A NEW ANCIENT WATER MILL: REMEMBERING FORMER TECHNIQUES

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Abstract: Waterwheels are one of the most ancient and most common machines. They appeared at the end of the second century B.C. and remained the most important source of mechanical energy beside that of humans and animals till the Industrial Revolution, driving mills, saws, pumps, bellows or hammers. Through a description of their design found in old texts, it has been possible to trace the conception of technology, beginning with the craft industry and ending with mathematical physics. In order to revive this extremely important technique, a water mill was constructed near Sion, using historical methods and workmanship. It includes a wooden waterwheel as well as all gears necessary to allow two millstones to rotate at a specified speed. Moreover, measurements were made on a scale model of the waterwheel with its ancient geometry, which has shown an efficiency of nearly 80 percent.

Keywords: waterwheels, energy, ancient techniques

1. INTRODUCTION

During the twentieth century, many waterwheels ceased their operation and were replaced by more powerful machines. However, for more than 2000 years they were employed as one of the most important sources of energy throughout Europe and Asia where water was abundant enough to power them. The development of water-related technologies was especially important in the difficult terrain of mountainous regions. Not only did people's requirements for potable and irrigation water need to be met, their lives, houses and cultures had to be protected from the damage water could cause when it was overabundant. Further water also had to be channeled and harnessed to power the mills for grinding cereals to provide food.

To understand the technology that developed to meet these complex and at times contradictory needs, we shall first look briefly at the history of waterwheels and see how they were treated in ancient miller's manuals.

E. Wiegandt (ed.), Mountains: Sources of Water, Sources of Knowledge, 211–220.

We then describe the mechanical parts of the new water mill in Nendaz near Sion, which was constructed using the historical methods and workmanship available in the past, and we finally present some results of efficiency measurements made on a model wheel.

2. A BRIEF HISTORY OF THE WATERWHEELS

According to current knowledge (see, e.g., Brentjes 1978; Capocaccia 1973; Daumas 1962; Singer 1954), waterwheels appeared independently in China and in the Mediterranean area at the end of the second century B.C. It seems that the horizontal wheel, also called Greek wheel because the first evidence of it was found in Athens, was a contemporary of the vertical or Roman wheel, of which examples could be found throughout the entire Roman Empire (Figure 1). Although known, these machines were, however, not in common use, either in Europe or in China until much later. This may have been due to the availability of large amounts of manpower, in the form of either handworkers or slaves, and to the will of the ruling classes to preserve employment and livelihood for their population despite the economic advantages that a more powerful technique might have brought. The contempt of technique and arts (both designated by the same word τεχνη in Greek) held by Greek and Roman philosophers and politicians could also have inhibited the broader development of waterwheels, although the craft industry was highly considered in these civilizations. However, the most probable cause for the failure to develop the use of these machines was the simple lack of the technical knowledge and skills amongst the population of the period to build, operate, and maintain them.

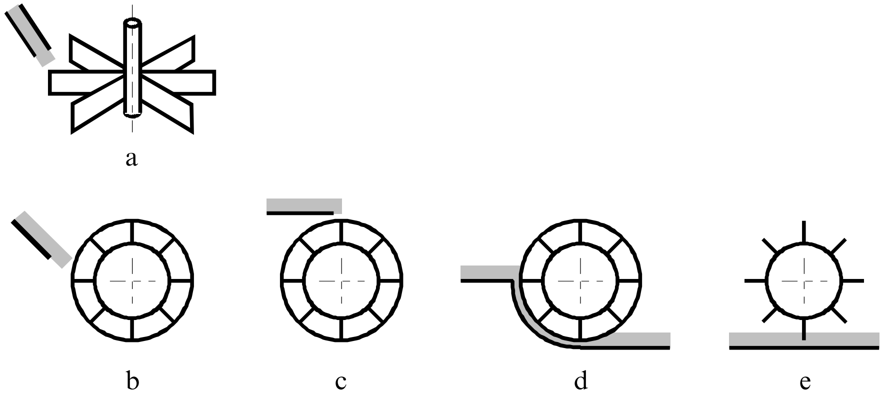

Figure 1: Main Types of Waterwheels. Top: a: Horizontal Wheel. Bottom: (Vertical Wheels). b: Impact Wheel; c: Overshot Wheel; d: Breast Wheel; e: Undershot Wheel.

A first industrial revolution occurred in Europe during the eleventh and twelfth centuries through the impetus of the Cistercian monks. In the context of a political environment in which wars were relatively infrequent, there was a significant expansion of the population, development of commercial trade, the creation of new markets, and an extension of agriculture requiring the clearing of large wooded areas to make arable land. At the same time, new technical advances were introduced such as the collar harness or shoes for horses, the rudder for ships, and the wind mill with a horizontal axis. The use of hydraulic wheels spread considerably, greatly increasing the amount of energy at the disposal of the population. As a consequence, the quantities of flour, oil and other goods produced by these machines increased steadily, leading to the development of the first real industries.

However, the Black Death that occurred in Europe during the fourteenth century reduced the population by almost one third, bringing with it a fundamental change in both society and its supporting structures. With fewer people there were fewer demands on the use of the soil for basic agricultural food crops, and more luxurious cultures began to develop. In the Alps, cow herding gradually replaced much of the rye, wheat, barley and oats fields, leading to new needs for water, now required to irrigate the extensive meadows. In Valais, water canals (called *bisses* in French and *Suonen* in German) were built in many places to meet this demand (see Giovanola 1999; Reynard 2002). These water courses, just like the water mills, were installed and run as common goods by whole villages, a practice which itself considerably influenced the development of social customs and policies in these communities. In mountainous regions, where the supply of water for drinking, irrigation, and for turning mills was scarce, the collective management of this precious resource required an organization with a high degree of order, solidarity and interdependence, where a joint sense of shared responsibility could lead to a coordination of labor (on this subject, see the contribution by E. Wiegandt to this book).

Techniques evolved slowly bu interactions between merchants, craftsmen, or soldiers were able to efficiently spread advances in knowledge over nearly the entire world (see the article of D. Crook in this volume and Pelet 1988, 1991, 1998), including the less accessible valleys in the mountains even though the transportation and communication systems were not as quick as those of today. As a result, each village became the owner of one water mill with a power of roughly 1 kW, which can be compared to the power represented by the equipment of a modern kitchen or of an automobile motor. This situation remained largely unchanged until the Industrial Revolution of the nineteenth century, when steam engines, or later combustion engines, as well as hydraulic turbines became new power sources. In remote regions such as in the Alps, however, some water mills continued to run into the 1980s; P.-L. Pelet reports for example (Pelet 1988) that in 1956 the Swiss Federal Wheat and Grain Administration granted a credit to renovate a water mill in Taesch near Zermatt with the aim of guaranteeing the flour supply in case of an international crisis.

Thus, for about twenty centuries waterwheels were essential as the most common prime movers for all sorts of machines for practically the entire northern hemisphere: they primarily drove mills, but also pumps, saws, hammers, bellows, etc. Their basic design remained largely unchanged although undoubtedly many parts were improved or also introduced, such as the crankshaft that appeared during the late Middle Ages, or the rounding of vanes that became possible when iron replaced wood during the Industrial Revolution.

3. WHAT OLD TREATISES SAY ABOUT WATER MILLS

As very common machines present in every day life, waterwheels appeared in the arts: poems, songs, or paintings. They were depicted in so-called "Theatres of machines", although with more of an artistic rather than a technical aim. They were also described in numerous miller's manuals and, later, in books about mechanical engineering. Thanks to these works, the development of techniques through time can be followed quite accurately. Building a mill, and especially a waterwheel, was long considered a craft rather than a technology as we understand it today. The methods used were essentially traditional, based on experience and not on theoretical knowledge, with the rules for their design and construction passed along orally and kept secret among the persons belonging to the concerned guilds.

Therefore, in our eyes, the descriptions of waterwheels appearing in historical texts suffered both in their quality as well as their completeness. As Sturm puts it in the preamble to his work (Sturm 1815) published at the beginning of the eighteenth century (translation from the German), "the views in such books are mostly perspective and not drawn according to geometric rules, rather sketched only by eyesight and freehand, so that no dimension or subdivision can be gained from them. The second fault is that few feasible schemes are presented, and many have been put together with bits and pieces, and are not suitable to practical use. Thirdly, when good inventions are present, the authors have intentionally distorted them, as if they had intended to show the connoisseurs that they knew the secrets but have concealed them with application so that those who ignore them cannot imitate them. Fourth, they have given no distinct explanation, nor knack, nor reason, nor calculation, which yet matters." Illustrations were a problem indeed, being difficult to draw and difficult to print. It is precisely for this reason that Sturm's work, with its fifty engraved plates, enjoyed such a great success, with no fewer than six editions appearing between 1718 and 1819. He did his best to show in each case a horizontal view and an elevation, and to provide comments on his drawings (Figure 2). Nevertheless, several of the constructions that he presents are inventions of his own and not proven achievements which can be recommended for practical purposes.

The text part of the Encyclopedia by Diderot and d'Alembert, published between 1751 and 1775, tends to be more precise, containing figures under the article entitled "Mills" describing the dimensions of the millstones, the number of teeth of the gears and the rotational velocities, but the wheel itself does not seem to be worthy of a detailed description. In the illustration part (Diderot 1762), several undershot waterwheels are shown, in all cases as part of a complete factory: corn-mill, sawmill, tannery, smithy, etc. (Figure 2).

In the middle of the eighteenth century, a decisive step forward was taken after mathematics, especially differential and integral calculus had made important advances. As soon as the theoretical works of Johann and Daniel Bernoulli and of Leonhard Euler on hydraulics and hydraulic machines appeared, the design of waterwheels began to be influenced by science, opening the way to the introduction of hydraulic turbines that a number of factories started to manufacture in about 1830. As soon as the physical laws and mathematical tools became better understood, they were used to describe and predict how machines work, as can be seen for example in the treatise of Bélidor published from 1737 to 1753 (Bélidor 1737). More and more complete technical descriptions were available in what can be considered as real textbooks on the mechanical design of mills, such as in the work of Benoît (Benoît 1836) in 1836 which is already devoted to industrial machinery. Until about 1950, the subject of waterwheels also played an important role in lectures on mechanical engineering.

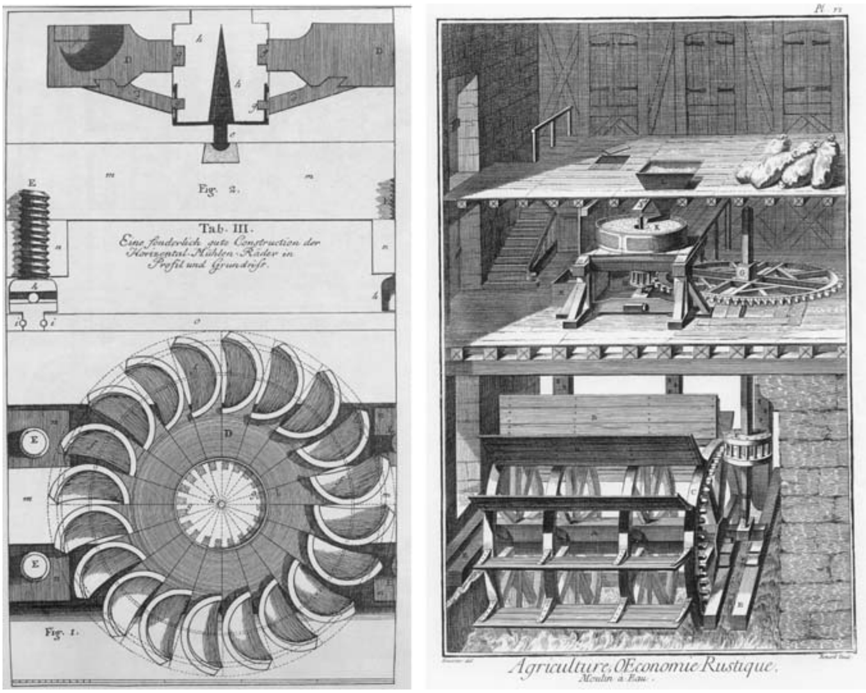

Figure 2: Waterwheels in Sturm's Manual (Sturm 1815, left) and in the Encyclopedia (Diderot 1762, right).

4. THE NEW MILL OF LE TSÂBLO AT NENDAZ

As we already said, a number of water mills continued to work as recently as 1950, particularly in mountainous regions where industrialization developed late. This explains why Valais, for example, still has a great number of these machines, some abandoned and in poor condition, others renovated and running on certain days for demonstration purposes. In the village of Nendaz above Sion, the last mill was demolished in 1984 to make room for a road; only some of the millstones and parts of wooden gear wheels were preserved. In the mid 1990s, the decision was made to build a new mill on the same stream as the old one but in another location. In order for the current generation of locals and visitors to see what the past looked like, the new construction adopted the ancient techniques formerly in use in the region, Although carpenters are nowadays still capable of copying or repairing existing ancient wheels or gears, the knowledge of determining their dimensions and their geometry has been lost. The Haute Ecole Valaisanne was therefore asked to design an overshot waterwheel as well as the gearing necessary to drive two pairs of millstones. Because the information given in the old treatises just described is so imprecise, additional data had to be collected from still existing installations.

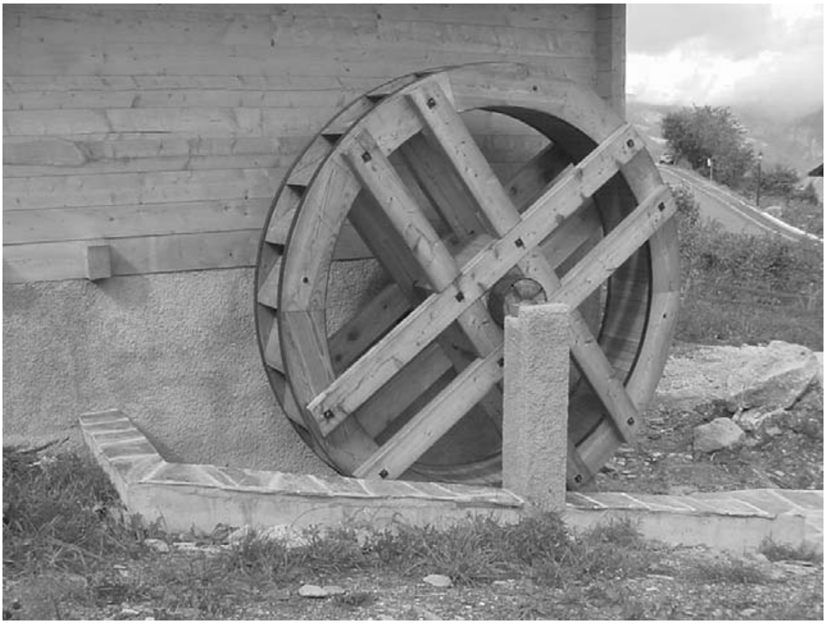

Figure 3: Overshot Waterwheel of Le Tsâblo (at that time still without water channel).

As is typical for a mountainous area, while steep slopes are available, the quantity of water is small. Under these circumstances, the outer diameter of the waterwheel was fixed at 3 m (Figure 3), to avoid a construction that would be too large, and, in addition, water is diverted from a canal to achieve sufficient discharge to let the mill run during demonstrations. On the basis of a rough estimate of the friction between two stones and by comparisons with other mills, the power required for driving two mills was calculated to be about 1 kW (which is about 1/4 of what Benoît indicated in 1836 for industrial machines). Assuming a conservative value of 70 percent for the efficiency, this led to a flow rate of 44 l/s. Following Müller's advice (Müller 1939), the circumferential velocity of the waterwheel was chosen as 1.3 m/s, which implied a rotational speed of 8.3 rpm. The number and the geometry of the buckets were also designed according to the recommendations of this author, which are precise on this point. As for the millstones, their rotational speed was fixed at 60 rpm, coinciding with what was usual in the region and also to the value given in Diderot's Encyclopedia (Benoît's millstones rotate about 1.5 times quicker).

Figure 4: Gear Transmission of Le Tsâblo. Left: Gear on the First Shaft, which carries the Waterwheel. Right: Second Horizontal Shaft with One of the Two Wheels with Lateral Teeth.

To connect the waterwheel and the millstones, a gear ratio of about 7 was necessary. In order to use gear wheels of the same dimensions as the preserved ones, two stages were planned: a first horizontal shaft carries the waterwheel as well as a big gear wheel, and on a second horizontal shaft are mounted a pinion and two wheels with lateral teeth which drive the lantern pinions of the two vertical shafts carrying the rotating millstones (Figure 4). These lantern pinions have only one disk with inserted cylindrical teeth and they can glide on their shafts, thus forming clutches that allow one millstone or the other to be stopped. All parts, except the shafts carrying the rotating stones, are made of wood (larch for the wheel; beech for the teeth) and are calculated to be able to bear the maximal possible loads that can occur when the mechanism is jammed and the wheel is full with water.

5. MODEL TESTING

In order to confirm the values of the efficiency of overshot waterwheels such as those described in Benoît or Müller for instance, tests were carried out on a model at a scale of 1:4.16, as is commonly done for hydraulic turbines. A test rig was built that allowed the measurement, on the one hand, of the hydraulic power at the disposal of the waterwheel, i.e., the flow rate and the net head, and, on the other hand, of the delivered mechanical power, i.e., the torque and the rotational speed. During these measurements, due attention was paid to the similarity laws, using dimensionless coefficients defined in a similar way as for Pelton turbines (more details can be found in Dubas 2005).

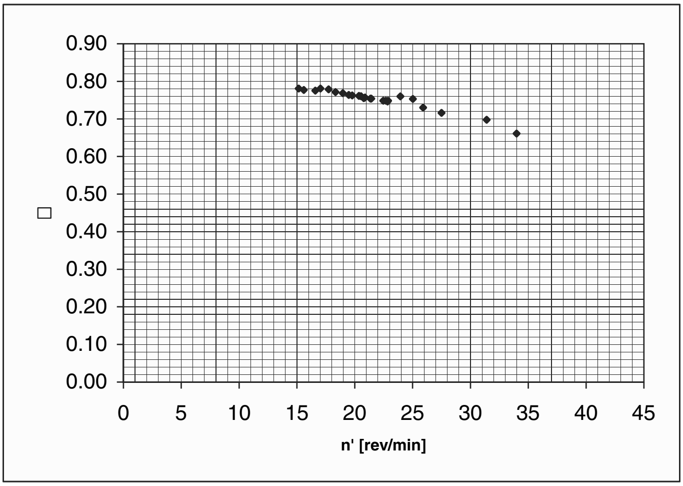

Figure 5. Efficiency of the Model Waterwheel in Function of the Rotational Speed. Channel Position and Flow Rate (1.2 l/s) Are Kept Constant.

These tests delivered the whole hillchart diagram of the efficiency. The top of the hill has its summit at 79 percent and is very flat, which means that the efficiency diminishes only slightly when parameters such as the flow, the rotational speed or the slope of the water channel are varied (see the section of the hillchart shown in Figure 5 with dimensional quantities). Moreover, when the wheel rotates more slowly, the buckets fill more, so that the torque increases. Conversely, when the wheel accelerates, less water enters the buckets and the torque decreases. This type of motor is thus particularly well suited to driving machines with varying loads, for instance saws. It was noted that energy was lost if the buckets contain too much water, in that water is poured off from the buckets before the lowest point of the wheel. This, along with friction problems leading to a possible locking of the wheel, imposes a lower limit on the rotational speed. Conversely, a too high wheel velocity is not recommended because water is ejected by centrifugal force. As this is the case for Pelton turbines, it can be assumed that the efficiency and the behavior of the model is very precisely the same as that of the prototype.

6. CONCLUSION

Waterwheels have been serving mankind for more than 2,000 years, supplementing and replacing the work of men and animals. Although different machines based on other physical principles and that can generate much more power have mostly replaced them since the nineteenth century (see the contributions of F. Romério and E. Wuilloud to this book), they remain very efficient prime movers in their power range, providing significant advantages in ecologic and economic costs, decentralization and independence (see also the similar conclusions in Müller 2004). Furthermore, the bearings, the gears or the millstones are nowadays designed in a completely different way than in past centuries; but the efficiency of waterwheels is such that their geometry can remain unchanged, except that thin steel plates usually replace wood and allow curved blades.