In-pipe Hydropower Vertical Axis Parallel Turbine Prototype

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ABSTRACT

A unique in-pipe hydropower prototype with a water separation feature, designated as P40 is developed in this research. Fabricated mainly using steel-based materials, it has two power generation (PG) channels with nozzles and turbines. Water flows into the PG channels and is controlled by inlet and outlet valves. From the experiment, it showed that all valves in P40 functioned well as it prevented water from flowing into the PG channels. P40 works effectively as a device that allows most water to flow uninterrupted. With a valve that works well, this system allows maintenance to be done without having to disrupt the flow of water to the consumer. It is also expected to generate more power compared to the previous studies.

Keywords: Hydropower; in-pipe hydropower generation; vertical axis parallel turbine

1 Introduction

Energy and water are closely linked in hydropower, which is regarded as a developed and economical renewable energy source. [1]. Hydropower has sustainability, affordability, and environmental friendliness that make this mature technology widely used by many countries [2], [3]. Hydropower has a versatile source of electricity that can be rapidly scaled up and down to be adaptable to changes in energy demand [3]. Therefore, hydropower gives a significant impact on the operational management of natural resources and artificial water supply systems [4].

Aside from the current hydropower systems, the new technology of in-pipe hydropower systems (IPHS) has great potential in urban areas [5]. The operation of water distribution networks generally requires a substantial amount of water, pressure, and energy. Throughout the distribution system, significant energy is used to deliver water to consumers. [1]. However, the water pressure of the distribution network is usually regulated using pressure-reducing valves (PRVs) within the lower and upper specification limits to satisfy consumer demand while minimising the possibility of pipe leakage or failure. [6]. Although PRVs effectively control the water flow, the kinetic energy generated by the increase in water pressure pipelines mostly goes to waste [7]. This untapped (excess) pressure can be harvested and converted to electrical energy with the use of the appropriate technology and planning [8][9]. In this respect, IPHS is designed to harvest the energy from the flowing water in the pipeline of the water distribution network without compromising the water demand. IPHS is equipped with turbines that rotate in response to the flow of water to harvest mechanical energy [10]. Hence, continuous water flow and excess pressure in the water pipeline make IPHS a far more reliable energy source [11], [12]. In Europe, the installation of hydropower plants on water distribution networks has found widespread use. [13].

Commercially, many developers were active participants in the promotion of IPSH. In 2018, for instance, Lucid Energy.com, a US-based company, first developed IPHS that lighted 150 households in Portland with an annual production of 1.1 GWh [14] Rentricity Inc. was active with many installations covering a power range of 10 to 50 kW in Oneida Valley, Halifax, Barre, and Westmoreland County [15]. Besides, Leviathan Energy Hydroelectric Ltd [16] and Soar Hydropower have implemented IPHS in the distribution pipelines of drinking water. In Japan, Daikin Kogyo company aggressively adopted and marketed the

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in-pipe technology with its system [17]. Also recently, in Hillsboro, Oregon, new technology is known as the In-pipe Energy In-PRVTM system generated an annual power of 185 - 200 MWh by bypassing an existing pressure relief valve [18].

Recently, Abdullah et al. [19] introduced a new vertical axis parallel turbine in-pipe hydropower generation system, namely, P20, with a water separator in the pipe. The flow of water was separated by 80% into the primary water channel and 20% (10% each) into two power-generation (PG) channels, with each channel having its turbine. The flow of the water through the PG channels was controlled by valves that were located at their inlets and outlets. If the PG channel needs to be shut down for maintenance or servicing, the primary water channel will continue to allow water to flow through it. A preliminary laboratory-scale evaluation of the prototype's functionality and performance yielded positive results. However, due to fabrication issues, the flow of PG channels, as well as its workability, were not evaluated.

Therefore, this study is developed based on a similar concept of P20. The objective of this study is to improve the design of in-pipe hydropower vertical axis parallel turbines by a previous study using primary steel material. The design improvement will be explained in detail in the next chapter. It is predicted that this new design will generate more power with bigger PG channels.

2 Theory and Calculation

2.1 Mathematical Expressions and Symbols

The hydropower resources are rated by their available power. The amount of hydraulic power (P_{Hy}) produced by using the potential energy of the following water can be calculated using Equation 1:

$$P_{\mathrm{Hy}} = \rho g Q H \text{ (Watt)} \tag{1}$$

where ρ is the water density (1,000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), Q is the flow rate (m^3/s), and H is the pressure at the meter head (mH).

However, it is also known that the flow rate can be calculated to Equation 2:

$$Q = \mathrm{A}\nu \tag{2}$$

where A is the cross-sectional vector area (m^2) and ν is the flow velocity (m/s). Therefore, it can be said that the increment in area and velocity will increase the flow rate value. According to this theory, this can be attributed to the increase in hydraulic power as in Equation 1.

Aside from hydraulic power, the output power from the turbine, known as mechanical power, can be calculated using Equation 3:

$$P_{\mathrm{Mech}} = \frac{2\pi N\tau}{60} \tag{3}$$

where τ is torque (Nm) and N is the turbine rotational speed (RPM). According to Power et al. [20], higher power output can be generated when a higher resistance force (torque) is applied to the turbine as the turbine size increases. Since this study is an extended study with a modification of the diameter of the PG channel, it is estimated that more power will be generated. This assumption is related to Equation 3. The next section will explain the details of the prototype design.

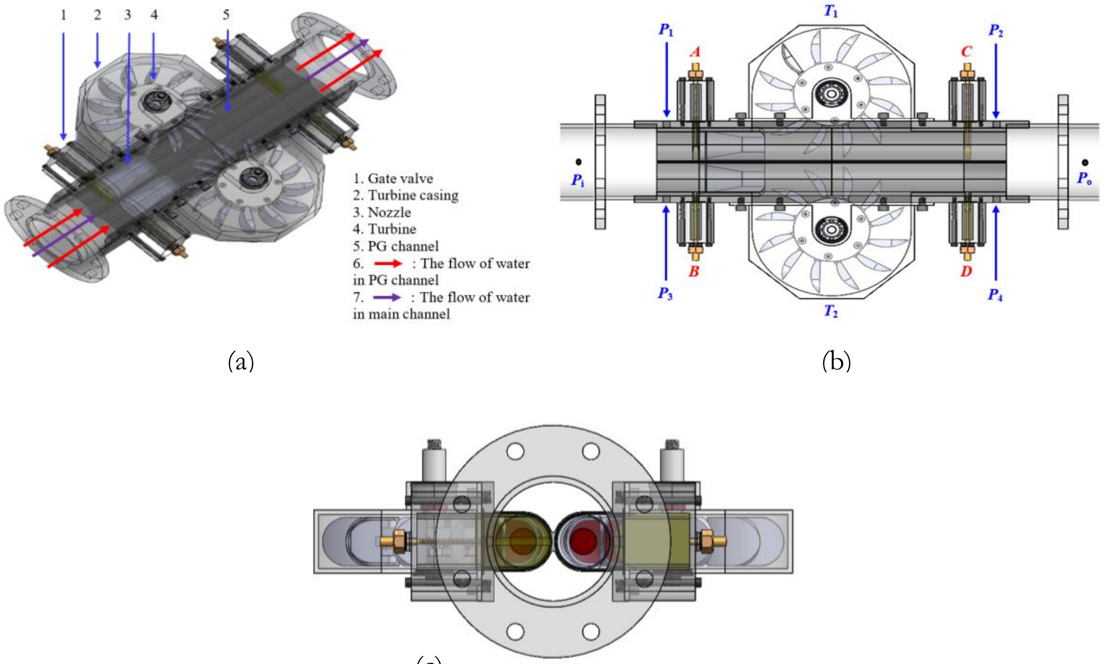
3 Methodology

3.1 P40 Prototype Design

As with most in-pipe hydro systems, the turbine design is almost par with the size of the pipe and located inside the pipe. This is done to harvest as much energy as possible. However, it will become lack accessibility for maintenance purposes, especially the need to shut down during repairs when the hydropower system has no bypass [21]. Hence, a bypass pipe must be added to counteract an uninterrupted water supply. It also requires additional space for the installation of the bypass. This will increase the cost of installation in some way [19].

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

Figure 1 shows the schematic diagram of the prototype P40 of this study comprising two PG channels. Each PG channel was about 20% of the cross-section area of the main five-inch pipe or in total 40% of the pipe's total cross-section area. There were four gate valves before the PG channels, i.e., two before inlets and two before outlets. The gate valves were closed at points A and C but opened at points *B* and *D* (Figure 1b), while P_i, P_1, P_2, P_3, P_4, and P_o denoted the pressure points, and T_1 and T_2 were the turbine locations. Each turbine had twelve blades connected by a shaft to the turbine casing. Pipes were connected with flanges and secured with bolts and nuts.



(a)

(b)

(c)

Figure 1: *Schematic diagram of P40: (a) the 3D views. (b) the top view with pressure point (P_i, $P_1 – P_4$, P_o) and turbine locations (T_1: Turbine 1, T_2: Turbine 2). and (c) the front view (valve opened on the right and closed on the left PG channel)*

Figure 2 shows the schematic diagram of the nozzle and turbine. Since the size of the PG channel has been increased, the size of the nozzle and the turbine, including the blades, has been increased as well. This is because turbine size is one of the factors that affect the efficiency of the system [22].

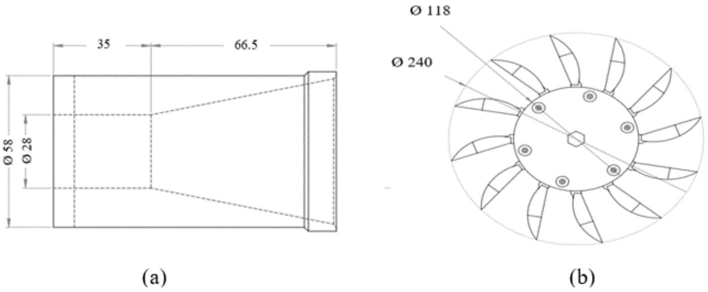


Figure 2: *The schematic diagram: (a) nozzle and (b) turbine*

3.2 Materials

Table 1 lists the materials used in the P40 system. Its main body, turbine blade, and casing are comprised of low-carbon mild steel, with a long-life span and maximum yield strength. Importantly, it was cost-effective. Meanwhile, the valve parts of the knife are comprised of brass, with excellent machinability, tightening effect, and corrosion resistance. Aluminum was used to fabricate the valve casing part because it is lightweight and cost-effective. The nozzles were made of 3D printed polylactic acid (PLA) since it offered more strength and stiffness than other polymers, such as acrylonitrile butadiene styrene.

Table 1: *Materials used in P40*

PARTS	MATERIALS
Main body	Mild steel
Turbine blade	Mild steel
Turbine casing	Mild steel
Valve knife	Brass
Valve casing	Aluminum
Nozzle	PLA

3.3 Testing and Evaluation

A test rig was constructed to simulate the flow characteristics of an actual application. The rig was attached to a concrete water reservoir of 8 m^3. A 7.5 kW motor pumped water from an inlet pipe of eight-inch diameter to a five-inch diameter outlet pipe. After passing through the P40 system, the water flowed back to the reservoir. The test rig was installed with two pressure sensors before and after the P40 system. The flow rate was controlled using variable speed drives (VSD). The flow was measured at 1.4 m before P40. Figure 3 shows the schematic diagram of the flow and the actual image with pressure gauge points shown in Figure 4a. Testing was done under two conditions. The first condition is when all valves are open, and the second condition is when all valves are closed. The pressures at P_i, $P_1 – P_4$, P_o were measured under both conditions. Only RPM and torque were measured in the first condition.

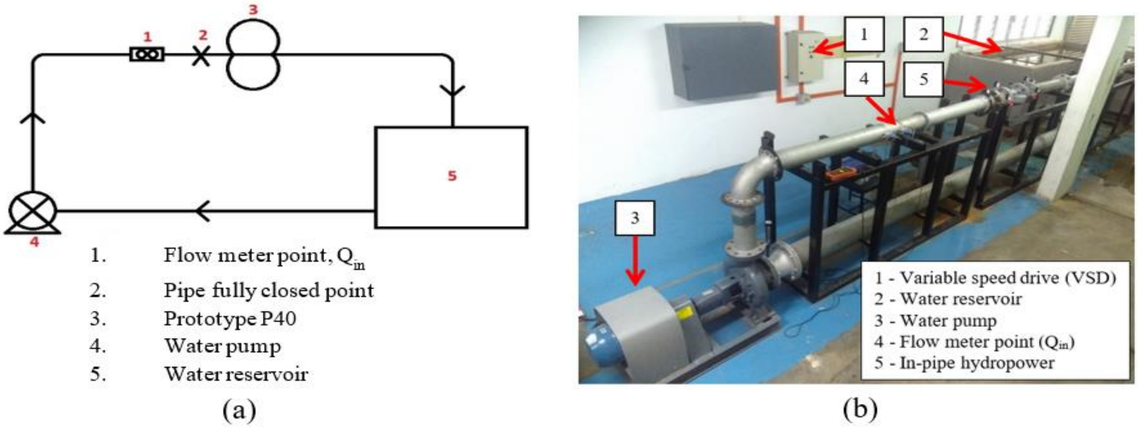


Figure 3: *The experiment test rig. (a) in the schematic diagram. and (b) actual image.*

4 Results and Discussion

4.1 P40 Prototype Outcome

Figure 4 shows the outcome of the P40 prototype. The P40 prototype was developed to be nearly identical to the design of the P20. Ideally, the PG channels would cover 40% of the five-inch main pipe area.

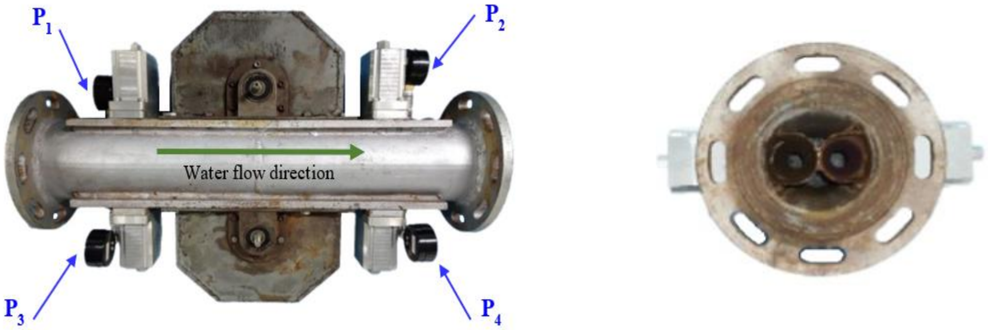


Figure 4: *The P40 prototype (a) P40 prototype with pressure gauges (P_1-P_4) (b) cross-section*

As mentioned earlier, the prototype's design was nearly identical to the previous study. Therefore, Table 2 shows the comparisons of this study to previous studies.

Table 2: *Design comparison between the current study and a previous study*

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

Figure 5 shows the relationship between the pressure and flow rate when the valves are open and when it is closed. The pressure increases with the flow rate.

For the first condition, the experiment was done when the valves were open. At the maximum flow rate, the pressure at P_1 and P_3 was 0.60 bars and 0.58 bars, respectively. Therefore, it can be suggested that the conditions in both PG channels were practically the same at all flow rates.

For the second condition, the experiment was done when the valves were closed. At the maximum flow rate, pressure at P_1 and P_3 gives a value of 0.64 bars and 0.73 bars, respectively. The pressure gave a higher value when the valves were closed compared to when the valves were opened. Since the valves were closed, the turbine was not rotating, as there was no water flowing in the PG channel. This proves the workability of the valve to stop the flow of water to facilitate maintenance work. Therefore, it will not disrupt the flow of water to consumers because the water is still flowing as usual in the main channel.

At both conditions, pressures at P_2, P_4, and P_o gave a zero value. This is because there was no resistance placed at the pressure point.

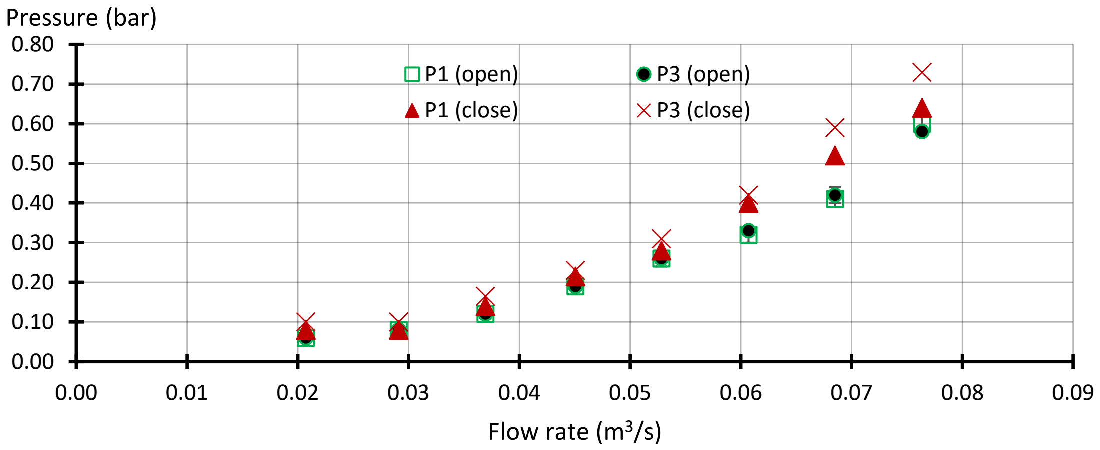


Figure 5: *The relationship between the pressure and the flow rates*

Figure 6 shows the relationship between the torque and the turbine rotational speed. Even though the P40 turbine size in this study was bigger compared to P20, the RPM value in both cases was almost similar. However, P40 torque shows a higher value compared to P20. This is because a higher resistance force was needed to stop the larger blade surface area compared to the smaller blades. The amount of torque required to turn on the generator is proportional to the power as in Equation 1. This causes the mechanical power to increase. This proves that P40 can generate more energy compared to P20.

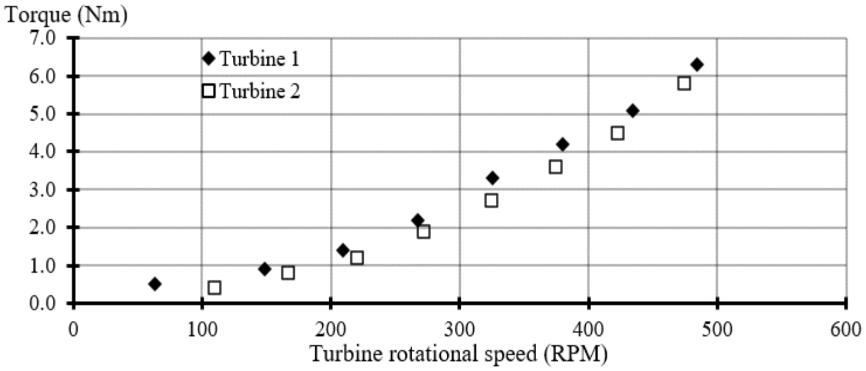


Figure 6: *The relationship between the torque and the turbine rotational speed*

5 Conclusions

This study developed a new in-pipe hydropower prototype, P40, and evaluated the workability of its valve. This P40 prototype allowed most water to flow uninterruptedly while allocating a certain amount of water pressure for power generation. All valves in the P40 prototype functioned according to the design to block water from flowing into the PG channels. The power generated from this study is also expected to be higher compared to the P20 system. Therefore, these designs need to be studied in more depth so that the amount of energy that can be generated can be calculated. Then, it can be recommended for use in water distribution networks, especially in urban areas, where it can generate renewable energy and reduce installation costs.

6 Declarations

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6.2 Funding Source

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6.3 Competing Interests

There is no conflict of interest.

6.4 Publisher's Note

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