BASIC PRINCIPLES OF 19th CENTURY WATERPOWER

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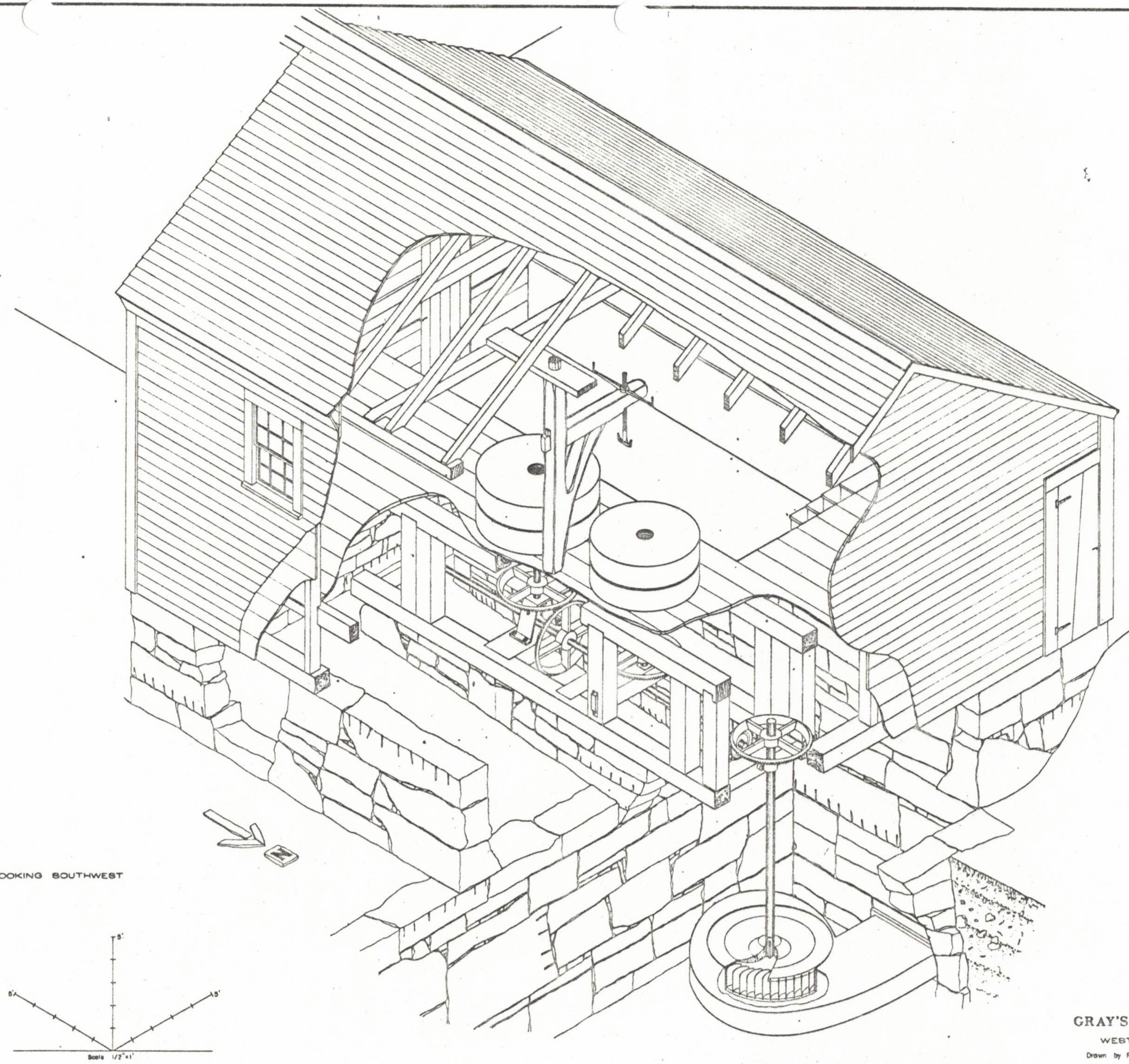

GRAY'S GRIST MILL

WESTPORT, MASS.

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INTRODUCTION

In reviewing the literature on hydraulic prime movers, a person new to the subject may run into difficulty when trying to understand the basic principles underlying the operation of water wheels and turbines. In many cases the literature assumes a level of understanding not particularly common these days when such machines are relatively rare. Even if one is well grounded in engineering or the sciences, the jargon itself can be bewildering. Terms such as impulse turbines, reaction wheels, flutter wheels etc. are hardly a part of every day vocabulary.

Having a clear understanding of the basic physics involved is the first step. Without such an understanding one cannot properly develop an appreciation for either the machines or for genius of those who were responsible for their development. An attempt is made here to first introduce some of the most basic principles that govern the flow of water, and in particular the flow of water through the wheel of a turbine. A few of the basic types of wheels that have evolved are then described and an attempt is made to interpret these designs in view of these hydraulic principles. This monograph is intended primarily for someone who, in just beginning to study the subject, is interested in a deeper insight than that provided by a strictly historical description. No attempt is made to include all of the developments.

SOME TERMS DEFINED

Water, like air, is a fluid, and both follow the basic principles of Newtonian mechanics, as do all particles of matter (at low velocities). Before we can understand the flow of water through a turbine, we must first understand some of the principles that govern the flow of water under more general circumstances. Some of these principles may seem elementary, but even so are worth a quick review.

PRESSURE is simply the force that is applied over a specific area. In this country we usually measure pressure in pounds per square inch (psi). In a column of water, the pressure increases with depth by about 0.4 psi for every foot of depth.

HEAD. In discussing water power, head may have either of two definitions. Gross head is the difference in elevation between the headrace and the tailrace. The headrace is above the turbine or wheel and supplies water. The tailrace is below the turbine or wheel and carries water away. Effective head is head that is equivalent to the pressure drop across the turbine, in other words the pressure that you would measure at the inlet to the turbine minus the pressure measured at the outlet of the turbine. It is the head that the turbine "sees". Head is also the column of water that creates pressure. The kind of head you use affects the rated efficiency of the turbine. This is not always clearly stated when reading descriptions of different turbines.

POTENTIAL ENERGY is the amount of energy that something has but hasn't been expended yet. For instance a heavy steel ball hanging from a cable 10 feet above the ground has potential energy, because if the cable were to break, the ball would come crashing down and hit the ground with a great deal of force, thereby expending its energy. Just as potential energy is energy <u>without</u> motion, kinetic energy is the energy <u>of</u> motion. It is the energy that the steel ball has as it is falling toward the ground. The water in a lake just <u>above</u> a waterfall has potential energy. The water <u>in</u> the waterfall has kinetic energy.

STREAMLINES are a series of parallel lines that represent the flow of water. They look like the marks that a garden rake leaves when dragged over fresh soil. When these lines appear smooth and flowing we have what is called LAMINAR FLOW, which simply means that all the water particles are moving smoothly along together in parallel rows like a parade of marching soldiers. They don't have to be straight, but they must flow smoothly around curves. Laminar flow is a very efficient way to move water.

When streamlines don't flow straight, but instead begin moving around erratically in a more or less random pattern, similar to water in a stream going through "rapids", we have what is called TURBULENT FLOW. In this case the water particles may be moving in any direction, even back against the flow, bumping into each other. When this happens, the resulting disorder is wasteful of energy. Machines like turbines, or airplane wings, are designed with no sharp corners or tight bends in order to preserve laminar flow as much as possible.

If you were to look down on a wide slowly moving river that suddenly flowed into a narrow valley, you would observe two different phenomena. First, the streamlines would crowd closer together, and second, the water would flow faster (through the narrow part). If the river where to widen again, the streamlines would diverge, the speed of the water would slow down, and the river would look exactly as it did before the restriction. Bernoulli's theorem states that the total energy in a flowing fluid must be the same at any point along the stream. This means that the three kinds of energy we have looked at, potential energy, kinetic energy, and pressure, (really a kind of potential energy) must always add up to the same number. For instance, consider where the stream is flowing slowly. Assuming that the potential energy doesn't change, we might measure the stream velocity, and also the water pressure that the stream exerts on the stream bank at that point. If we measure the velocity of the water at the rapids and find that it is flowing faster, then we know that the pressure it exerts on the banks must be less than it was where the water was flowing slowly. This has to be true because the sum of the three energies must add up to the same number. If you increase one you must decrease another. So a general rule might be made that whenever streamlines converge, water must flow faster, and the pressure must be less. Whenever streamlines diverge, water must slow down and the pressure must increase. This is what is commonly called BERNOULLI'S theorem.

The SPECIFIC SPEED of a turbine is simply the number of revolutions per minute (rpm) that the turbine must turn in order to produce 1 horsepower (hp) with a 1 foot head. Specific speed is a convenient way to compare the performance of different turbine designs under a common set of circumstances. For instance a large diameter slow turning turbine might produce 1 hp. with a 1 ft. head at 50 rpm., while another smaller faster turning design might produce 1 hp. with a 1 ft. head at 100 rpm. They both produce the same power under the same conditions. The only difference being the first has a specific speed of 50 while the other has a specific speed of 100. Specific speed assumes the that turbines under consideration are operating under optimum efficiency and full power.

REACTION is one of the more confusing terms, or confusing uses of a term as applied to turbines or wheels. Webster defines reaction as "the force that a body subjected to the action of a force from another body exerts in the opposite direction", which says what Newton said and is still believed by most scientists today, that for every action there is an equal and opposite reaction. If this definition were to hold then all wheels must be reaction wheels since any energy extracted from the water by a wheel must in effect be a reaction to the action of the water.

Addison[1] differentiates between Impulse and reaction or pressure turbines by defining reaction turbines as operating under varying degrees of pressure and velocity, while being completely submerged. Hunter[2] in discussing the Howd wheel writes "They reveal the essential character of the Howd wheel as a turbine, that is, a waterwheel acting not by weight, impact or impulse, but by pressure and reaction". One of the first reaction wheels ever built was known as "Barkers" mill. It operated using the principle of the rocket. By expelling a stream of water at relatively high speed, the reaction of the wheel to the escaping water turned the wheel. It resembled the common lawn sprinkler. Although the efficiency of this type of reaction wheel is low, other types may be highly efficient. With these thoughts in mind, we might define a REACTION TURBINE as being one that:

1. Operates completely submerged.
2. Operates under pressure.
3. Extracts energy from a moving stream by slowing the stream or by changing the angular momentum of the water. (More on this later)
4. Does not make use of impulse.

While some or all of this may at first appear to be complex, even the most sophisticated turbine operates using the basic principles outlined above. No matter what wheel or turbine we are dealing with, its basic operating principles must always be the same. In its simplest terms the problem may be viewed as follows. We begin with some specific amount of water at some specific height. We also have a specific distance through which that water can drop. These two conditions alone establish the maximum amount of power available. Given the flow of water (the specific amount in a given time) and the head (the maximum distance that the water can drop) all that remains is to design a wheel that can take that flow of water and using the given head extract the maximum possible energy. The turbine designer's success in so doing is measured as the efficiency of the turbine.

First, Carnot's conditions of maximum efficiency must be observed. The greatest efficiency can only be obtained when the water enters the turbine without shock and leaves without velocity.[3] The term shock may be considered as the expenditure of energy in a wasteful way, something we obviously want to avoid. We can minimize shock by not having any sharp turns or obstructions to flow in our turbine. The second term, that of having the water leave without velocity, simply means that we have been successful in extracting all of the energy from the moving stream. In other words, if we allow the water to drop through its head, it will have a certain amount of energy associated with its position and velocity. At the very beginning of its fall it will have mostly potential energy and a little kinetic energy.

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[1]. Herbert Addison, Treatise on Applied Hydraulics. p. 192.

[2]. Louis C. Hunter, Waterpower, A History of Power in the United States. p. 314.

[3]. Edwin T. Layton Jr., Scientific Technology 1845-1900: The Hydraulic Turbine and the Origins of American Research. p. 70.

At the end of its fall it will have almost all kinetic energy with a little potential energy. The type of wheel that we use depends in part on whether we prefer to use the water's potential energy as in an overshot wheel or its kinetic energy as in an impulse turbine or some of both as in a mixed flow turbine.

We might add to Carnot's theory by stating that to extract the maximum amount of energy from a given volume and head of water, the turbine must process that volume in the shortest possible time, with the lowest possible angular momentum at the exit. Now, this last statement might at first seem a contradiction, how can water possibly move rapidly through the turbine and have little or no velocity or momentum at the exit? It was precisely this problem that faced the turbine designers of the 19th century.

HISTORICAL BACKGROUND

Many of the prime movers used in the early saw and grist mills of this country were what are commonly known as water wheels. They were of three major types, overshot, undershot and breast wheels. Both overshot and breast wheels are powered primarily by the potential energy of water. While the impact of the stream on the buckets may contribute some small amount of energy, the primary force comes from the weight of the water acting at some distance from the axis of rotation, providing the torque to turn the shaft or gearing. With overshot wheels, the water flows over the top of the wheel by means of a headrace or sluice, where it spills into the buckets of the wheel, the weight of the water turning the wheel. The operation of the breast wheel is similar except that the water is admitted to the upstream side of the wheel at some distance down from the top so that the breast wheel turns in a direction opposite to that of the overshot wheel. The water flows down the "back" of a breast wheel. This is an advantage in times of flood when the tailwater rises enough to submerge a part of the wheel. Depending on the direction of rotation, the wheel must then operate either with or against the flow of the tailwater. The breast wheel, turning in the same direction as the tailwater wastes little energy, while the overshot wheel turning against the tailwater wastes a considerable energy.

One of the problems that these early wheels created for their designers and builders was the great amount of torque that was produced. Torque may best be understood as the amount of twisting force applied to a shaft. Cossons writes that by the end of the 18th century: "Wheels developing as much as 100 hp were becoming common, and contemporary wheel shafts, even those made of iron, could not transmit this power at the low speeds then employed."[4] As an example of the amount of stress applied to a shaft in the above case consider that if a wheel

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[4]. Neil Cossons, The BP Book of Industrial Archaeology. p. 73

rotating at 10 rpm generated 100 hp., the torque would be about 53,000 foot pounds. This may best be understood by thinking of a shaft held stationary (not allowed to rotate) at one end while a twisting force is applied by affixing a one foot lever to the other end, and attaching a 53,000 pound weight to the end of this lever, in much the same way as a long wrench is used to tighten a bolt. Now, 53,000 pounds is equivalent to roughly 18 automobiles or 312 people! The torque or twisting force on the shaft is enormous. Such huge forces obviously created serious design problems for the millers. This problem was largely solved by using the rim of the wheel as a gear and taking the power off at that point. In this way, the shaft only had to support the weight of the wheel and was free to rotate with no applied torque. Since at a given hp torque varies inversely with rpm, doubling the rpm reduces the torque by one half while transmitting the same hp. Transmitting power at high rpm always places less stress on a shaft. This is why an automobile engine can produce the same 100 hp as the above wheel and do it safely with a shaft less than 2 inches in diameter. This fact is also one of the reasons that by the latter 19th century designers were working to increase the speed of hydraulic turbines.

OVERSHOT AND BREAST WHEELS

Hunter[5] credits overshot wheels with efficiencies between 50 to 70 percent, with over 80 percent possible, and the efficiency of breast wheels between 40 and 60 percent. Both overshot and breast wheels were limited by the height of the fall. Overshot wheels could obviously not be any higher than the drop between the headrace and the tailrace. Breast wheels (also called pitchback wheels) on the other hand, might have a diameter substantially larger than the head, but they were still limited to moderately low heads. Because of this limitation the only way to increase the power of such wheels was to make them wider, thereby increasing the volume of water input to the wheel. A disadvantage common to both of these wheels, and to undershot types, is that the number of revolutions per minute of the wheel decreases in direct proportion to the diameter, a large wheel turning slower than a small wheel with the same flow of water. Another way to say this is that these wheels have a low specific speed. To overcome this shortcoming gearing was usually necessary to increase the rpm of the shaft going to the driven machinery. While this may not have been a great disadvantage in the types of applications that was customary for these wheels, gearing is both expensive and also wasteful of energy. The less gearing required, the greater the usable power.

Another serious disadvantage of overshot wheels versus breast wheels was the problem of a fall in the level of the head water. If the water in the headrace were to drop too low, as during times of scant rainfall, the level in the mill pond or stream might be below that of the top of the wheel and could not be used, placing

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5. Hunter, p. 87.

the mill out of operation. Breast wheels then, have an advantage over overshot wheels in times of both excessively high or low water. This is one of the reasons that the breast wheel was chosen for the Lowell mill site where large breast wheels were used in the early to middle 19th century to power the huge textile manufacturing complex.[6]

UNDERSHOT WHEELS

While the undershot wheel closely resembles, in appearance, the overshot wheel, in terms of their operation they have little in common. The undershot wheel is essentially an <u>impulse</u> wheel. It extracts energy from the moving stream as a result of the "impact" of the water on the paddles or blades that protrude from it's circumference. An analogy to this method of operation might be the movement of a tin can when knocked off of a fence post by a small stone. If one chooses a stone of the correct weight and throws it with the correct velocity, the stone will hit the can and immediately drop to the ground while the can, taking up the energy imparted to it by the stone, will go flying away at some velocity (depending on the weight of the can). The problem concerning the weight and velocity of the stone is the same as that of the amount and velocity of the stream impacting the undershot wheel. The efficiency of a perfect undershot wheel is limited to 50 percent. This is true because the energy comes from the impact of moving water transferring its energy (kinetic) to the blades of the wheel. If the wheel were to travel the same speed as the water, then there would be no impact, hence no energy transfer. So an undershot wheel must necessarily travel at some speed slower than the water, with a resulting loss of efficiency. A perfect undershot wheel is most efficient when the blades are traveling exactly half the speed of the water. At this speed it can extract only one half of the available energy.[7] Since, in reality, the volume and velocity of streams vary, and undershot wheels are not of perfect design, actual efficiencies are from 15 to 30 percent[8], well below that of even a poor overshot or breast wheel.

The Flutter wheel is an undershot wheel of a special type. It derives its name from the sound of the action of water against its blades. The flutter wheel is of small diameter and of proportionally greater length. It is in some respects the opposite design of a conventional undershot wheel which has a large diameter with relatively short blades. The small diameter of a flutter wheel allowed it to run at a relatively high rpm in cases where speed was required such as in a sawmill. This wheel had a higher specific speed than an ordinary undershot wheel, but was still of the same low efficiency.

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6. Patrick M. Malone, <u>Canals and Industry, Engineering in Lowell, 1821-1880</u>. p. 3.

7. Addison, p. 108

8. Hunter, p. 87.

Hunter describes the tubwheel as being common in both America and Europe as a small wheel used by individual families for the grinding of grain.[9] It was also used in saw mills as a means to move the log carriage back after a board had been cut. These wheels were often of only fractional horsepower, the largest seldom exceeding 4 or 5 horsepower. As Hunter notes, these wheels resembled a wagon wheel with blades replacing the spokes. These spokes were inclined to the axis with the whole resembling a modern cooling fan. Some tub wheels had a wooden rim resembling a tub connecting the tips of the blades, hence the name. They operated on the principle of impulse like the undershot wheel with water falling on and impacting the blades, and although horizontal like a turbine, they could not be operated submerged. Since they were of small diameter they tended to have a relatively high rpm. Their efficiency is as we might expect, relatively poor, being on the order of 10 or 15 percent. Their chief advantage was that of simplicity, their speed often allowing direct drive with no gearing required. It has been said that because they were common in France, and horizontal in nature, that they were the forerunner of the turbine.

THE TURBINE

The 19th century saw the metamorphosis of America from an agricultural society to the beginnings of an industrial society. The water power technology available in the early part of this period would not be adequate to support the growth of manufacturing that was to occur. More reliable prime movers were required. The loss of time and of production that were a result of the traditional waterwheel's inability to operate under a wide variety of adverse situations, such as extremes of high and low water and ice, limited the wheel's usefulness. As manufacturing facilities became larger, water shortages began to occur and efficiency of water use became increasingly important. More efficient wheels were needed, and designers began to look for new solutions. The hydraulic turbine was the result of these efforts. The process of development began in Europe, primarily France, during the first part of the century, but the major effort and the credit for the development of the modern mixed flow turbine must go to the United States. This technology was developed and perfected in the U.S. in the latter half of the century.

There exist essentially only three basic types of turbines that the term "modern" may be applied to. They are the Francis reaction turbine, the impulse turbine, and the propeller-reaction type. The term modern is used in the sense that it would be likely that one of these three would be the turbine of choice for a current day installation of any appreciable size. In light of this fact, we would not be too far

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9. Hunter, pp. 71-83.

of the track if we consider these three types as being the "natural or inevitable" solutions, developed slowly by a process of evolution, for three separate conditions or problems created by nature, that needed to be solved by man. In their simplest form these are:

1. High head with a relatively low flow.
2. Moderate head with moderate flow
3. Low head with high flow

The term "flow" is used here to mean the amount of water moving past a fixed point in a specific period of time. It is usually measured in cubic feet per second, and that number along with the velocity of this flow is what determines the type of turbine we choose. The first situation, high head, applies to situations where the head is in excess of 500 feet less than 5000 feet. Impulse turbines such as Pelton wheels serve this need. The third situation,low head with high flow, are served by axial flow propeller or Kaplan turbines. In reviewing the modern literature, it seems that the axial flow turbine with its high speed, simple but robust design, and the highest efficiency of any of the three would be at the pinnacle of evolution rendering the Francis turbine obsolete, but this doesn't seem to be the case. Since we are interested in the development of small waterpowers such as might be used to power small mills, we will confine our discussion to low to moderate heads and flows. The Francis turbine is often used under these conditions. With this in mind we can now take a brief look at the development of this turbine.

THE REACTION TURBINE

The primitive reaction wheel or Barker's Mill has been described above. In its simplest form it may best be exemplified by the common lawn sprinkler, an "S" shaped tube pivoted at its center with streams of water exhausted from its ends, the revolution of the "S" being a reaction to the force of the expelled water. More highly developed forms of this type were the Rumsey and Wing reaction wheels, the latter being similar in appearance and operation to those rotating ventilators commonly seen on the roofs of barns. While these reaction wheels would operate submerged, their efficiency was according to Hunter, usually only 30 to 40 percent[10]. One of the greatest contributions of the reaction wheel to later turbine design was probably the fact that these wheels did operate under water, and the problem of high tailwater during times of flood, was minimized.

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10. Hunter, p. 304.

Hunter[11] describes the change in construction materials from wood to iron necessary for the development of the turbine. Wood was difficult to shape into the complex forms necessary for efficient turbine design, and it had a tendency to change its shape over time. While previously not a problem with traditional waterwheels, because of the low relative velocity of water to the wheel, erosion by water borne sediments would be a serious problem if wood were to be used in the faster turning turbines. Sediments like sand would quickly erode the buckets or blades resulting in a serious loss of efficiency. Another important factor that must be considered is that as these wheels became more efficient and with higher specific speeds, in order to maintain the thin blade sections necessary for the efficient flow of water, wood simply did not have the strength required for structural integrity. The "energy density" of the wheel environment was too high for wood as a structural material. It was therefore necessary to use materials with higher tensile and compressive strengths such as iron, steel, bronze and finally in this century stainless steel.

The necessary breakthrough in reaction wheels did not happen in this country until 1827, and then only as a result of an accident. Two men, Zebulon and Austin Parker[12] who had recently constructed a Grist mill powered by a reaction wheel of their design, had a plank jam in the forebay. Apparently this plank was lodged in place in such a way that it gave a "whirling motion" to the water entering the wheel. As a result, the speed and power output of the wheel increased dramatically. The outcome of this accident was the discovery of the effects of a "helical sluice", a casing that imparts a whirling spiral motion to the water before it enters the wheel. The brothers patented this device in 1829 and sold licensing agreements to those interested in using this wheel. The wheel itself was of the outward flow type, with water entering at the center and exiting at the perimeter.

Austin Parker in 1833 also developed the draft tube which was simply a tube that elevated the turbine above the tailwater. Such a device allowed easy access to the wheel for maintenance and repair. They found that as long as the tube was watertight and airtight, the efficiency of the wheel was not affected. The efficiency of the Parker wheels was between 60 and 70 percent.[13]

Meanwhile in France Benoit Fourneyron, in 1827, built a wheel that he called a "turbine". This was a horizontal outward flow wheel with a series of fixed spiral guide vanes that diverted the water entering the wheel into a circular motion. The flow of the water entering the turbine was first down then, turning a right angle, outward. The efficiency of the Fourneyron turbine was very high for the times,

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[11]. Ibid., p. 302

[12]. Ibid., p. 310

[13]. Ibid., p. 312.

ranging from 70 to 78 percent.[14] The reason for such high efficiency lies, as in the Parker turbine, in the "whirl" of the water and, just as important, in the angle at which the water strikes the advancing blades.

The Fourneyron and other European developments serve to illustrate the difference between Europe and America in their creative techniques. The literature, in general, makes the case that the Europeans, especially the French, relied primarily upon scientific analysis to solve developmental problems, while the Americans tended to use a more empirical approach. Layton, in discussing the work of the Parker brothers, claims that they were unaware of the theoretical work done by the French, and that the Parkers also lacked the "mathematical training" required for this type of analysis.[15]

This is a very interesting theory since it follows that such approaches must come not only from environmental influences, but also from ideological influences. The frontier spirit of the rugged individualists who often found themselves in situations where the only available help had to come from themselves must have had a profound effect on the individual's approach to solving problems. Since "experts" were likely rare, individuals had to have been proficient in many different areas. While perhaps not the most efficient approach, the evidence of the immense technological progress that took place during the 19th century, is certainly a testimony to the validity of not only the empirical approach, but to the ideology that supported it.

It must not be assumed however that a strict empirical approach is always desirable or in some cases even possible. The secret to successful research must be to learn as much as possible about the subject first, and then proceed from this established level; each stage creating a new plateau on which succeeding improvements and discoveries may be built. We must keep in mind that at the beginning of the 19th century relatively little scientific or empirical information regarding turbines had been either proven or widely accepted as fact. The laws of theoretical fluid dynamics do not always "flow" in the same direction as simple logic might suppose. It is possible that these exceedingly pragmatic men with relatively little formal education in the laws of fluid dynamics would not be ready to abandon those creative instincts, which in the past had served them so well, and take up theories which often do not parallel such instinct. Or, as Layton implied, these men may simply have been unaware of the current level of technology.

In reading The Lowell Hydraulic Experiments[16], one quickly comes to realize that while not filled with mathematical equations, Francis' graphical approach appears to be scientific. It is certainly analytical, as he meticulously plots the flow

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14. Ibid., p. 320.

15. Layton, p. 69.

16. James B. Francis, The Lowell Hydraulic Experiments.

of water through a turbine. Its great disadvantage is that it is specific and lacks wide general applicability, as equations describing the flow would be. But as Layton points out, Francis' reasons for using his method of experimental research were because the equations that had been developed by the mathematicians of the time were of a too general nature and of little practical use to an engineer designing a turbine.[17] The history of invention, at least in earlier times, was apparently not always preceded by a mathematical prediction of results. Inventions or discoveries were often developed by trial and error, the results often depending to a large extent on the craftsmanship and attention to detail of the inventor, with the equations being written at a later date (oftentimes by others) in an attempt to account for the actual result. Only when a sufficient inventory of experimentally reinforced theory existed could a greater reliance be placed on theory to predict results. Such an inventory was definitely lacking during this early period of water power development.

In 1838 Samuel Howd patented the inward flow wheel. Taking a design approach opposite to that of Fourneyron, Howd designed his wheel so that the water entered the wheel at the perimeter, then turned 90 degrees downward, and exited at the center. Before the water entered the wheel, it passed through guide vanes arranged around the perimeter which imparted a circular motion to the water. The wheel was not built with a great deal of precision, and was intended to appeal to a wide market.[18] The importance of the Howd wheel lies in the fact that its design was the forerunner of what was later called the Francis turbine or the American mixed flow turbine.

Uriah A. Boyden and James B. Francis sought to improve the Fourneyron turbine during the late 1840s, and built two large wheels of at least 700 hp each for the Merrimack Manufacturing Co. in Lowell. Boyden's work is important because, although these turbines were basically Fourneyron in design, they contained several improvements and were of large capacity for the time. Boyden's improvements also allowed the Boyden-Fourneyron turbines to have efficiencies of 80 percent. The Lowell Hydraulic Experiments[19] contained the test results made by Francis on Boyden-Fourneyron turbines. These turbines still resembled the outward flow Fourneyron in both appearance and operation. Although the Fourneyron turbines as modified by Boyden achieved high efficiencies, they were not without disadvantages. Since their performance depended to a high degree upon precision and care in manufacture, they were expensive and they tended to become less efficient as their surfaces became worn with age and use.

Another turbine that should be mentioned is the Jonval. In the Jonval the water passed through the turbine without turning as it did in the Boyden-Fourneyron. The turbine resembled a multi-bladed fan set in a tube with

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17. Layton, p. 77.

18. Hunter, p. 317.

19. Francis, pp. 1-43.

water entering one end and exiting the other. A ring of stationary blades was set just in front of the wheel to give the water a whirling motion prior to entering the wheel. In this respect it was similar to the Fourneyron. Since the water passed straight through and made no change in direction this method of operation is termed "axial flow". These wheels were popular in Europe, and were manufactured here beginning in 1849. Their efficiency ranged from 60 to 75 percent.[20] Between 1847 and 1851 James B. Francis designed and constructed three versions of the Howd center vent wheel. Although manufactured with a great deal of care and precision, their actual performance was disappointing. These three designs seem to be the limit of Francis' actual experience in the manufacture of turbines. Hunter argues that while the direct contribution of Francis to the development of the inward flow or center vent turbine was limited, his greatest achievement lies in his work on establishing the "direct-drive waterpower base for a large industrial city"[21] In spite of this, his name is still used a synonym for the modern American mixed flow turbine, the Francis turbine. Since the modern Francis turbine is based upon the principles of the Howe-Francis design, Francis' actual developmental work, although perhaps not an immediate success, did in the long run and possibly as a result of Francis' influence, provide the base from which the modern turbine was to be built.

Safford and Hamilton describe the period following 1860 as the "cut and try" period.[22] During this period, except for the larger installations, much of the work of Fourneyron, Boyd, Howd, and Francis was ignored and a large majority of the turbines manufactured were of poor design. The manufacture of water wheels was a growth industry and many profit hungry manufacturers began selling wheels of low efficiency. This quote from Hunter may best sum up the period: "every free-born American citizen considers it among his inalienable rights and privileges to invent a patent medicine and a water wheel, and he usually does both with usual ignorance of and indifference to the laws of both hygiene and hydraulics."

But while the majority of wheels built during this period were of dubious quality and design, progress was being made by a few people dedicated to the improvement of the turbine. One of these men was Asa Methajer Swain. Swain based his design upon the basic Howd-Francis inward flow turbine, but in order to increase its capacity to produce power, the blades or buckets were extended downward and curved in such a way that they would discharge the water downward. He built a model in 1858 then a full size wheel in 1859. The limited capacity of the earlier inward flow wheels was due in part to their limited ability to discharge the water. Exhausting the water toward the center tended to cause a "pile up". Swain sought to alleviate this problem by directing the flow downward.

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20. Hunter, p. 326.

21. Ibid., p. 339.

22. Arthur T. Safford and Edward Pierce Hamilton, The American Mixed Flow Turbine and its Setting. p. 1255.

In order to place these and future improvements in the proper perspective we must look at them in terms of water flow. We saw earlier that the maximum amount of energy available to the wheel was dependent upon only two circumstances, the amount of water available in a given time namely the flow, and the velocity of this flow. We also recall Carnot's principle that the highest efficiency could only be obtained when the water exited the wheel with a velocity equal to zero. Unfortunately, Carnots principle leaves us at an impasse, because if the turbine is designed to stop the water then no new water can enter and no power can be produced. This situation is analogous to our column of marching soldiers encountering a barricade enroute. A pile up would be inevitable. This problem was solved by Leonhard Euler a Swiss mathematician who lived from 1707 to 1783. His theory says that "the power of a turbine in steady motion equals the angular velocity multiplied by the change in angular momentum experienced by the mass of water flowing in a unit time in its passage through the turbine."[23] Euler says nothing about the water having to have a zero velocity at the exit of the turbine. As it turns out, this theory is much easier to apply.

Euler said that the power of a turbine is proportional to the "change in angular momentum" of the water as it flows through the turbine. In other words you can extract energy from the water simply by changing its direction. Now, this concept is extremely important as it is the basis for the design of efficient turbines. The most basic function of a turbine then is to change the direction of the water flowing through it. The second item mentioned by Euler is that of the mass of water flowing in a given time. This is our term "flow" showing up again. Euler is saying that the power that a turbine extracts from the water is proportional to the amount of water flowing through the turbine in a given time, the flow. So the second function of a turbine must be to not impede the flow of water, because any impediment will reduce the flow, thereby reducing the power. The design must be such that for a given flow (near maximum power) the turbine must present the least possible resistance to the water passing through. This theory is quite different from that of a literal interpretation of Carnot's theory, unless we interpret Carnot's theory of zero velocity to mean zero angular velocity.

According to Euler, the water as it approaches the turbine wheel must have an angular velocity. In other words if, for instance, it approaches the wheel in a round tube, such as a large pipe, it must be whirling around in that tube. The motion of the water if seen as though through a glass tube by an observer standing on the outside, must appear similar to a wood screw working its way into a piece of wood; that is turning while advancing. In practice, this is most easily accomplished by placing a series of guide vanes attached to the walls of the tube just ahead of the wheel. If these guides are set at some angle relative to the flow of water, they will impart a spiral motion to the water as it approaches the wheel.

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[23]. Theodore Baumeister ed. <u>Marks' standard Mechanical Engineers</u>, p. 9-188.

With these two criteria in mind, that is the necessity of both angular momentum and maximum rate of flow, the events leading up to the development of the mixed flow turbine begin to make sense. Fourneyron in 1827 was obviously well aware of these rules when he designed his turbine. It is also interesting that since Fourneyron apparently coined the term "turbine", and since one definition of turbine is "whirl", one wonders if the name was intended to describe the machine or to describe the principle. In any case, Fourneyron's fixed spiral gave the water the necessary "whirl" or angular momentum just prior to the water's entering the wheel. This energy of rotation was then expended upon the wheel as the water passed through, the wheel taking up the energy and turning and the water exiting with little whirl or energy remaining. The water still had some velocity however.

The accident of the Parker brothers had much the same effect, the plank lodged in the forebay providing the necessary angular acceleration of the water. Whether the Parker brothers really understood what was happening remains a question. Their design of the helical sluice imitated the effect of the plank but with greater efficiency. In principle this was not much different than the effect achieved by Fourneyron. The Howd turbine did much the same thing, the difference being that the water flowed inward instead of outward as in the Fourneyron. The Howd wheel used a series of fixed guide vanes around the perimeter to turn the water. And the Francis, Boyden and Jonval all worked essentially the same way. In the case of the Jonval axial flow turbine the water flowed straight through, but was still given a whirl by the stationary guide vanes that preceded the wheel.

To what extent this theory of angular momentum was understood by these men is not clear. A great deal of Francis' Lowell Hydraulic Experiments is devoted to charting and understanding the flow of water through the turbine. Although his method is primarily graphic, it goes a long way in illustrating the relationship between the real and relative motions of water in relation to the blades, and to a stationary observer. A part of this method involves ascertaining the volumetric relationships as they change as water proceeds from the perimeter to the inner radius of the wheel (in the case of a center vent wheel). It is clear that Francis' work at that point was to maintain (as much as possible) "laminar flow" in the water as it passed through the passages in the turbine. Remember that turbulent flow is inefficient and causes a loss of energy. The Tremont turbine was a Howd-Fourneyron and of outward flow design. Because the perimeter of a circle becomes larger with increasing radius, the area of the water passages and consequently the area of the water passing through must become greater as the water moves from the inside to the outside of the wheel. We saw from our explanation of the Bernoulli theorem that as the stream widens, the streamlines diverge, pressure increases, and the velocity slows. If the streamlines diverge too quickly, the flow is likely to become turbulent with a resulting loss of efficiency. This problem is inherent in the design of an outward flow turbine. In the inward flow design however, the opposite happens. As the flow moves from the outside to the inside, the passages narrow, the streamlines converge, pressure decreases, and the velocity increases. In this case turbulence is less likely. It was partly for these reasons that Francis chose the inward flow design for his prototype.

In regard to the blades themselves, Addison[24] gives formulas for calculating the proper blade angles. The angle of the outer portion of the blade must be such that the blade is exactly parallel to the apparent velocity of the water at this point, otherwise shock and a reduction of efficiency will result. The blade angle at the inner part of the blade must be such that the water leaves the blade without whirl, thus fulfilling Euler's condition of zero angular momentum. The importance of these two conditions relating to the angles of the blades must not be overlooked. This angular relationship is probably the most important factor controlling turbine efficiency that is related to the shape of the blades. The dramatic drops in efficiency of most of these early turbines when running at partial gate is in part related to the change in the angle of the moving water to that of the blades. When running at partial gate openings the change in water angular velocity relative to the angle of the blades, which were fixed, changed and efficiency dropped. There also were other causes such as turbulence caused by poorly designed gate mechanisms etc., but these would probably be of a more obvious nature than that of blade angles, especially if these relationships were not clearly understood.

The ability of a wheel or turbine to produce power is termed its "capacity". This may interpreted as its capacity to produce power or the wheels capacity to process a large volume of water. It was capacity in this latter sense that caused Swain to modify the basic Howd-Francis turbine. As discussed earlier, in the basic Howd-Francis wheel the water entered at the perimeter and exhausted radially inward. In order for the water, now devoid of whirl or angular momentum to move out of the way and make room for new water coming through. The water had to make a 90 degree turn downward and eventually find its way out via the tailrace. This unsupervised 90 degree turn downward must have been a logical place for turbulence to develop with a resulting loss of efficiency. At best it limited the capacity of the wheel. Swain's attempt to resolve this problem consisted of increasing the length of the blades in a downward direction thereby guiding the water in a downward direction. So in this turbine the path of water was both inward and downward.

By providing greater guidance for the water, Swain increased the ability of the wheel to move water through with a minimum of resistance thereby increasing its efficiency. This turbine is considered by some to be the first of the generation of mixed flow turbines, meaning that the flow was inward and downward. The next step in the development of the Mixed flow turbine was known as the Hercules turbine developed in 1876 by John B. McCormick. In this turbine we see a design similar to Swain but the wheel has become smaller in diameter and much taller, shaped more like a drinking glass than a cake pan. In the Hercules we find a relatively small wheel that is able to produce substantially more power than a Swain of the same diameter. By increasing the height of the wheel the ability of the turbine to process large flow rates is increased. Since the flow is increased, the

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[24]. Addison, p. 199.

power absorbed from the water must also be increased. To this end, the Hercules was designed to move water inward, downward, and slightly outward. The gain in capacity is best exemplified by a quote from Hunter: "From the Howd-Francis inward-flow wheel of 1847 to the Hercules wheel of 1876, capacity increased sevenfold for the same diameter of wheel and construction costs were reduced in about the same proportion."[25]

Another benefit of reducing the diameter of the wheel was the gain in speed or rpm of the turbine. The specific speed of the first Francis was 19 while that of the Hercules was 48. Specific speeds of modern mixed flow turbines run up to 100.[26] Reduction of the diameter alone, however is not sufficient to create such dramatic increases in speed. In order to increase the speed and at the same time increase the flow rate, the number of blades were reduced. Fewer blades turning at high speed offered less resistance to the flow of water while still absorbing great energy in much the same way as a relatively small two bladed airplane propeller is able to absorb hundreds of horsepower from an engine, transferring that energy to the movement of air.

As electric power was being developed, water power was to become increasingly important for electrical generation. This was to place a demand on hydraulic engineers to develop very large turbines. Since electrical generators become more efficient and less expensive when running at relatively high speeds, emphasis was going to be placed on developing turbines with high specific speeds. But that is another topic.

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Westport, Ma.

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25. Hunter, p. 361.

26. Baumeister, p. 9-186.

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