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EVOLUTION OF SIMPLE REACTION TYPE TURBINES FOR PICO-HYDRO APPLICATIONS

M.B. Farriz[a]*, H. Boejang[a], M. Masjuri[b], M.S.M. Aras[c], N.H.A. Razik[d], S. Mat[e], K. Sopian[e]

[a]Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, Malaysia
[b]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia
[c]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia
[d]MARA Junior Science College, MRSM Terendak, Melaka, Malaysia
[e]Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Malaysia

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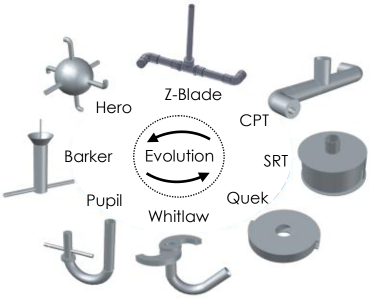
*Corresponding author
mbfarriz@gmail.com

Graphical abstract



Abstract

This paper aims to explore the history and development of eight types of reaction water turbines, namely Hero's turbine, Barker's mill, Pupil's turbine, Whitlaw's mill, Quek's turbine, the cross pipe turbine, the split reaction turbine and the Z-Blade turbine. These water turbines are discussed in terms of the complexity of the designs, the manufacturing processes involved, and the applications. It has been observed that even though most reaction type water turbines, except for the split reaction turbine and Z-blade turbine, have undergone different levels of design-related modifications and manufacturing processes, they are considered as being unsuitable for low-head and low-flow water resources in pico-hydro systems.

Keywords: Low-head; low-flow; pico-hydro; reaction turbine; Z-blade

Abstrak

Kertas kerja ini bertujuan untuk menerokai sejarah dan pembangunan lapan turbin air jenis reaksi seperti turbin Hero, kincir Barker, turbin Pupil, kincir Whitlaw, turbin Quek, turbin paip silang, turbin reaksi pisah dan turbin bilah-Z. Turbin-turbin air ini dibincang daripada segi kerumitan rekabentuk, proses pembuatan yang terlibat serta aplikasi sesuatu turbin. Daripada pemerhatian yang telah dilakukan, walaupun kebanyakan turbin air jenis reaksi ini telah mengalami beberapa tahap pengubahsuaian dalam proses pembuatan dan rekabentuk, namun kebanyakan turbin air ini kecuali turbin reaksi pisah dan turbin bilah-Z, masih tidak sesuai untuk sistem piko-hidro yang mempunyai sumber air berketinggian rendah dan beraliran rendah.

Kata kunci: Kepala rendah; aliran rendah; piko-hidro; turbin reaksi; bilah-Z

1.0 INTRODUCTION

Recently, there has been a growing worldwide concern with regard to the adverse effects of using non-renewable energy resources such as petroleum, coal, gas and nuclear [1]. The use of these resources cause greenhouse gases to be emitted and would have adverse effects on a country like Malaysia due to climate change [2]. Furthermore, the economic impact on the resources is that it will lead to an increase in electrical tariffs and major monthly overheads for consumers because of the scarcity of fossil fuels. As the dependency on this non-renewable energy is still high, the role of renewable energy, such as solar, wind, and tidal energy, etc., has been recognized as an important alternative and sustainable energy source of the future. Pico-hydropower is one example of renewable energy with potential application for future power generation [3,4]. This paper introduces the chronological evolution of simple reaction turbines for pico-hydropower applications, offering a description of a number of works devoted to the subject.

2.0 PICO-HYDROPOWER

For over hundreds of years before the use of advanced fossil fuel-based generation technology, mankind has been relying on hydropower for the generation of electricity. However, hydroelectricity is largely disregarded as a source of renewable energy because it causes environmental concerns due to the need to construct large dams [3]. The construction of large dams involves making drastic changes to the landscape and waterscape, and disrupting the natural flow of small rivers as well as causing widespread deforestation, which has a significant greenhouse effect [2,4].

On the other hand, small hydro, mini hydro, micro hydro and pico-hydropower plants provide alternative ways to generate electricity without causing damage to the environment. Figure 1 shows the classification of hydropower with reference to the power output. Pico-hydropower is defined as a small-scale green energy generation with a capacity of less than 5 kW without relying on any sources of non-renewable energy [2,5]. Pico-hydro technology is typically implemented by means of the run-of-river approach and the plant is built on a small area of land. It is generally considered to be an affordable technology for the generation of electrical power for rural communities [6,7].

In the majority of the less developed countries, more than 75% of the people in rural areas have no access to electricity, while the other 25% of these rural communities are supplied with electricity through extensions of the local contribution grids [8]. However, the expenses involved in the delivery of electricity by means of transmission lines are costly [9] and, as a result, it is not a popular alternative for supplying electricity to small isolated areas [3]. An example is the state of Sarawak in Malaysia, which consists of rural areas separated from each other by long distances. Hence, to generate electricity in Sarawak, the government has had to build a wire grid system for hundreds of kilometres solely to the small remote village areas, and this investment has not been cost effective [11]. In addition, to fulfil the standard requirements for electrical appliances, the power that is transmitted by the high tension electricity wires needs to be reduced through the use of a high voltage transformer, and this work consumes a lot of money and involves many infrastructural issues. As a solution, pico-hydropower is an attractive prospect for satisfying the basic electricity needs of remote communities [7,12]. Pico-hydropower is a smart alternative because the generated power is transmitted by means of a simple wiring system and can be stored in a low DC voltage battery. The battery will then be connected to an inverter system that suits the requirements of the electrical appliances. The cost for transmitting and converting the electrical power by this scheme is extremely low.

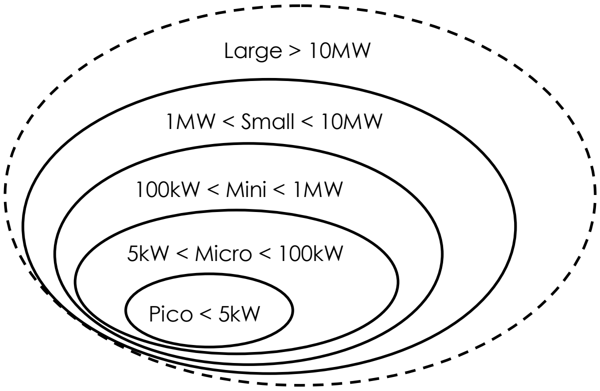
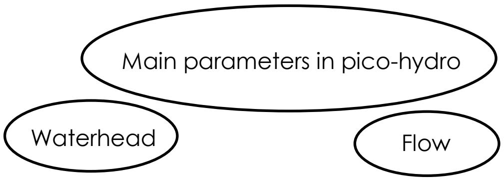


Figure 1 Classification of hydro power according to power output

According to [13], 69% of the global market for pico-hydro technology comes from South and Southeast Asia. It is estimated that around 4 million pico-hydro generation system units are needed by the less developed countries (Southeast Asia, the Indian subcontinent, sub-Saharan Africa and Latin America) [14]. Currently, because of increased awareness of the need to reduce climate change and global greenhouse gas emissions on a personal level, there is an increasing demand for pico turbines in some developed countries, such as Japan [15]. This green scheme in being applied in an attempt to meet energy demands.

Besides that, the most important factors which dominate the performance of pico-hydropower are the waterhead and the water flow rate. Figure 2 presents the two main parameters that are involved in a pico-hydro generation system, as reported by [2]. Theoretically, by increasing the value of these two parameters, the power output produced by the pico-hydro generation system will also be increased. As mentioned by [16] and [17], the performance characteristics of the pico-hydro turbine, particularly for a simple reaction hydraulic turbine, can be explored based on the parametric analysis performed via the governing equations by applying the principles of mass conservation, momentum, and energy.



- Vertical drop of the water
- Water pressure
- Elevation difference between water intake and turbine
- High head < 30m
- 10m < Medium head < 30m
- Low head < 10m

- Water flow rate
- Water quantity
- Volume per time
- High flow < 30L/sec
- 10L/sec < Medium flow < 30L/sec
- Low flow < 10L/sec

Figure 2 Head and flow as main parameters in pico-hydropower system

Figure 3 shows a typical application range chart [18], where most turbines are produced for high-head high-flow conditions, low-head high-flow conditions and high-head low-flow conditions. However, not much research has been carried out on the development of turbines that perform in low-head low-flow conditions. Generally, there are many sites around the globe with waterfalls or small streams (low-head and low-flow) which have the potential to be utilized by pico-hydro turbines [4, 18-20]. Even though the potential energy production at low-head and low-flow areas is not significant compared to large hydropower dams, by making improvements to the hydro-turbine design, this small potential energy can be harvested with high efficiency. To date, there is no simple reaction hydraulic machine-type turbine commercially available that can be implemented for low-head and ultra-low flow hydro applications. The closest research work found consists of a split reaction turbine, but it is only suitable for low-head, and not for ultra-low flow, hydro sites [16-17, 21-23]. Besides that, for many years, this simple reaction hydro turbine has been considered to be inefficient and uncontrollable for use with low-head and low-flow water resources.

Hence, in this paper, a simple reaction water turbine that is suitable for use in low-head low-flow areas is proposed. This paper explores the history and examines the development of eight types of reaction water turbines, namely Hero's turbine, Barker's mill, Pupil's turbine, Whitlaw's mill, Quek's turbine, the Cross Pipe Turbine (CPT), Split Reaction Turbine (SRT), and the Z-blade turbine, which is one of simplest reaction turbines that can operate with a low waterhead and low water flow. This paper also highlights the advantages and disadvantages of each simple water turbine from the perspective of its design and manufacturing complexity.

2.1 Water Turbine Scenario

Water turbines can be divided into two main categories, namely impulse turbines and reaction turbines, depending on their working principles [9, 24]. In a pure impulse hydraulic turbine, the process of power generation starts when the water jet directed by the nozzle hits the turbine blades and consequently, causes the blades to revolve [16,21].

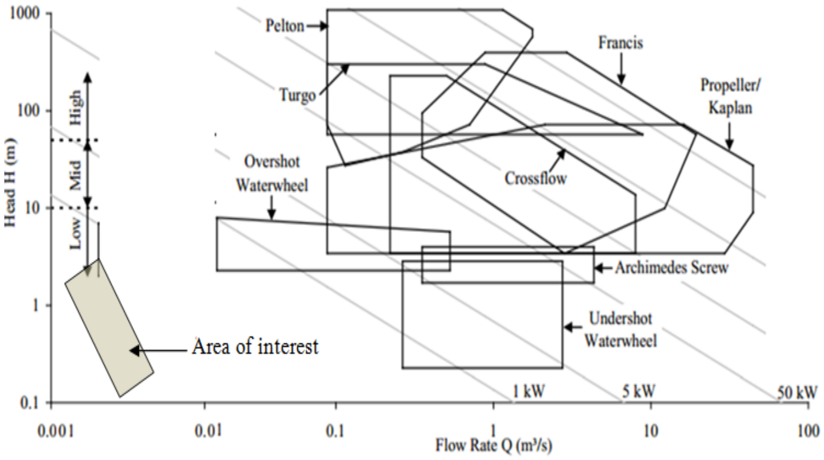
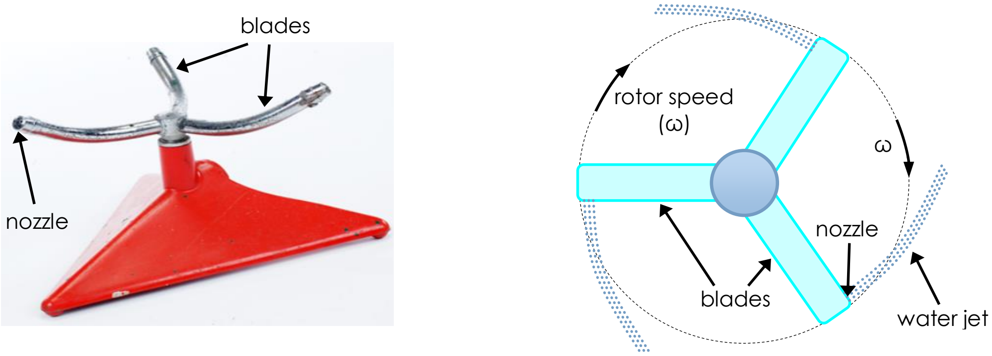


Figure 3 Typical application range chart [18]



a) Actual whirling sprinkler

b) Basic concept of a reaction water turbine

Figure 4 Example of reaction turbine: water sprinkler

The garden water sprinkler, as shown in Figure 4, is the most common example of a reaction water turbine. In a pure reaction hydraulic turbine, the water stream is pressurized and flows through the guiding mechanism to rotate the moving blades or moving nozzle [16]. As the water glides through the moving blades, the pressure is reduced, and the velocity of the water stream relative to the moving parts is increased. Uniquely, the pressure not only comes from the potential energy but also from the centrifugal head due to the self-pumping effect during the rotation of the turbine [17].

Typical and well-known reaction turbines include the Francis turbine, Kaplan turbine, tubular turbine, propeller turbine, bulb turbine, and pump as turbine. However, all these turbines are complicated in terms of their design, development, installation and maintenance. In addition, these water turbines require expensive machining due to their complexity, which leads to higher development costs. Therefore, the turbines have not been categorized as simple reaction turbines, although these machines are well known as reaction hydro machines. It should be noted that the first well-designed inward flow pure reaction turbine was built in 1949 by the hydraulic engineer, James B. Francis [9-15].

Extensive efforts were made during the 18th century and early 19th century to explore simple reaction turbines, and several units were fabricated and used for research works [16]. During the early stages of development of the simple reaction turbine, many challenges were experienced in terms of its research, development and implementation. The research efforts, however, were halted for quite some time from the middle of the 19th century until the middle of the 20th century. In recent years, this type of turbine has been revisited by many researchers, who have mainly focused on gaining an in-depth understanding of its potential applications and on trying to eliminate the drawbacks that appeared in the previous turbines [4]. Currently, there are eight types of simple reaction turbines, ranging from Hero's turbine, developed around the first century AD, to the latest invention, known as the Z-Blade turbine. As such, a comparison of these particular types of turbines, spanning from the first turbine to the latest turbine invention, is presented in the next section.

3.0 SIMPLE REACTION HYDRAULIC TURBINES

Generally, water pumps and water turbines operate on different principles [19]. For a water pump, electrical power is fed to drive the blades to collect water. In contrast, for a hydraulic turbine, the water drives the blades to rotate and finally produce electrical energy.

A reaction water turbine applies a method of propulsion, where it uses the reaction produced by the acceleration of a fluid through an orifice or nozzle to move an object forward [21]. The fluid completely fills the runner passages where the impeller is located, and any head change or pressure decrease will occur in the impeller [21,26]. This characteristic makes a reaction turbine suitable for a wide variety of heads, ranging from very small to medium heads. Moreover, for a reaction turbine, the liquid flows from the larger end and exits at a smaller gap to cause the blade to rotate [16,17]. The blade starts to turn once the tangential velocity of the rotor exists. During this time, the potential energy of the liquid consistently decreases when approaching the small gap. Simultaneously, the kinetic energy of the fluid becomes higher due to the increase in the angular velocity of the rotor.

There are seven types of simple reaction water turbines, as discussed by [16,17,21-23]: 1) Hero's turbine, 2) Barker's mill, 3) Pupil's turbine, 4) Whitlaw's mill, 5) Quek's turbine, 6) cross pipe turbine, and 7) split reaction turbine, including the latest version of a simple reaction water turbine, known as the Z-blade, which was developed by Farriz in 2014 [27]. Figure 5 shows the chronological development of eight types of reaction water turbines starting from the Hero's turbine until the latest invention known as the Z-blade turbine.

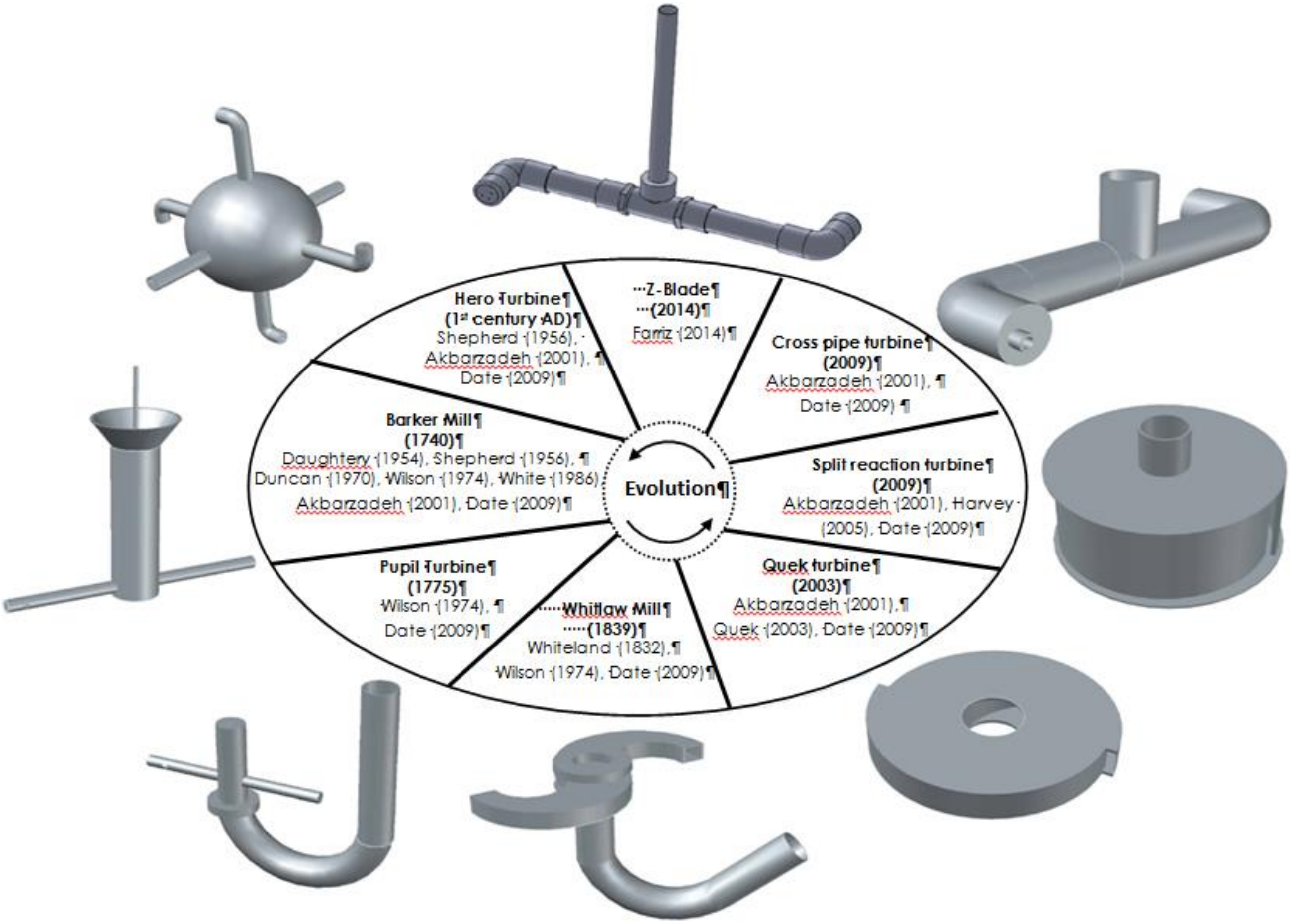


Figure 5 Chronological development of simple reaction turbine (adapted from [4,6,16-18,21-23,25-30])

3.1 Hero's Turbine

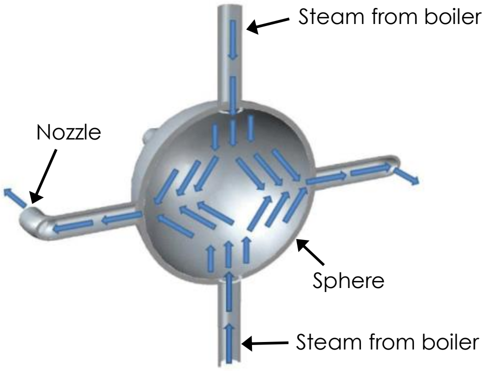


Figure 6 Hero's Turbine

The earliest historically recorded outward-flow steam turbine was discovered during the first century AD [28]. Approximately 2000 years ago, a mathematician from Alexandria, Greece named Hero developed the first reaction turbine driven by steam, called the "aeolipile" [16,21]. Hero's turbine, as shown in Figure 6, consists of a hollow metal sphere with nozzles pointing in the opposite direction tangentially to the sphere along the same axis. Two tubes are used for the flow of the steam generated by the sealed boiler to the sphere. This causes the steam to flow into the sphere and exit the nozzle, thereby resulting in the rotation of the sphere. The turbine does not produce power, but Hero demonstrated that steam power could be used to operate machinery [21].

3.2 Barker's Mill

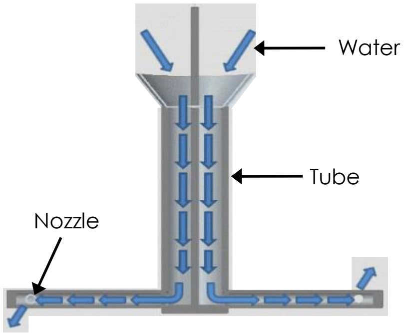


Figure 7 Barker's Mill

In the late 17th century, Dr. Robert Barker, an English engineer, invented Barker's mill [16,17,21,26,29]. Barker's mill, as shown in Figure 7, is a modified version of the Hero turbine and it is capable of operating with the potential energy of the water that is stored in a dam or reservoir [21]. Barker was one of the earliest pioneers to explore an outward-flow reaction water turbine [16]. The characteristics of the turbine are similar to those of the Hero turbine, except that the source of power is water instead of steam. The design of the tube is configured so that the water enters from the top of the turbine. A reaction force is generated when the fluid exits the nozzle tangentially, thus resulting in a movement in the reverse direction that will cause the rotor to rotate, thus generating mechanical power [17].

However, according to most analyses, this turbine fails to perform optimally because the centrifugally-induced increase in pressure simultaneously increases the water flow rate throughout the rotation [16]. Besides that, it is particularly inefficient at low rotational speeds because at such speeds the water still has significant kinetic energy when it leaves the nozzle turbine [17]. However, Barker's mill has been used as a reference in most simple reaction turbine concepts in terms of design and working principles. One good example of the working principle of this turbine is the garden water sprinkler.

3.3 Pupil's Turbine

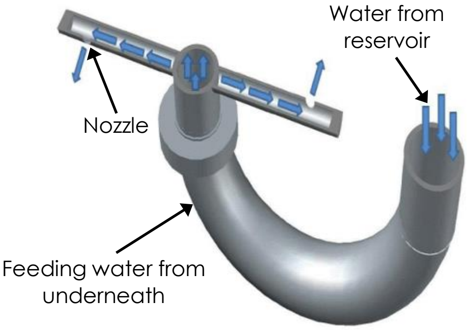


Figure 8 Pupil's Turbine

Pupil, in approximately the year 1775, improved on the design of Barker's mill [16,30], and this has been described in detail in [21]. In Pupil's turbine, the water is fed into the turbine from the bottom, unlike Barker's mill. This approach reduces the friction force, where this innovation allows the pressure (head of water) to be in the opposite direction to the load of the moving turbine. The increased water pressure from below the turbine acts as a cushion and provides resistance to the pressure from the water turbine [21].

However, this configuration reduces the vertical height (head) and the physical difference between the water level in the reservoir and the position of the turbine [2,16,21]. As discussed in Section 2.0, the waterhead, H, is the most important parameter in the generation of hydroelectricity [6-8]. This shows that the approach of Pupil's turbine does not fully utilise the potential energy available and therefore, this turbine, as shown in Figure 8, has become unpopular.

3.4 Whitlaw's Mill

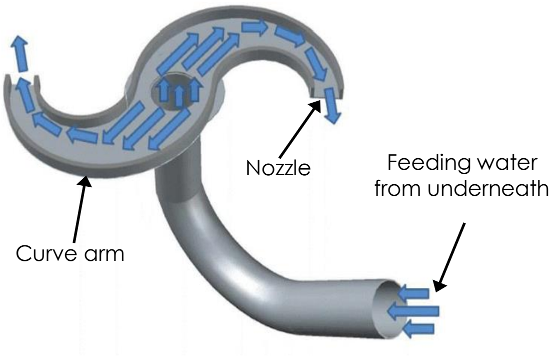


Figure 9 Whitlaw's Mill

In 1839, James Whitlaw invented the "Scotch Mill", which is relatively similar to Barker's mill, with the exception of the nozzle arm [30]. Whitlaw redesigned the arm of Barker's mill, making it curved, as shown in Figure 9, thereby creating a higher exit velocity because he believed that the arms would increase the efficiency of the turbine. However, Whitlaw's mill did not attract public attention because it was introduced at a time when more efficient reaction hydraulic turbines with complicated designs, such as those by Francis, Fourneyron and Thomson, were invented [21]. Hence, Whitlaw's mill was not explored further so much so that it was underestimated and underutilized by the people at that time.

3.5 Quek's Turbine

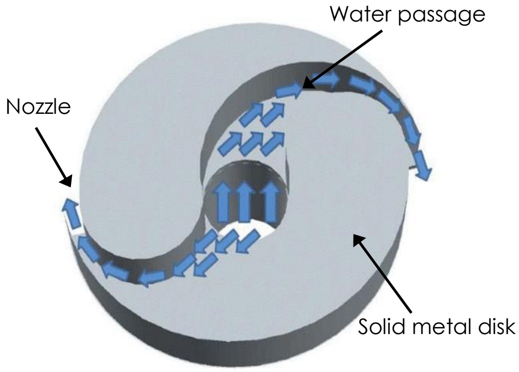


Figure 10 Quek's Turbine

In 2001, Quek, developed a high head reaction turbine, as shown in Figure 10. It has a water passage (grove) that is machined into a solid metal disk using a CNC machine. Quek produced a turbine that had a turbine diameter of less than one meter and a total nozzle exit area of 0.0003 m^2 [21]. The turbine is costly because the design of the rotor is so complicated, making it difficult to manufacture because it requires machinists with a very high level of skill and a programmer as well as specialized machinery.

The expensive machining process and the low efficiency indicate that this type of simple reaction turbine requires redesigning so that the shape of the turbine will be less complex and the manufacturing cost will be reduced. Significant effort is required to improve the efficiency of Quek's turbine if it is intended to be used for low head micro-hydro applications. Besides that, the experimental investigations performed by Quek in 2003 revealed that the efficiency of the turbine is less than 45% when the waterhead is set between 10 m to 25 m [21]. The level of efficiency is low since the turbine is supplied with high potential energy and supposed the efficiency of small hydro systems tend to be in the range of 60% to 80% [3].

3.6 Cross Pipe Turbine

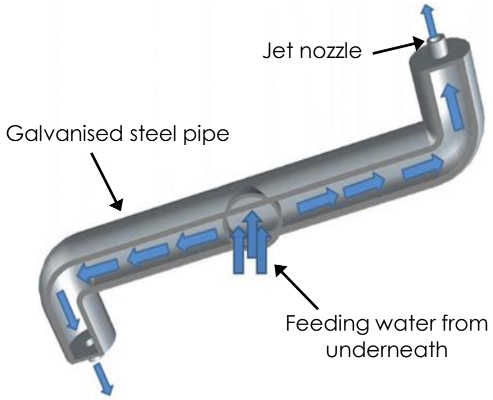


Figure 11 Cross Pipe Turbine

The Cross Pipe Turbine (CPT), shown in Figure 11, which was developed by [22], uses standard galvanized steel pipe fittings with four important turbine parts: a cross pipe at the centre, two arms composed of male adapter fittings, two reduction elbows, and solid stream jet nozzles fixed at the exits of both elbows through a reduction bush [21]. The purpose of the nozzle is to cause the water to flow out tangentially to the diameter of the rotor and to maximize the velocity of the water flowing out of the nozzle.

The obvious disadvantage of this turbine is that it is difficult to achieve a smaller rotor size and a flexible diameter for the nozzle exit areas. This disadvantage is due to the fixed dimensions of the standard galvanized steel pipe fittings, even if the cross pipe is joined together with the shortest possible standard pipe fittings [21]. The smallest diameter of the turbine that can be made was reported to be approximately 0.4 m. When the water flow rate is low and when the rotor has a large diameter, the angular speed of the CPT is found to be slow, thereby resulting in inefficient performance [21]. Due to these constraints, recent research works no longer investigate the CPT.

3.7 Split Reaction Turbine

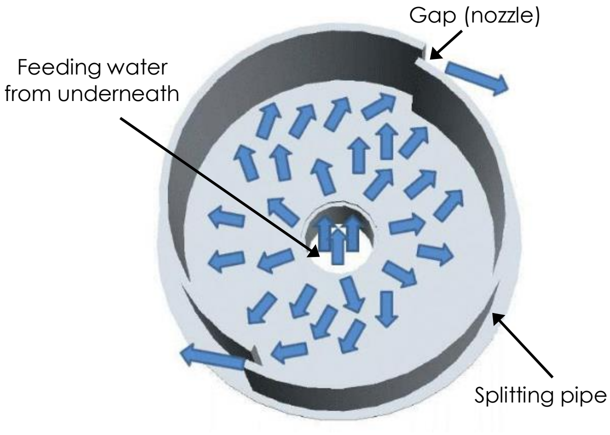


Figure 12 Whitlaw's Mill

Interestingly, the Split Reaction Turbine (SRT), shown in Figure 12, was developed with reference to the disadvantages of the CPT. Efforts were made to further improve the design of the simple reaction water turbine so that the turbine would have nominal performance or efficiency while allowing it to be manufactured with simple or straightforward manufacturing processes, simultaneously reducing the development cost.

In 1970, Duncan [29] claimed that the Barker's mill approach was deemed obsolete and not economically viable despite the design modifications that had been made to increase its efficiency [21]. By contrast, Akbarzadeh et al. [17] revisited the obsolete Barker's mill and believed that all types of simple reaction turbines that are based on Barker's mill were, to some extent, being underutilized, except in the form of garden sprinklers. According to [16], many incorrect conclusions had been presented in the published literature and many analyses indicated, to a large extent, that the simple reaction water turbine had been misunderstood and almost forgotten. For many years, simple reaction turbine was said to be only suitable for high heads and to have less energy conversion efficiency and high air drag. However, by improving on the shape of the rotor design and playing around with the parameters, such as mass flow rate, rotor speed and centrifugal pumping effect, this type of turbine can definitely be converted from a low-head hydro power to a highly efficient mechanical power [16,17].

In 2009, A. Date used Akbarzadeh's parametric analysis discussed in [17] to investigate the new development of a cylindrically-shaped Split Reaction Turbine (SRT). The system is able to generate high energy conversion efficiency under a low hydro-static head, starting from 2 m, and a mass flow rate starting from 10 L/sec [21]. Specific descriptions of the manufacturing process of the SRT, which has a capacity up to 1.5 kW, were mentioned in [21-23]. This manufacturing process involves cutting a grey polyvinyl chloride (PVC) pipe and splitting it into two, off-setting the centres by a few millimetres, and joining these with upper and lower lids.

However, the SRT still has some limitations, particularly with regard to the design and assembly of the top and bottom cover plates, the inlet port, and the flange coupling, which must be watertight. In addition, adjusting the nozzle exit area requires special skills and tools as well. Moreover, a big issue arises when debris accumulate inside the turbine [31], as it is quite difficult to clean and service the SRT.

3.8 Z-Blade Turbine

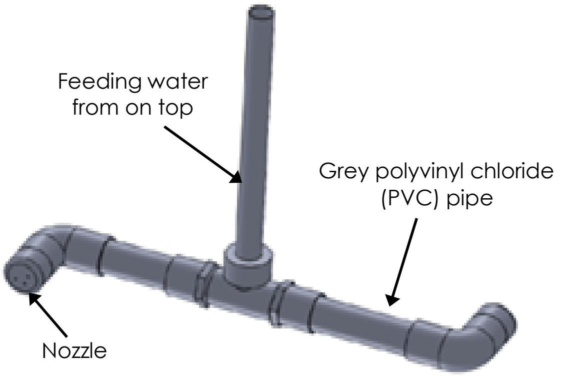


Figure 13 Z-Blade Turbine

The Z-blade turbine, which was developed by Farriz in 2014 [27], is the latest version of the simple reaction turbine. Compared to the seven other turbines described above, this innovative turbine is considered to have the simplest geometrical design and fabricating process. As such, this turbine, as shown in Figure 13, is inexpensive, user friendly, and easy to install and maintain.

The development of this innovative turbine was based on the design, experimental investigations and parametric analysis of the SRT and CPT, as previously reported by [16,17,21-23]. A few modifications to the CPT design were made to suit the Z-blade for low-head and low water flow rate conditions. This turbine uses standard PVC pipe fittings, which are readily available in local markets and can be easily modified. It is easy to assemble because it is not so complicated as to require high levels of expertise or skills [4]. In short, this turbine only requires people who have basic knowledge and expertise in plumbing systems. In addition, the newly invented water coupling combined with the Z-blade turbine has successfully enhanced its performance and efficiency.

The theoretical analysis and experiments prove that the Z-blade turbine performs successfully at a low operational waterhead (less than 5 m) because of its capability to achieve high rotational speeds, high mechanical power, low energy loss, and high efficiency with minimal mass flow rate (less than 2.5 L/sec). On average, the efficiency values given by the experimental data are within the range of 82% for 4 m of waterhead. In contrast, the turbine efficiency of the SRT is only 70% when the waterhead is at 4.2 m. Looking at the performance of the Z-blade turbine, it is considered to be very economically feasible because it only requires a small investment but is capable of achieving a higher power output. In addition, the Z-Blade turbine is believed to be capable of overcoming constraints with regard to the depletion of the quantity of water due to drought. Similar to Barker's mill, the Z-blade operates by using water stored in a dam or reservoir.

As shown in Figure 13, standard PVC pipe fittings were used to develop the Z-blade turbine. This turbine has four important turbine parts: (a) a T-joint pipe at the centre, (b) two arms made of PVC male-threaded adapter fittings and PVC pipes of various lengths, (c) two 90° PVC elbows, and (d) two PVC end caps. The nozzle for the water stream jet is produced by drilling the PVC end cap. No spray nozzles are fixed at the exit of both elbows, as used in the CPT. The Z-blade turbine also exhibits features that are better than those of the CPT and SRT, given that it has no fixed dimensions for the nozzle exit area. Thus, the nozzle exit area can be easily adjusted and modified. All the components, such as the male adapter fitting, PVC pipe, 90° PVC elbow, and end cap, are easily available off the shelf at local hardware stores.

Based on the experimentation and parametric analysis via the governing equation, the optimum diameter of the Z-blade turbine can be identified by referring to the peak of the bell-shaped lines. These lines are obtained when the angular speed is plotted against the diameter of the turbine for a constant operating head. The optimum diameter is defined as the diameter corresponding to the maximum rotational speed for a given water head. In addition, the angular speed of the SRT will increase until the jet nozzle interference speed occurs. In contrast to the SRT, the turbine speed of the Z-blade will decrease after reaching the optimum diameter without facing the jet nozzle rotor interference. This is like a non-interference turbine rotational speed.

4.0 CONCLUSION

Hero's turbine and Barker's mill are acknowledged as being the source of inspiration for the evolution of simple reaction turbines. Later, both these turbines were further refined to produce many different turbines, such as Pupil's turbine, Whitlaw's mill, Quek's turbine, and the cross pipe turbine, but the results of their performance were still unsatisfactory and they were not suitable for applications in the community. At one time, this type of turbine was even declared to be inefficient and uncontrollable, and continued to be ignored. However, the emergence of the split reaction turbine and Z-blade turbine has given a different perspective in terms of the capabilities of simple reaction turbines, which had previously been underestimated and underutilized. Both turbines have inherent potential as pico-hydro turbines for applications at low-head low-flow water reservoirs for the production of clean power. Compared to the other six turbines in the family of simple reaction turbines, the split reaction turbine and Z-blade turbine have non-complex geometrical designs and are very simple to fabricate, as have been proven experimentally.

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