The Francis Turbine: Analysis of Its Evolution

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***Abstract*-This article analyses the evolution of the Francis Turbine within the context of the metal product manufacturing industry. It examines the evolving design of the turbines and technological change within the industry. It is argued that the production of artefacts and equipment as machinery can only be understood according to the concept of technological change both in the equipment itself and in the related industry. These technological changes refer not only to the initial design of the turbine itself, but also to the production processes necessary to its improvement. This article presents a series of data from the main producers of turbines from the 1920s to the mid-1990s, and the sites at which they were installed. The technical resume of these turbines is captured by means of specific speed following other studies before presenting analysis, and results are in good agreement with previous studies. However, this article also explains the evolution of the turbine according to the industry sector.**

Keywords- Evolution; Hydraulic Turbines; Specific Speed; Metal Product Manufacturing Industry; Dam Hydrological Resources Exploitation

I. INTRODUCTION

Technological changes in the turbine and the metal product manufacturing industry (MPMI) are explored by analysis of the evolution of the Francis Turbine. This research builds on earlier work focused on the evolution of the hydraulic turbine [1, 2, 3]. Previous studies have focused on the evolution of the turbine from the perspective of specific speed (N_s), as this was a key factor in the understanding of turbine performance. Other analyses have focused on the MPMI [4, 5, 6, 7] by examination of how N_s has co-evolved with the turbine industry. In order to understand the structure of technological changes in products, such as hydraulic machines, it must be determined whether such a change occurred as a result of the design process or whether the evolution of turbines as induced by changes in the MPMI itself.

This analysis proposes that the source of technical change which resulted in the employment of higher specific speeds within the last two decades of the 20th century is derived from scientific, technological, or managerial grounds. Differences between the technologies of the 1940-60s and the 1970-90s are respectively examined. Whilst changes in the MPMI during the 1970-90s were rather radical and dynamic, the former period took nearly 20 years to manifest technological changes in a new turbine. Particularly important is possibility to relate technical change to specific speed. This article examines the role of the MPMI in the development of improved turbines as well as results induced by large-scale construction dam infrastructure projects. It is proposed that a new technology does not necessarily make an old one obsolete, as it takes time to master, and implementation is not immediate.

One way to comprehend the evolution of the Francis Turbine is to analyse the processes involved during the transformation of the material-input (given that it is all composed of different kinds of steel), to aid in understanding the complexity of technical change in an industry associated with a technology, the industry sector and the field itself. This article concentrates on the evolution of the turbine, with special attention given to specific research already mentioned above, which formed part of the global turbine industry and took place in companies with international operations. What follows is a review of technical changes in the turbine industry.

There are various perspectives regarding the way in which technological change is conceived, and how it is understood and transformed to complement production. First, we address the conception of technical change, particularly the role of routines, diversity, and the research program as the basis for generating a new approach which could be used to modify a previous product or process.[1]

Second, the extent to which the process modifies the original idea is separated from the process required by production. The modification of a product or a process cannot be an exclusive result of a technological change. In other words, product modification does not necessary imply technological change.

In addition, the design itself can be separated from both production and transport processes. A new development corresponds to both design and production (considered conjoined processes), but it can be either a joint or separate operation. If it is a joint operation, the design is typically coupled with production, i.e. it takes into account the production capabilities. In the case of separate operations, designs do not necessarily complement production capabilities. New changes in production

[1]Indeed, technological change by itself has not a specific determination. It can be referred to the modification of the original idea which in turn can correspond to some part of the equipment, the complete equipment, and material. Also it can be referred to the process. However, it always referred to some basic comparison which in turn can have degrees of complexity. From the point of view of technology (and time), quality would suggest that one technology is superior to another.

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considered to be innovations are extensions of the common innovative patterns. New designs can evolve from many sources, and can emerge from various industries, technological groups or institutions.[2] There is third way in which a design might emerge, through a connection between industry production, the technological group or an institution.

From the perspective of those who organise production, the role of firms as institutions is crucial. A firm could accomplish the overall work, that is the innovation during the design as well as adaptation in the production (lane), that is necessary for reproduction. However, very few institutions can accomplish all related work; indeed, many institutions outsource either phase (design or production) to institutions in different industries. The role of Systems of Innovations is crucial to understand the overall process of innovations in firms. In fact, this issue is a subject of current discussion in the field of Evolutionary Economics and New Institutional Economics.

The firms and the industry of one finished piece of equipment (turbine) and one highly related industry are considered here. The organisation of the industry follows a market criterion, and the technological change is related with many factors. Technological change is linked to both industrial and technological groups. In this case it may be observed in firms producing equipment and heavy parts and bellowing for the turbine industry. In turn this is a technological group linked to the metal products industry and other technological groups within that industry. The Francis Turbine is the focus of this paper because it is a mature industry, necessary for the analysis of modifications in both product and production, both of which are required to replicate the turbine design. The metal products industry has been the innovator of radical changes in the production of different equipment, machinery, intermediates and parts in the same industry, but its fragmentation and complexity makes it difficult to analyse.

The turbine industry is a mature one, in which there have been many important technological changes that have made the hydraulic turbine able to work at greater than 94% efficiency. These efficiencies have been favoured by radical transformations from other sectors, specifically from the metal mechanic industry, structural steel alloys, and the development of new materials for welding and soldering. Design processes have made possible not only to build and produce different constructive turbines, but have also demonstrated repercussions on cost and on the development of equipment in the civil and construction industries, which have simultaneously contributed to hydraulic projects. There are many different technologies for the conversion of energy, and hydroelectricity has occupied an important role in energy history. However, in recent decades, it has had to share prominence with dominant thermal technology, nuclear energy, and with renewable technologies that are capable of obtaining identical products[3].

The turbo-machine is associated with three technologies: generator technology; the compact-technology for forming, cutting, fixing and transportation; and control technology. With the first, the nexus become important as the design of the turbine must coincide with the design of the generator in terms of radial velocities, dame infrastructure and the electricity sector. Both turbo-machines and generators use a process similar to construction technology used in the metal mechanic industry. Control and regulation technologies have changed drastically from mechanical to electro-mechanic and electronic, and have become more dependent since automation has become typical. In recent years, digitalization has also become embedded in all processes. However, the digitalization of process, equipment, and materials has not directly influenced the MPMI and the turbine industry. However, accuracy and precision have been greatly affected by digitization, and it has had an enormous impact in increasing variety and size to enable more operations with increasing returns. However, this process has occurred in the 21st century, and it is not included in this analysis.

Hydraulic turbines belong to a technological group which is closely related to hydraulic machines. The technological group refers to the capacity to design machines assigned to group of institutions belonging to different industrial sectors. The design process of the machine and the design and projection about how to produce it are some of the most valuable proprieties provided by institutions and firms.

From an industrial perspective, hydraulic turbine production is related to three industries: the metal product manufacturing industry (MPMI), the electricity industry (power generation, transmission and distribution), and the construction industry, where the overall hydroelectric project is conducted.

Whether there has been an evolution of the hydraulic turbine cannot be directly determined; it must be viewed from different perspectives. On one hand, the evolution of the machine itself can be seen as a kind of result or output. One way to analyse the hydraulic turbine is by the specific velocity (Ns), which can be considered a technological summary of the hydraulic turbine. Other ways to analyse the turbine is to analyse the power, size, and efficiency. All of these refer to the intrinsic characteristics of the turbine, including performance results that would comprise a technological analysis. The evolution of the turbine can also be analysed by achievements in the production line: as a reflection of changes in the process, equipment, and materials. It is possible to make a connection between the result of better turbines in terms of specific speed and efficiency, as well as the progress of the industry in terms of process, equipment and materials used by the MPMI. This may be observed by changes which took place in the process of building turbine parts. What changes partially is the foundry

[2]No doubt also, they can came from an individual as a base science or a technological breakdown.
[3]There are countries where hydroelectricity has reach important levels of production such as Brazil, Canada and now China, however in general electricity from this source is declining, even its recent importance relationship with a sustainable development.

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process: this is substituted in part by the process of unifying steel parts through soldering. On the one hand new material of strong rolled tensile steel structures permitted the construction of bigger parts. On the other hand, there were improvements of soldering techniques. There were many innovations for over two decades which make possible the consolidation of this new technological trajectory.

The following section analyses the evolution of the Francis Turbine. Section III provides a description of the constructive process, as well as the equipment, machinery and materials of the related industry, and the spin offs which gives rise to technological change in turbine production. Section IV investigates the presence of radical technological change in the turbine industry or in related industries, and the development of new technological trajectories. Finally, some conclusions are offered.

II. EVOLUTION OF THE FRANCIS TURBINE

General speaking, a machine takes energy from a particular form and transforms it into another form. In a hydraulic machine, the flux which has interchanged energy does not change its density (and volume) when it is processed by the machine, in comparison to a thermal machine in which there is variation. This characterisation helps to classify machines, because the compressibility of the solid, liquid or gas will produce an equivalence in terms of thermal or hydraulic machines[4].

One way to classify machines is by the runner, which is the most important component of machines and the location of energy exchange. The runner movement can be rotational and alternative; the change and direction of the absolute value of the speed is different according to the type of movement. Pumps (generators) and hydraulic machines (motors) are turbo-machines which behave in a rotational manner. Hydraulic turbines are strongly related to hydraulic machines, specifically pumps for liquids and gas, and ventilators, which also maintain a strong relationship to electric machines.

Background

Turbines can be classified according to their degree of reaction: when this is null, such as in the case of a Pelton turbine, the turbine is considered dynamic. Otherwise, if the direction of the flow is diagonal, this indicates Francis turbine; if it is axial, it is either a Kaplan or Bulb turbine. Such turbines can regulate flow through their mobile blades. The key features of these turbines are altitude pressure and flow, which were difficult to design and apply in previous decades. Straflo turbines (a sub-set of the Bulb turbines) and standardised turbines were historically gaining importance. In the last years of the 20th century, Francis turbines predominated and comprised more than 60% of the MWs installed in the world. However, from an installed unit perspective, the Bulb turbines were more important. This article analysis the Francis Turbine as a model. This turbine is a reaction (motor) flux machine with an extensive range of height (m) and flow (in m^3/s).

Basic changes in turbines which took place in the mid-19th century drastically modified their efficiency. Technological changes emerging out of this sector took place in the formative stages of this industry (as they now take place in the metal-mechanic industry). The evolution of turbines coincided with the evolution of technological change. The first turbines were derived from modifications made by Combe to outgoing water pipes so that they would adjoin, originating in a change in the hydraulic wheel and turbine. It is widely acknowledged, however, that present-day turbines originated from the modification which occurred when part of the Cadiat turbine was modified by adjusting the blades within the wheel to make the water flow in one direction. This modification, combined with the immersion of the wheel in water, produced low absolute speeds at the outlet and became what is formally acknowledged as the first turbine.

The Henschel Joval turbine, by introducing a suction tube which enabled the available waterfall to be fully harnessed, represented another significant modification. Of particular interest is that these changes in the design are in some way similar to the modifications made to the steam engine in order to incorporate the condenser (cooling system).[5] The Francis Turbine design modified this model by facilitating external water access and by developing a radial turbine or vortex which makes the jet of water reach the blades and exit in a parallel direction to the rotational axis. A constant regulation system was made possible by the introduction of the Fink vanes, manufactured by Voith in 1873; by regulating water access, the turbine reaches more efficient charge levels.[6] Minor adjustments were made to each of these modifications to the extent that by the beginning of the 20th century, both American and European companies were clearly in a position to describe the efficiency ceiling under different charges, and companies such as Morgan Smith Co. began to record their routines using efficiency diagrams.[7]

The efficiency of a turbine depends on its hydraulic, volumetric and mechanic losses and in turn, hydraulic turbine efficiency can be divided into two distinct stages.[8] Before directional blades were made mobile at low charges, turbine efficiency varied between 45% and 65%. After mobile blades became common, efficiency with the lowest charge reached 85%. Since then, efficiency has not varied greatly, and improvements have been relatively small. In 1920, Francis Turbines

[4]When the flux is incompressible it will be referred to another machine

[5]See [8] for the role played by the condenser in the Combe steam engine.

[6]There were further modifications, which took place mainly in factories where it was possible to reproduce them on a larger scale. Other developments included the tangential wheel of Zuppinger in 1842 especially for higher falls and reduced flow. Girard made improvements to the Fontaine wheel which were based on the axial turbine of Jonvall and used for larger flows. In 1912 the Kaplan turbine was developed. See [9].

[7]See for example, [10] for a discussion of hydraulics and turbines of the period.

[8]The efficiency can be determined whereas the internal and the mechanic output efficiency or considering the volumetric-hydraulic and mechanic efficiency. In both case the efficiency do not depend of the head. See [11].

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operated with an efficiency of approximately 85%; thirty years later it had reached 90%, and by the 1980s it had marginally increased again, reaching 93%.[9] Small changes in efficiency have been under 1%, in recent decades and efficiency is expected to increase at a steady rate while total kW cost installed will increase even faster than previously.

The Specific Speed (Ns) of the Francis Turbine

The evolution of the Francis Turbine can be measured by the specific speed (Ns), which summarises the turbine's most important characteristics. The Ns is determined by rotation speed (rpm), the height of the fall (m) and the water flow (m^3/s). Another way of interpreting Ns is by considering the turbine power[10] in (kW). Specific speed aids in understanding of turbine evolution and to put aside dimensions of the turbine to make possible the comparison of turbines with different features.

Turbine power is associated with the exploitation of a natural resource, where hydroelectric development (in terms of potential head and flow) has been designed for a specific location. Turbine size, power range, and efficiencies vary greatly, and are defined by an iterative calculation that takes into account the first data and initial estimates of the location's potential.[11] Various design options are generated based on a comprehensive determination of the main variables and forms, resulting in an understanding of all the processes required to obtain an optimum turbine, in addition to the pipe and the generator. Historically, however, there was no uniform formula for the manufacture of turbines. Some experts have argued that emphasis was placed on variable cost reduction rather than on investment [1]. Others insist that maximum potency at a minimum cost was the key factor [3]. These two positions differ considerably: one prioritises replacement cost reduction, whereas the other places an emphasis on overall cost. Each corresponds to a different generational technology which implicitly emphasizes minimizing cost reduction as a standard concept in conventional economics, and which does not always hold in the long term.

Although changes in turbine efficiency and specific speed are not necessarily dramatic, they are incremental. The most dynamic changes took place in the 19th century. Those changes that took place in the 20th century were significant in the technological sector itself, but have not had major repercussions in efficiency and their effect on Ns is not clear. Fig. 1 shows specific speed and height over several decades, demonstrating a change in Ns over time as an upward displacement curve.

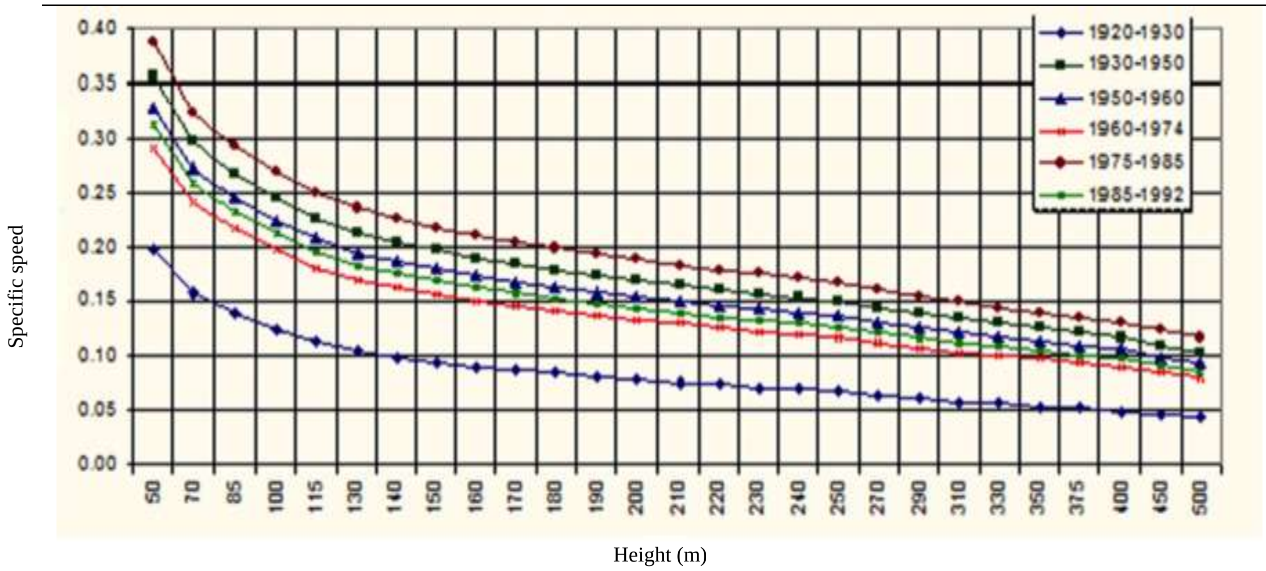

Fig. 1 Specific speed 1920-1992

Source: Author's calculation based on data of primary producers.

Turbine changes can also be analysed by the H-Ns component, which is developed here and represented by **(X):**

$$\mathbf{X} = \sum_{i}^{h} \left((Ns_i - Ns_0)^2 + (H_i - H_0)^2\right)^{½}.$$

This component of the height (H) and specific speed (Ns) is given by the sum of the distance from the origin (0, 0) to the plotted points (H-Ns), given a regression function to Ns = f(H) which measures the sum of the distances by the association between height (H) and specific speed (Ns) under different regression curves in different periods. The specific number of revolutions (Ns) allows us to classify the hydraulic machines according to geometric similarity criteria, by which turbines can be compared according to their specific speed (Ns) independent of their size. This is a useful, direct result since it allows us to

[9]During the sixties, the highest efficiencies reached 93.5%. For a more complete review see [1] and [12].
[10]Two common ways to calculate the specific speed are $Ns= nP^{0.5}H^{-1.25}$ considering the power, and $Ns=nQ^{0.5}H^{0.75}$ considering the flow.
[11]An optimum design in for specific speed, potency, and efficiencies, is reached after several iterations. See [13], [5], [14] and [11].

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make a synthesis of each hydraulic machine. It is a design variable because it contains information referring to the power (MW), the speed (rpm) and the height (m).

The analysis of the turbines produced globally by different companies demonstrates a correlation between height and specific speed for different periods. This correlation is reinforced by previous researchers [2, 3] who analysed the 1960-1974 and 1975-85 periods, respectively. The specific speed (Ns) alone cannot measure different turbines in time. However, the introduction of the H-Ns component can help trace the overall development of turbines.[12] Table 1 depicts the value of the H-Ns component.

TABLE 1 H - NS COMPONENT (X)

Period	Value
1920-30	6,889
1930-40	7,847
1940-50	8,630
1950-55	8,405
1955-60	7,765
1960-64	7,559
1965-69	7,755
1970-74	7,829
1975-85	8,713
1985-95	7,902

Source: Author's calculation based on data of the primary producers. See appendix.

Other studies have analysed this issue by focusing on turbine production during the latter half of the 20th century, and have concluded that specific speeds (Ns) incur measurable changes at higher falls but not at low falls. In this regard, previous researchers [4, 6] analysed the Francis Turbine and the progress of specific speed. According to previous and current analyses (1950-1980), during the forties, the component H-Ns was high in low drop waterfall harnesses. Two technologically distinct periods can thus be observed: one corresponding to the period 1940-1950, and another corresponding to the period 1975-1985. Even though the H-Ns value is greater in the latter period and they were designed and built differently, both adhere to the same fundamental principles. The idea that lower heads imply greater options for synchronous generators in turn favours the thesis that technological capacity in the forties (both the exploitation reservoir magnitude and the turbine design and manufacture) was important enough to obtain a larger Ns. This was not surpassed until the period 1975-1985, once the technology for turbine production and its association with electric generators had been mastered.

Capacity, Height, and Size

The capacity of turbines has witnessed constant growth. Prior to the 1950s, the power of turbines measured in MW (mostly exploited in waterfalls) had potencies less than 60 MW. However, in the following two decades, the exploitation of higher waterfalls and larger volumes of water necessitated the construction of more powerful turbines, some of which reached up to 600 MW. This may be observed in Fig. 2 (power average in the 1920-1992 period). The value of the H-Ns component during the period 1920-1955 is associated with the steady growth of turbine potency. After 1960, although capacity increased dramatically, the value of H-Ns did not. Nevertheless, in the 1980s the H-Ns component increased and peaked slightly higher than the maximum value which was observed in the 50s. Although there were radical changes in turbine potency, this was not accompanied with parallel average height, since the exhaustion of available exploitation waterfalls declined (Fig. 3). Another result of this situation was the development of more intricate and available resources which necessitated the creation of more powerful turbines (of greater size and rotor diameter) for greater volumes of water, in contrast to a greater number of smaller and less powerful turbines as were proposed in the hydro-power dam developments of earlier decades.

[12]Specially turbines where potency is bigger than 15 MW to the largest types.

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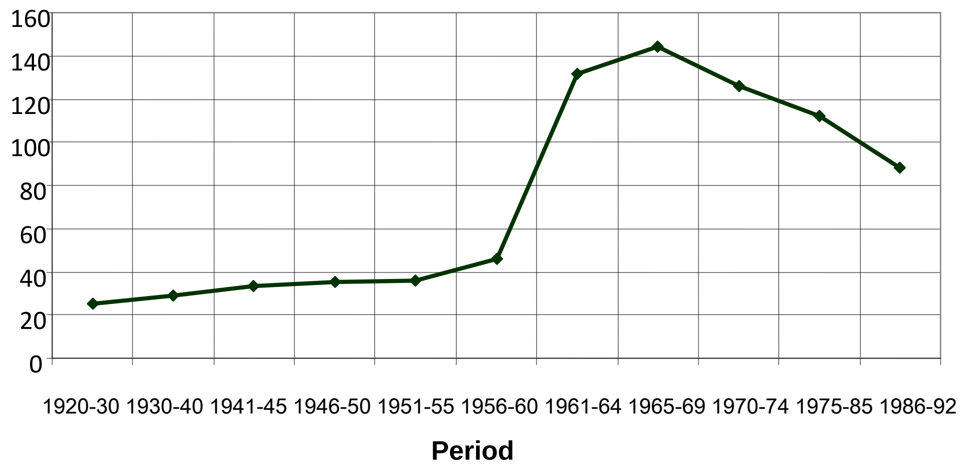

Fig. 2 Average Power of Francis Turbine (MW)

Source: Author's calculation based on data of the primary producers.

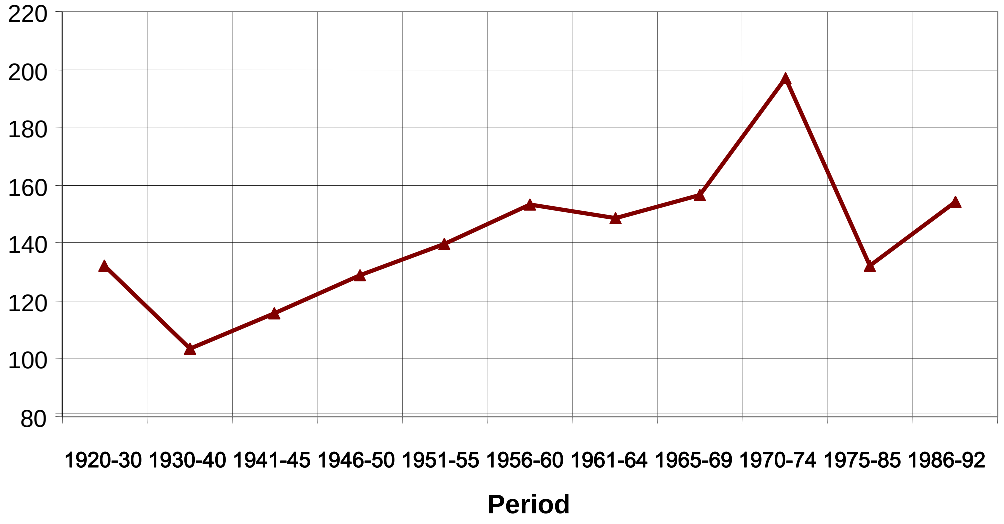

Fig. 3 Average-height (m)

TABLE 2 MANUFACTURED TURBINES GROWTH RATE IN INSTALLED MW

Period Rate	%
1930-40	7.1
1941-50	7.0
1951-60	3.9
1961-70	8.8
1971-80	5.0
1981-93	-4.2

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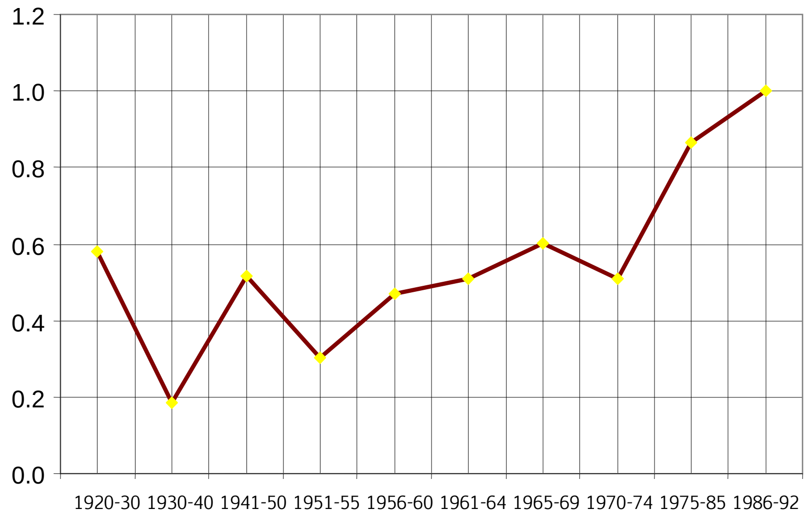

Fig. 4 Index cost MW-turbine (1920-1990)

Source: Own calculation based on data of the main producers

An association between the average exploited height and the growth rate of the MW of manufactured turbines can be observed. Following the 1970s, the growth rate of hydrological exploitation declined. This is associated with smaller harnesses and waterfalls available for exploitation, since the rate of turbine production (installed MW) fell from 8.8% (1961-1970) to -4.2% (1981-1993). It can be observed that globally, the exploitation of hydrological resources has been decreasing with a corresponding reduction in its participation relating to total electric power capacity (Table 2).

When there were larger volumes of water, it became more economical to install turbines of a larger capacity, but this does not necessarily imply a definitive association between a larger capacity and size nor a reduction in cost of the MW, from the perspective of the hydroelectric project as a whole and the MW turbine. Although the cost of MW had not been as high as it was in the 1920s, this situation changed after the 1970s, as shown by Fig. 4. The same situation occurs when investigating the cost of MW of the overall hydroelectric project, in which the rate of change increased more than the cost of an MW turbine (since the index cost of MW hydroelectric project was estimated from 0.2 in 1920 and growth to 1 in 1990). Increased costs of skilled manpower and raw materials have also had a major impact on the costs of MW turbines and MW hydroelectric projects after the 1960s. This effect was reduced in the 1990s by using cheaper skilled labour coming from developing countries and more flexible machine tools.

Sources of the Design

It is difficult to insist that the theoretical foundations of hydraulic machines have changed, in particular for the turbo-machine where it has not been necessary to develop a new analytical basis, since the hydrodynamic principles of Bernoulli and Euler's equations still form the basis for their design. In the design process, there have been assumptions based on the viscosity, the incompressibility of liquids, and the flux continuity of a particle. However, it is difficult to support the view that the theoretical basis to design, particularly the Euler Equation, viscosity, incompressibility and the ideal gas assumptions have ceased to be the core of the design.[13] On this basis, it has been possible to design machines with significant technological developments. In turn, the limit layer theory has helped to solve situations in which the flux is not ideal and the viscosity is as light as air, and water particles on micro-surfaces where the strongest forces of torsion and deformation can be observed [11, 15]. More recent designs have been possible and due in large part to technological achievements not only in the methods for band detection of permissible parameters, but also through laboratory experiments using new measuring equipment. These have been supported by collaborative research amongst companies and industries conducting research in dynamic analysis.

III. TECHNOLOGICAL CHANGE IN TURBINE PRODUCTION

Related Industry

Turbines in connection with dam-infrastructure developments were an essential component of the evolution of the turbine as a complex item of equipment. Once construction was no longer dominated by a skilled workforce and turned into a scientific and technological industry in the 20th century, newer designs for larger hydraulic machines were made possible by infrastructure works in situ. Nevertheless, engineering works in situ are not completely responsible for radical change; they

[13]Even if the velocity microscopic analysis of the particles, there is not a dramatic impact in the turbo-machine.

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rather contribute to the development of hydroelectricity by taking and applying technological achievements from other sectors. These advances, such as the development of large scale machinery and heavy machinery for transport of materials and for the machinery of turbines themselves, the development of special steel and other materials, and varieties of cement, made possible the development of the construction industry which in turn led to larger hydraulic turbines. Simultaneously, it was still possible to build the complete turbine in a shipyard.[14]

It is possible to arrange the technological development into three categories of development: the use of artefacts and equipment (E), the development of materials (M) especially steel, and the process (P) for creating turbines. Thus, if the technology changes in any one of these categories, the overall change of E, M, and P will also be affected. The size of the turbines and projects that were developed during the previous five decades altered, reaching their peak by the end of the 1950s. This increase was a result of forming-forging and smelting-founding processes, together with new technologies to join materials based on milling, drilling, riveting, trimming and rolling. This technology reached its peak in those years and then began to decline due to latent technologies. It can be resumed according to the following recommendations.

Changes in the Production Process for the Manufacture of Turbines

i) The forming process such as forging, smelting and cutting were affected by the supply of larger parts from other manufacturing industries such as the iron and steel industry, by the introduction of a soldering process, and also by improvements to foundries themselves. The supply network bringing larger parts helped in turn to grow capacity as the industry itself grew. The role played by the rolled high tensile strength steel started to change the conventional process of foundries, and riveting presented challenges to the construction of larger fixed and mobile parts.

ii) The much-improved process of welding and soldering (W&S) makes possible transformation in the size of equipment as it enabled the production of larger parts for turbines.[15]

iii) The transportation of larger parts was made possible by the development of infrastructure and equipment. This encouraged in situ installation.[16]

iv) The design process was improved following a greater understanding of cavitation. Methods of reduction included the combination of hard materials, soldering and reduced friction by exposing specific parts to higher pressures. In the 1990s, the application of the finite element method permitted the optimisation of a larger number of possibilities promoted by the intensive use of supercomputers. The basis for this design process did not emerge from scientific change, but rather from informatics, a technology that allowed the simulation of different prototypes.[17]

Changes in the Technology and Process

With the development of new design processes, numerical control equipment, and more adequate materials, it became possible to build larger turbines. Aided by improvements in the production process this led to increases in the specific speed, which can be explained as follows.

i) Research conducted by turbine aeronautical constructors using new equipment to experiment in large industrial capacities helped to overcome the problems and obstacles to cavitation and allowed the creation of turbines with a higher revolution. These problems were solved through understanding the effects of speed variations.[18]

ii) A reduction in process time, specifically in the forming and metal cutting operations, helped increase productivity due to improvements in the machinery itself.[19]

iii) The replacement of smelting processes by others that involved joining materials through welding required a new kind of equipment. The equipment used in present-day welding still has potential for research and development.

iv) The more intensive use of numerically controlled equipment, which has introduced higher intensity hardware and more complex software, resulting in improved design (which reduced the cavitation problem) and fewer losses through friction[20]. In addition, owing to better visualization of the internal zones of pressure in mobile parts, it was possible to redesign some parts of the turbine by re-shaping the surfaces which were subject to severe pressure.

Steel and Welding Compounds

The introduction of new materials and the W&S processes enabled the construction of new and larger turbines for large-scale exploitation. Improved materials such as stronger and tensile strength steel based on a combination of Cr/Ni (13/4,

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[14]In this aspect see [16].
[15]Previously, the process included smelting, milling, drilling, trimming, rolling and bolting parts with different sets of screws. See [14] for the application of welding process in large turbines.
[16]Moving and placing equipment *in situ* was supported by new cranes with greater capacity and size, which in turn was made possible by the W&S process and the more extensive supply network.
[17]Reference [17] have analyzed this path in this industry.
[18]Based on studies on fluids and the progress in hydrodynamics applied to hydraulic machinery. See [13].
[19]This is thanks to a greater automation and numerical control of the equipment. Similarly, more time was devoted to design rather than forming and cutting operations.
[20]In the nineties the intensive use of CAD/CAM (and its evolution) was crucial for improved design.

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16/5) began to substitute for steels with less Ni content (13/1) in mobile parts, especially in the runner, the part which determines the size of the turbine. Hence, this directly improved the Ns.

Very similar to the new steel alloys, the new combination of steels applied to W&S compound (Ni/Cr/Mo) together with better welding and soldering processes based on improvements in the electrodes, resulted in greater degrees of hardness, and an improvement in the use of stainless steel to counter cavitation. Hence, not only did the development of the soldering process itself turn out to be important, but also its association with techniques to reduce rusting resulted in important advances for complete substitution[21]. W&S, in addition to introducing materials, also introduced the joining of materials, which in turn implied a process of new-substitution by means of re-shaping with another kind of milling and drilling, and advancing towards others forms of founding. This had immediate consequences not only on size, but also resulted in higher speeds, which in turn increased the specific speed.

IV. RADICAL TECHNOLOGICAL CHANGES IN THE TURBINE INDUSTRY

It is not clear if the evolution of the Francis Turbine was interrupted. Its size and potency after the 1950s suggest a breakthrough in the earlier technology. However, this is not immediately evident, because once the size and potency of turbines became larger, specific speed (Ns) did not necessarily change in the period between 1920 and 1990, as shown in Fig. 1.

Simultaneously, an alternative analysis might show a much larger increase in turbine potency and size beginning in the 1960s, associated not only with increased height exploitation, but also from the perspective of the hydrological dam resource as a whole. This would suggest new technological changes, since these are not explained by incremental transformations. Alternatively, changes in other industrial sectors related to the manufacturing industries and the production of electricity can be considered radical. Measuring the magnitude of these technological changes implies an association with a set of variables which in turn enables this qualitative leap.

The value of H-Ns reached two peaks: one in the late 1940s, and another in the early 1980s. However, there was no continuous increase between these two periods, as the component did not vary much from the overall H–Ns component. Therefore, no radical change in the H-Ns component can be observed in comparison to potency and size. This would suggest a difference in terms of technological change which cannot be strictly interpreted as radical shift, and in turn leads to a complex discussion in regard to the continuity or discontinuity of technical progress. What must be emphasized, however, is that a change is radical in as much as it employs different technology, which is observed in a decrease, rather than an increase, in the value of the H-Ns component, in both technologies. In other words, the turbine constructions based on the process of foundry and traditional forming by cutting steel and those based on structural plates of stronger tensile steels joining with W&S. Both of these are incremental, since the first started to decline and the second started to dominate. The latter is incremental in as much as it obtains its maximum as a technology. This trajectory and analysis is limited since the decrease in value of the component H-Ns is associated with a new technology, and because it is generally assumed that new technology brings improvement. It was noted that it took more than twenty years for the H-Ns component to reach and/or supersede the value yielded by the displaced technology. Hence, to understand stability improvements it is necessary to know how the new technology was mastered once the problems of the process of W&S become solved by firms and it became possible to reduce the risk of cracking owing to stronger pressure in mobile parts and to reduce cavitation and periodical revision of the turbine.

Nevertheless, the new turbine of the 1960s did embody radical changes, explained not by specific scientific theory, but because it was possible to design and craft a more reliable turbine. It is not the case that a change in power was developed in an incremental way, but a radical shift under scientific paradigm would imply changes in the specific speed or changes in the dimensional values, which indeed did not occur. Design did not stop being governed by Newtonian mechanisms of constant velocities, under the Euler and Bernoully basis, because nothing happened to the assumptions of constant velocities and smooth acceleration. Even so, there is a now a renewed understanding in regard to what happens to micro-particles under very high pressures. This has aided the understanding of cavitation problems, which has created more relievable turbines. This difference can be understood as a radical change in the scientific paradigm as a result of a technological change. Naturally, in the hydraulic turbine, this would correspond to a change in the technological paradigm explained by an increase in potency and in the size of the turbine, in turn corresponding to the incorporation of new materials and significant changes in the processes, which together increase the specific speed (Ns).

Design changed the way in which turbines have been analysed because it became possible to adapt the dynamics of the fluids owing to other methods of analysis; for example, using the infinitesimal method. This gave way to an improved design which made it possible to understand method by which to reduce friction and cavitation problems, which in turn led the way to solving other problems related to vibrations, noise, and durability.

Finally, whether or not the process of digitalization has affected the overall MPMI through the substitution of mechanical and automatic process is a question for the future analysis. In this analysis, it is possible to say however, at this stage, that the

[21]New techniques are associated with new machines and welding equipment.

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small decrease in the H-Ns component after 1990 could be explained by the introduction of digitalization and the recovery after the 20tth century will happen.

V. CONCLUSIONS

Radical change is not possible without modifying the dominant design of the turbine itself. Additionally, a radical technological change does not necessarily imply a dominant design in term of design conception based on scientific validity. It is possible, however, to have a dominant design as well as a technological change. Radical technological change derived from the power and size of the turbines, and the change in the compound H-Ns, are both reflections of a new dominant design. However, it is difficult to support the perspective that the theoretical basis of design, particularly the Euler Equation and the viscosity, incompressibility, and the ideal gas assumptions have ceased being the active core of the design. Hence, a deep technological change or an interruption of a technological regime does not necessarily indicate change in the dominant design from a strictly scientific basis.

Change in production must have occurred in order to design and produce new turbines; these changes also involve economic organization. The design process in the development of the turbine is necessary, but even more important is the development in the production process, laboratories and management. The co-evolution of both industries (turbines and MMI) can only exist within the context of their technological group. The interrelation of the industries can be supported by the development of technologies; it is therefore necessary to specify the dynamics of the technologies.

The role played by firms and institutions cannot be separated from the technological group itself. Industries as a conceptual construct can lead to an understanding of the organization of markets and industries as a consequence of the division of labour. However, the technological group influences the rate and direction of the industries, and in order to understand technological change it is necessary to discuss specific technologies. The firms – i.e, the coordination of routines, institutions and systems – are the context of technological change, and this must be analysed further in order to understand the success of new technologies.

APPENDIX

Calculation of the specific speed and H-Ns component are calculated from different information and data sources. The data analysis demonstrated in the figures, graphs and tables was based on: i) Direct information from turbine manufactureing, primarily based in Europe and Mexico, with special contributions from Neypirc, Sulzer-TEISA, Sulzer E&W, Voith, CFE, and Japanese companies obtained via ministry officials. ii) Official statistics of the metal mechanic industry in the EUA, Germany and Mexico [a, b, c, d, e, f]. iii) Statistics and technical data of primary turbine manufacturing [h, i, j, k, l, m].

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