Major historical developments in the design of water wheels and Francis hydroturbines

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Abstract. The first record of water wheels dates back to ancient Greece. Over the next several centuries the technology spread all over the world. The process of arriving at the design of the modern Francis runner lasted from 1848 to approximately 1920. Though the modern Francis runner has little resemblance to the original turbines designed by James B. Francis in 1848, it became known as the Francis turbine around 1920, in honor of his many contributions to hydraulic engineering analysis and design. The modern Francis turbine is the most widely used turbine design today, particularly for medium head and large flow rate situations, and can achieve over 95% efficiency.

1. Introduction

In order to better grasp the current challenges and future potential of hydropower equipment, it is important to have a knowledge of the contributions made in the last 3000 years by countless wheelwrights, inventors, and engineers to improve the performance of hydraulic equipment. This paper presents a brief history of the development of the hydroturbine and what inspired improvements to the technology. Additional details can be found in [1].

2. The Water Wheel

The ancient Greeks were the first recorded society to successfully develop a form of hydropower—the water wheel [2]. The Greek water wheel was designed as a work of art rather than science, and was highly inefficient [3]. However, the torque from the simple water wheel was successfully used to grind wheat into flour. The Greek flour mill was later adopted by the Romans, and by 500 A.D. the invention had spread throughout the known world [4]. However, the availability of slave and animal labor restricted its widespread application until the 12th century [5].

The original Greek water wheel later became known as an undershot water wheel, as the water passes underneath the wheel (see Figure 1(a)). Undershot water wheels are the least expensive to construct, cause negligible change to the river, and are typically installed in large or swift moving rivers with minimal elevation change. The undershot water wheel may be installed directly in the river, or as part of a millrace system with flow control gates. In modern vernacular, the undershot water wheel would be considered an impulse, or kinetic turbine, as it operates exclusively on the transfer of momentum from the moving fluid to the paddles of the wheel. The volume and speed of the moving water determine the maximum power output.
Figure 1. Water wheel design schematics by millwright Olivar Evans. The undershot water wheel (a) was originally developed by the ancient Greeks, and is considered the first form of hydropower. The overshot water wheel (b) was a significant improvement in efficiency. The breastshot water wheel (c) combines the advantages of both previous designs, and supplied the majority of U.S. industrial power during the industrial revolution. Source: Evans et al. [6].

The overshot water wheel design first appeared during the Middle Ages. In an overshot water wheel, the weight of the water filling the buckets causes the wheel to rotate, producing power from the change in potential energy of falling water (see Figure 1(b)). One major advantage of overshot water wheels is that they are able to utilize the complete fluid stream, giving them a higher operational efficiency. However, compared with an undershot design, overshot water wheels have significant construction costs as the water from the river must be diverted to pass through a flume or penstock at the top of the wheel. Overshot water wheels are preferred for mountain streams, where the elevation change and limited water flow can be leveraged.

By the 1700’s, water wheels were used extensively for milling [7]. Saw mills, textile mills, paper mills, and flour mills formed an important role in local economies where any amount of moving water was available. Mining operations also used water wheels to lift water, ore, and personnel. As industrial power requirements continued to increase, water wheel efficiency became an important concern. John Smeaton, a British civil engineer, performed the first scientific evaluation of the water wheel in the mid 1700’s [8]. He developed methods for determining the efficiency of the water wheel. Smeaton found that on average the undershot wheel used 22% of the energy in the water passing through the wheel, while an overshot wheel used 63%. Smeaton’s work led to changes in water wheel design that resulted in a dramatic increase in performance.

The breastshot water wheel followed Smeaton’s findings, and incorporated the advantages of both the undershot and overshot designs (see Figure 1(c)), extracting energy from both the fluid momentum, as well as the change in potential energy. The breastshot water wheel is also able to
harness significantly larger flow rates than are possible with an overshot design. The increased flow rate allowed greater power output to be achieved, though breastshot water wheels had an average efficiency of only 50%. The breastshot water wheel gained significant popularity in the United States in the early 1800’s and was the workhorse of the industrial revolution [4].

In 1824, a French engineer, Jean-Victor Poncelet, first demonstrated the use of curved buckets on undershot water wheels. The curved profile caused the water to exit the bucket at something close to 180 degrees from the incidence angle, thus extracting the maximum fluid momentum from the fluid stream. In addition, Poncelet adjusted the wheel rotational speed such that the water left the buckets with a very low velocity compared to when it entered. His two design modifications increased the efficiency of undershot water wheels to more than 60% [9].

2.1. The Pelton Wheel, the Modern Impulse Hydroturbine

Beginning in the 1820’s, the water wheel began to be superseded by the smaller and more efficient water turbine (see Section 3). However, in 1866, Samuel Knight invented the tangential water wheel, which was capable of matching the performance of the hydroturbines of the day. Knight was inspired by the high pressure jet systems used in hydraulic gold mining [10]. The Knight wheel utilized water delivered through a pipe to the wheel from a dam at much higher elevation. The water was then accelerated through one or more nozzles and directed to impact the rotating buckets of the wheel. The large hydrodynamic head that can be utilized by a tangential water wheel is not limited by the diameter of the wheel, as is the case with traditional water wheels.

In 1878, Lester A. Pelton improved on the Knight wheel [11]. Pelton proposed a double bucket design, with a half-cylindrical profile (see Figure 2(a)). The half-cylindrical exhausted the water to the sides of the wheel, reducing some of the inefficiencies in the Knight wheel, which exhausted water against the center of the wheel.

![Figure 2. Pelton’s design (a) was an improvement on the Knight wheel, and used a half-cylinder profile to exhaust water to the side. The Doble bucket design and notched tip (b) improved momentum transfer and decreased the interference with the jet. Source: (a) Pelton US Patent No. 233692 (Oct. 1880), (b) Çengel and Cimbala [11], Courtesy of VA TECH HYDRO.](image)

William Doble later took over the Pelton company, and in 1895 he proposed an elliptical bucket that included a cut at the tip [12]. The elliptical bucket improved the momentum transfer from the jet, and the cut at the tip allowed the jet a cleaner entry to the bucket (see...
Figure 2(b)). Though the Doble bucket concept remains the standard bucket design for modern tangential water wheels, Pelton was the first to file a patent for the tangential water wheel, and did much to promote its popularity. As a result, his name was attached to the design.

Modern Pelton turbines have several nozzles positioned around the wheel to more effectively utilize each bucket and to balance the forces imparted to the wheel. A range of torques and flow rates can be achieved by adjusting the nozzle openings. Pelton wheels are commonly installed in locations with limited flow rates, but high heads, and can achieve efficiencies up to 90% [11].

3. Early Water Turbines

The word turbine was introduced by the French engineer Claude Burdin in the mid 1800’s and is derived from the Latin word for “whirling” or “vortex” [13]. The main difference between a water turbine and water wheel is a swirl component of the water which passes energy to a spinning rotor. This additional component of motion allows the turbine to be smaller than a water wheel of the same power. Turbines can adjust the amount of water processed by changing either the inlet gate openings or the rotational speed of the turbine. Turbines are also able to utilize much greater heads than possible with a water wheel.

The first known water turbines were installed in Chemtou and Testour, present day Republic of Tunisia, in the second century. These turbines were a Roman adaptation of the Greek water wheel, and consisted of a horizontal wheel with angled blades, installed at the bottom of a circular cistern (see Figure 3). The water from the millrace entered the cistern at an angle to add pre-swirl to the water passing through the fully submerged wheel [14].

In spite of the Roman turbine being more efficient than a water wheel of the same size and flow rate, few were ever installed. However, during the industrial revolution, the increasing power needs began to highlight the main shortcoming of the water wheel–size. The flow rate and head that could be harnessed were limited by the bucket width and wheel diameter, respectively. As the need for industrial power increased, the development of the modern water turbine became a priority [15]. The migration from water wheels to modern turbines took about one hundred years, and various types of water turbines were developed to suit the large variety of heads and flow rates seen in waterways throughout the world.

In 1826, Benoît Fourneyron, a French engineer and former student of Burdin, developed an outward-flow turbine that achieved close to 80% efficiency. In the Fourneyron turbine, water was passed through a stationary inner core and then directed outwards through curved horizontal guide vanes. The guide vanes not only imparted swirl to the flow, but distributed the water around the entire inner periphery of the rotating turbine wheel. Over the next decade Fourneyron improved his design, eventually producing over 50 Horsepower (37.3 kW) [9].
In 1844, Uriah A. Boyden, an American engineer from Massachusetts, developed an outward-flow turbine that greatly improved on the performance of the Fourneyron turbine, achieving a peak efficiency of approximately 80%. Boyden added a conical approach passage for the incoming water to reduce the losses due to the abrupt area changes in the Fourneyron design. Boyden also recognized the lost potential in the discharged water, and added a submerged diffuser at the discharge of the wheel and a diverging exit passage (see Figure 4). The diffuser and exit passage converted part of the kinetic energy of the discharging water into pressure energy, and therefore increased the effective head across the turbine [16]. The addition of the diffuser increased the efficiency of the turbine by approximately 3%, though Boyden predicted 5%. Although the Boyden turbine was later superseded, Boyden remained a prominent figure in the hydraulic industry and other fields of scientific research, including chemistry and physics. In 1890 the Harvard Observatory moved from Lima, Peru to Arequipa, Peru, and was renamed the Boyden Observatory in memory of $238,000 willed to the Harvard Observatory upon his death in 1879.

![Figure 4](image)

**Figure 4.** Boyden horizontal outward-flow turbine, 1844. The Boyden turbine was an improvement on the Fourneyron turbine, with a conical approach passage and submerged diffuser at the wheel discharge. Source: (a) Emerson [17], (b) Francis [18], (c) Ripley and Daina [19].

Though widely used in their day, outward-flow turbines have several mechanical disadvantages. As water flows outward through the turbine it decelerates. The decrease in velocity not only reduces the available kinetic energy in the flow, but the diverging flow also tends to become unstable and separate. In addition, these machines were expensive to manufacture, difficult to maintain, and the speed could not be governed closely [16]. Despite these disadvantages Fourneyron and Boyden style outward-flow turbines remained highly popular for more than 70 years, even after more efficient turbine designs were available, as evident by their use in the original Niagara Falls hydroelectric installation in 1895 [16].

Returning to 1826, the same year that Fourneyron developed his outward-flow turbine, Poncelet also proposed placing the water wheel with curved buckets in a horizontal position (see Figure 5). In a vertical position, the curved blades caused reverse flow in the buckets as the water was exhausted toward the oncoming stream. By placing the wheel in a horizontal position, the water passed through the interior of the wheel. Though he never implemented it, Poncelet also considered introducing water around the periphery of the wheel [9].

In 1838, Samuel B. Howd, an American engineer, received a U.S. patent for the inward-flow turbine [20]. Howd’s patent included the inward-flow concept, as well as the admission of water around the complete circumference of the turbine wheel using fixed guide vanes. Howd was not a turbine designer or manufacturer, but rather licensed the intellectual property to American wheelwrights and turbine designers [21]. As a result, it took another 10 years before the inward-flow design could match the performance of the Boyden turbine.
This process of improving the Howd inward-flow turbine began in 1844, when the first outward-flow turbine designed by Boyden was installed in Lowell, Massachusetts, for the cotton mills of the Appleton Company. For the following three years, James B. Francis, Chief Engineer for Locks and Canals Company in Lowell, carried out a series of systematic tests on Boyden’s inward-flow turbine. These tests led to the development of a standardized method for hydroturbine performance evaluation. Francis also developed a scientific turbine design method based on analyzing the path of water particles for different relative velocities under a given head, a technique which had first been attempted by Boyden [21].

In 1847, after purchasing patent rights from Howd, Francis designed and built his first model-scale inward-flow turbine (see Figure 6). The Francis model was an adaptation of the Howd and Poncelet inward-flow wheel designs, and achieved a peak efficiency of 71% [21]. The guide vanes were almost identical to the simple straight blade sketches in the Howd patent, with the addition of a gradual vertical area change to add acceleration. The turbine blades were also short, with no curvature. Though incurring a loss in performance, the straight blades allowed for simple calculation of the respective flow angles used in Francis’ turbine performance theory.

In 1849, the first full-scale turbine designed by Francis was installed at the Boot Cotton Mills. Francis made several improvements to his previous design, introducing the water from the penstock offset to one side of the turbine to add pre-swirl, adding curvature to the turbine blades and fixed guide vanes, and including a curved discharge after the water passed through the turbine wheel. The most impressive aspect of the original Francis turbine design was the accuracy of the performance prediction. Francis calculated a peak efficiency of 79.31% from his design and testing of the installed turbine showed an efficiency of 79.37% [21].

Francis is regarded as the originator of the scientific method for testing hydraulic machinery [16]. Francis and Boyden were the first to apply a design method based on the analysis of relative flow angles. Francis also utilized new building materials and the skilled workmen of the Locks and Canals Company to introduce a new standard of turbine construction [21]. In 1855 Francis published his work in Lowell Hydraulic Experiments [18], which is considered one of the most outstanding American contributions to hydraulic engineering [16]. Francis was the Chief Engineer of the Locks and Channels Company for 48 years. He founded the American Society of Civil Engineers, and was elected president in 1880 [16]. For his many contributions to the advancement of hydraulic engineering, the modern mixed-flow reaction hydroturbine bears his name, though it has little resemblance to the turbine he installed at the Boot Cotton Mills.
4. The Modern Francis Runner Wheel

Modern reaction hydroturbines are divided into two major categories: Francis turbines and Kaplan turbines. Both Francis and Kaplan style turbines originated from the early inward-flow turbine designs. The primary difference between them is the direction of fluid flow as it passes through the runner. The process of arriving at the modern Francis runner design took from 1848 to approximately 1920. Figure 7 shows a timeline of major design changes to the Francis runner blades. The dates shown indicate that the majority of these advances took place during what became known as the “Cut and Try” period (1860-1890). Though these changes were often implemented with little analysis, the final result was a successful turbine design.

The blades designed by Francis in 1848 were short in comparison to the runner diameter, and discharged radially inward. With such shallow blades, very little energy could be extracted from the water and the flow rate was limited. Boyden recognized these limitations, and in 1849, he increased the depth of the Francis blades, curved the band downward to change the flow direction to be slightly axial, and angled the trailing-edge to maintain the axial flow direction. These changes significantly increased the flow rate and turbine power output.

By 1859, the “Cut and Try” period had begun. The blades of what was then called the American wheel were taller than the Francis or Boyden designs to allow larger flow rates, but the trailing edge was cut parallel with the leading-edge to simplify its construction. The American turbine was also the first stock turbine, and some designs included adjustable guide vanes [21]. Manufacturers of stock turbines would produce a turbine design that could be scaled to fit some general combination of flow rate and head. This method was suitable for supplying power to mills and factories, and a similar approach is used today for small and medium sized pumps. The use of stock hydroturbines continued until the early 1900’s and ended with the shift to hydroelectric power, when it became economical to produce an optimized design for each site.

In 1862, a revolutionary stock turbine design appeared on the market produced by James Leffel & Co. The Leffel turbine utilized a double discharge runner wheel, with the upper blades and flow passage shaped similar to the American runner wheel, and the lower blades discharging axially (see Figure 8). The turbine included adjustable guide vanes at the runner inlet, but no
spiral case or diffuser, although a short discharge tube was utilized to raise the turbine wheel above the tailrace. The original Leffel turbine achieved an efficiency of approximately 74% [21]. Though the American turbine was more efficient, the Leffel turbine could handle increased flow rates with a smaller diameter wheel, and was thus capable of producing more mechanical power. The Leffel turbine quickly became popular, the common belief being that the double wheel design was more efficient, though the designers could not fully justify their reasoning, and testing performed by Emerson found that most of the theories were incorrect [17].

![Figure 7. Timeline of major design changes to the Francis runner blades. For each image, the rotational axis is located at the far right. The images show a gradual process of evolution to arrive at the modern Francis runner design. Source: Safford and Hamilton [21].](image)

(a) Francis, 1848  
(b) Boyden, 1849  
(c) American, 1859  
(d) Swain, 1858  
(e) Ridison, 1873  
(f) Hercules, 1876  
(g) Samson, 1902  
(h) Francis, 1920

Figure 8. 1862 James Leffel & Co. turbine, utilizing a double discharge wheel. This turbine achieved an efficiency of approximately 74%, and no diffuser or spiral case was included in the design. Source: (a) Safford and Hamilton [21], (b) Ohio Historical Society, Image No. 83-3.
In 1858, one year previous to the release of the American turbine, Asa M. Swain performed an experiment with a six inch model runner having blades that extended far into the central discharge region of the runner. The blades were also curved away from the inlet edge to form a shallow bucket to better transfer the fluid momentum before the flow. The water was then discharged in both the radial and axial directions. In 1870 Swain deepened the buckets even further, which increased both the flow capacity and the power output. In 1874 Francis tested a 72 inch Swain turbine (see Figure 9) and found it had an efficiency of 84%. In 1909 the same turbine was tested with a draft tube and produced an efficiency of 86.1% [21].

![Figure 9. 72 inch radial-flow runner wheel designed by Asa M. Swain in 1870, and tested by Francis in 1874. This turbine produced an efficiency of 84% without a draft tube, and 86.1% with a draft tube. Swain’s runner design is considered one of the most influential contributions in the development of the modern Francis turbine. Source: Safford and Hamilton [21].](image)

Though the Swain turbine was originally overshadowed by the popularity of the American and Leffel turbines, from 1870 onward all subsequent radial-flow and mixed-flow turbine designs followed the Swain runner design. Swain’s revolutionary blade design became the precursor to the modern Francis runner. Some scholars, including Safford and Hamilton [21], even argue that the modern Francis turbine should have been named after Swain.

In 1873 the T. H. Ridison Company modified the Swain design by extending the upper edge of the runner blades to produce a runner with complete axial discharge. Ridison turbines were designed with fixed guide vanes and no spiral case. The Ridison Company was the first since Boyden to incorporate a diffusing draft tube. Ridison turbines were the premier turbines of the day for low-speed and low-flow conditions, achieving 73% efficiency at half-load, the best obtained up to that point in time, and 90.5% at BEP with the diffuser [21].

The next major design improvement came in 1876, when John B. McCormick developed the Hercules turbine (see Figure 10(a)). McCormick made the buckets of the runner even deeper than the 1870 Swain design, and extended the buckets below the band, making the discharge slightly outward to further diffuse the flow in the runner. The blades were also fitted with fins that ran parallel to the flow directions for approximately half of the blade chord. The theory was that fins would help improve the part-load efficiency [21]. The Hercules turbine had an efficiency of 89.2% at high flow and 73% at half-power [17]. The following year, Stilwell and Bierce produced the Victor turbine (see Figure 10(b)), which removed the fins and further extended the buckets, causing the discharge to be angled slightly outward to create a short diffuser [21]. The leading edges of the blades were also swept back to create a deeper bucket.

Countless other turbine designs were produced during this time, including the Angell, Barber, Blackstone, Bodine, Case, Curtis, Cook, Geyelin, Hummingbird, Hunt, Luther Scroll, Tyler, Upham, and Whitney. Many turbines were locally designed and manufactured, had little impact on future developments, and quickly disappeared. James B. Emerson tested almost all of these...
turbines in his lab in Holyoke, Massachusetts, and published performance results and sketches of each turbine in a four volume treatise between 1878 and 1892 [17].

Between 1880 and 1900 turbine designers and manufacturers began to converge on a handful of stock designs. The cause of this convergence was that scientific hydraulic analysis methods were reintroduced into the design process, and hydroturbines were once again designed rather than just manufactured. The “Cut and Try” period came to an end as customers began to require turbine manufacturers to provide acceptance testing and performance guarantees [21]. By 1902, McCormick developed the Samson turbine, with a peak efficiency of over 90%. The Samson turbine was widely produced by several turbine manufacturers, James Leffel & Co. even produced a double-wheel version of the turbine (see Figure 10(c)).

By 1920, the basic design for the modern high-speed mixed-flow turbine had emerged (see Figure 11). The primary motivation in the design was to increase the rotational speed of the turbine, without suffering a loss in efficiency [21]. The increased rotational speed was essential for electrification, as electrical generators required larger speed-to-torque ratios to efficiently produce electricity.

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**Figure 10.** Runner wheel of the 1876 Hercules turbine (a) by J. McCormick, 1877 Victor turbine (b) by Stilwell and Bierce, and 1902 double-wheel Samson turbine (c). Source: (a and b) Emerson [17], (c) James Leffel & Co. [22].

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**Figure 11.** Interactive 3-D model of the GAMM Francis runner wheel. *Note: Adobe Reader 10, or later, is required to view the 3-D model.*
The runner blades in the modern design extended only slightly past the band. The leading-edge of the blades slanted away from the guide vanes to create a mixed-flow inlet. The leading edges of the blades were also wrapped, or swept, around the inlet plane so that the upper-edge of the blade was connected to the crown at a different circumferential location. The wrapping of the blades greatly reduced the amount of curvature in the blades, and ensured that each runner blade cut through the wakes shed by multiple guide vanes, thus reducing the risk of frequency lock-in and large amplitude vibrations in the runner.

5. Conclusion
From 1849 to the present, countless wheelwrights, inventors, and engineers have contributed to improving the performance of hydroturbines. As a result of their efforts, it is now possible to achieve over 95% efficiency [11]. The modern Francis turbine is the most widely used turbine design today, particularly for medium head and large flow rate situations [5].

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