors. Compact blade arrangement for this design as offered by 20 bladed turbine prevents water to pass through the blades smoother and thus, lower force is exerted on the blades to rotate the turbine.

From the experimental results, it is obvious that DC PMSG can provide higher efficiency when tested on the cross flow turbine in the water piping distribution system. This is due to DC PMSG relying on carbon brushes and commutation ring to switch the direction of the current and magnetic field polarity in a rotating armature [21]. The interaction between the internal rotor and fixed permanent magnets induces the rotation of the rotor part. Thus, even at low rotating speed, power still can be converting better as the stator and rotor field are always 90 degrees of each other. In contrast to AC PMSG, even though PMSG is used, it still needs to operate at its rated speed. The ac motors are meant to operate at a specific point on the characteristic curve [22]. This curve coincides with the peak efficiency of the motor. Outside of this point, the efficiency of the motor drops significantly [22].

5. CONCLUSION

The optimum cross flow water turbine for 110mm water piping system that designed for UTM's water piping distribution system has been successfully performed. From the executed study, it can be concluded that the 12 bladed cross flow turbine demonstrates the best performance when attached to the STD MTR QK1-4637 24V DC PMSG, compared to 6 blades and 20 blades turbine. This is due to the highest force that can be exerted on the blades' surface. Besides the factor of blades geometry and design, it could be concluded as well that the type of generator also play important role in terms of electrical generation efficiency. For the STD MTR QK1-4637 24V DC PMSG and SKU348657 24V AC PMSG, DC PMSG presents best performance in terms of electrical generation efficiency where this DC PMSG can perform 15.1% better than the selected AC PMSG for the purpose of electrical generation via water piping distribution system.

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